RECENT AND HISTORICAL COASTAL CHANGE

UNDER RISING SEA LEVEL,

MCNAB'S ISLAND AREA, HALIFAX, NOVA SCOTIA

by

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Abstract

A lengthy historical record of coastal evolution was combined with measurements made at weekly to bi-weekly intervals over approximately 550 days of coastal monitoring to investigate the evolution of the McNab's Island area, a transgressive drumlin shoreline hosting gravel beaches.

Sub-annual to annual-scale records of bluff retreat, bluff erosion, foreshore erosion, till water content, well water level, sea level, waves, winds, precipitation, and air temperature demonstrate that storms are important in causing bluff and beach failure and retreat. Increased wind speed, wave height, water level, and precipitation accompanying storms interact with barrier beaches and clay-rich till bluffs and cause geographically variable coastal change over sub-annual time scales.

Historical charts, airphotos and records of sea level, winds, and waves indicate that rates of coastal change are spatially and temporally variable and that the interactions of rising sea level, storminess and sediment supply to barrier beaches have controlled the evolution of the study area over decadal time scales.

Rapid coastal change occurs only when sediment supply limitation, rapidly rising sea level, and increased storminess coincide, as between 1955 and 1964. Storminess and sea-level rise are both related to the North Atlantic Oscillation and affect sediment supply, giving rise to nonlinear and cyclic behaviour. Episodes of rapid beach and bluff retreat are preceded by long periods of stability and beach progradation during which offshore sediment reserves are depleted and the beach is morphodynamically conditioned to future failure due to accelerated sea-level rise and increased storminess.

List of Abbreviations and Symbols

Abbreviations

ASTM	American Society for Testing and Materials
CHS	Canadian Hydrographic Service
GPS	Global Positioning System
GSC	Geological Survey of Canada
IPCC	Intergovernmental Panel on Climate Change
MEM	Micro-Erosion Meter
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
PANS	Public Archives of Nova Scotia
RMS	Root Mean Square error
RTK-DGPS	Real-Time Kinematic Differential Global Positioning System
RSL	Relative Sea Level
SO	Southern Oscillation
SOI	Southern Oscillation Index

Symbols

S_u	undrained shear strength
w	% water content
n	number of samples
σ_w	standard deviation of water content
σ_{Su}	standard deviation shear strength
V	volume of sediment
X	amount of horizontal bluff retreat
L	bluff length
H	bluff height
E_x	error of horizontal retreat measurement
E_v	error of sediment volume calculation
R	bluff retreat rate
T	time interval between measurements
E_R	error of retreat rate calculation
T_{min}	minimum time requirement

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Chapter 1

Introduction

1.1 Introduction and Statement of Problem

Relative sea level is currently rising at Halifax due to the combined effects of post-glacial eustatic sea level rise and isostatic subsidence of the crust, resulting in conceptually well understood transgression of a drumlin shoreline. As the erosional front of the transgressing shoreline moves landward, glacial sediments, primarily in drumlins, are eroded. Sediment is supplied to the shoreline and reworked to gravel barrier beaches and a shallow offshore sand sheet. As drumlin sources are consumed, supply to beaches dwindles and they cannot continue to grow and keep pace with rising sea level. Barriers overwash and retreat, are destroyed, and redeposited at a more landward location (Boyd *et al.*, 1987; Carter and Orford, 1988).

Details of this process over a variety of time scales remain unclear. Over decadal time scales the relative contributions of beach sediment from eroding bluffs (defined here as sea cliffs in eroding unlithified sediments) and sediment moving landward with transgression are uncertain. The Inner Scotian Shelf is relatively sediment poor (Forbes *et al.*, 1991b), yet bluffs have been shown to supply lesser amounts of sediment than required to maintain barrier beaches (Piper, 1980; Sonnichsen, 1984). Additionally, the presence of beaches protects bluffs from erosion, implying a morphodynamic feedback relationship between beaches and the bluffs that supply them. The implications of feedback relationships between bluffs and beaches and the effects of varying sediment supply on coastal change over decadal time scales are not well known.

At shorter (sub-annual to annual) time scales, the detailed processes of transgression are also not well understood. Annual retreat of bluffs and beaches has been measured at many locations in Nova Scotia since the mid-1970s (*e.g.* Bowen *et al.*, 1975; Sonnichsen, 1984; Taylor *et al.*, 1985, 1995) yet the relative importance of the sub-annual erosional processes driving this retreat are largely unknown.

Recent estimates of current global sea level rise range from 0.6 mm/a to 1.8 mm/a (Gröger and Plag, 1993) and the Intergovernmental Panel on Climate Change reported several different scenarios of future accelerating rates of eustatic sea-level rise in response to greenhouse-induced global climate change. These range from 1.6 mm/a to 4.7 mm/a over the period 1995 to 2100 (IPCC, 1995), with a worst case scenario of 6.4 mm/a to the year 2500 (Raper *et al.*, 1996). If these are simply added to the maximum rate of historical relative sea-level rise at Halifax, rates may reach 9.4 mm/a over the next 100 years (*cf.* Shaw *et al.*, 1993).

Global climate change may also result in changing patterns of storminess (Emmanuel, 1987; Agee, 1991; IPCC, 1995). Storms increase energy incident on the shoreline; accelerated coastal change may be associated with storms and increasing storminess (*e.g.* Davis and Dolan, 1992; Forbes *et al.*, 1997).

Numerous studies on the Eastern Shore of Nova Scotia have identified several areas of active shoreline retreat, particularly at the entrance to Chezzetcook Inlet (*e.g.* Carter *et al.*, 1990a; Forbes *et al.*, 1995a; Taylor *et al.*, 1999). An excellent historical record consisting of charts and airphotos depicting Halifax Harbour since 1711 shows that the McNab's Island area has also undergone rapid coastal change in historical times;

the causes of decadal-scale variability in coastal response to climatic forcing are not well understood.

Investigation of historical, decadal-scale shoreline changes coupled with field study of sub-annual to annual causes of bluff and beach retreat may assist in further determining the responses of drumlin shorelines, and specifically the McNab's Island area where significant historical and recreational resources exist, to both greenhouse induced relative sea-level rise and changing storminess over a variety of time scales.

1.2 Objectives

1) To investigate and identify major contributors to the assailing and resisting forces determining annual and sub-annual bluff retreat and erosion and the processes by which these occur.

2) To investigate the historical evolution of the McNab's Island area to determine the relative importance of sediment supply from bluff and offshore sources to shoreline evolution.

3) To identify and investigate anthropogenic and environmental factors forcing decadal-scale coastal change.

1.3 Structure of the Thesis

Chapter 1 is an introduction to the thesis and briefly presents some previous research, the problem and objectives of the thesis, and the study area. Chapter 2 presents the methods used and results obtained in addressing the thesis objectives. These methods and results are referred to and re-examined in Chapters 3, 4, and 5, which address specific problems and issues. Further background and previous research of relevance to the objectives are given in each chapter. Chapter 3 considers sub-annual to annual time scales of bluff and beach retreat and erosion over approximately 550 days of monitoring from 1997 to 1999. Chapter 4 explores the historical record of coastal change in the study area and outlines the roles of beach mining and the sediment budget in controlling coastal change. Chapter 5 builds on the discussions and conclusions from Chapters 3 and 4 and considers the roles of changing climate and storminess, relative sea-level rise, and sediment supply in contributing to the historical coastal evolution of the Thrumcaps at the southwestern end of McNab's Island. Chapter 6 summarizes the previous chapters, placing the various time scales investigated in context with each other.

1.4 The Study Area

The McNab's Island area lies at the entrance to Halifax Harbour at the southwesternmost end of the Eastern Shore and includes McNab's and Lawlor Islands and the adjacent mainland to the east from Eastern Passage to Hartlen Point (Fig. 1.1). To introduce the study area, the physiographic setting, Late Quaternary stratigraphy, coastal geomorphology, and relevant marine geology will be briefly described.

1.4.1 Physiographic Setting

The Eastern Shore, to the east of Halifax Harbour is glaciated and submergent, incised by fault-controlled, northwest trending basins eroded into slate and meta-greywacke of the Cambro-Ordovician Meguma Group. Eroding drumlin headlands formed by up to four stacked till units (Stea and Fowler, 1979; Sonnichsen, 1984) divide the coastline into discrete morphodynamic cells (*cf.* Carter and Woodroffe, 1994). The

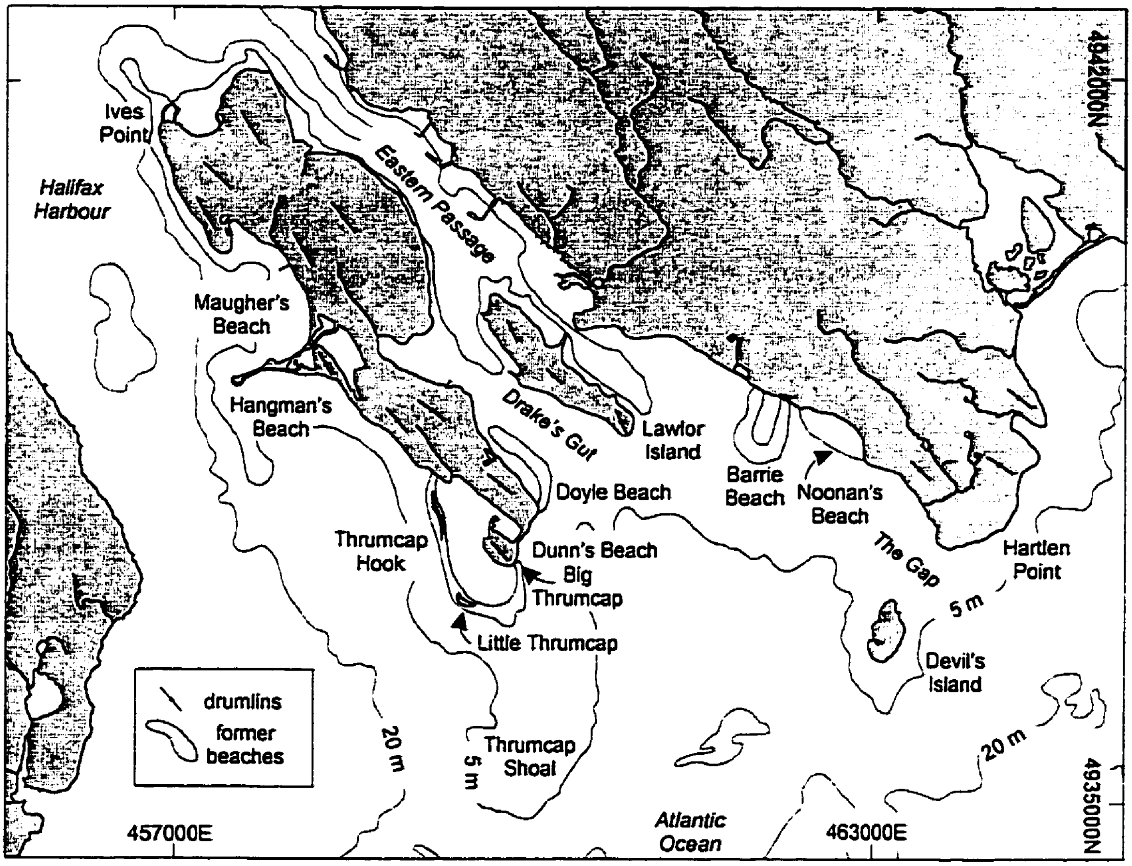


Figure 1.1 Map of the McNab's Island area, Halifax Harbour.

morphology and physiography of the western entrance to Halifax Harbour is more representative of parts of the South Shore; coastal cliffs are formed in white granites of the Devonian South Mountain Batholith and surficial sediment is generally thin.

Halifax Harbour is open to the Atlantic Ocean and McNab's Island shelters the inner harbour from storm winds and waves. Winter storms and hurricanes affect the study area. Winds may reach as high as 100 km/h and deep-water wave heights may reach 10 m. Halifax Harbour has an approximately 2 m tidal range and is generally ice-free. Ephemeral sea-ice forms in sheltered embayments with a supply of fresh water, and back-barrier lagoons may freeze from December to March.

1.4.2 Late Quaternary Stratigraphy

McNab's Island is approximately 4.5 km long and composed of 10 southeast-trending drumlins reaching a maximum elevation of 45 m (Figure 1.1). Lawlor Island is composed of 3 sinuous drumlin forms also trending southeast reaching a maximum elevation of 27 m. Bluffs in the study area are formed usually across drumlin axes but may also be formed in the sides of drumlins nearly parallel to their trend.

Two tills outcrop in bluffs in the study area. The lowermost Hartlen Till is a dense grey lodgement till (Nielsen, 1976) deposited by ice flowing from a centre in New Brunswick and Quebec, during the Caledonian ice flow phase (Stea *et al.*, 1992) approximately 70 to 30 ka (Stea, 1995). This till is found at the base of bluffs at Hartlen Point (Figure 1.1) and on the west side of McNab's Island and underlies the Lawrencetown Till below a sharp contact with associated boulder pavements in the Lawrencetown Till.

Most bluffs are formed in the red, clay-rich Lawrencetown till (Nielsen, 1976) deposited approximately 21 to 18 ka (Stea, 1995) by ice flowing from Prince Edward Island or the Minas Basin during the Escuminac ice flow phase (Stea *et al.*, 1992). The thickness of this till in most places in the study area is unknown as the bottom is not exposed, but can be greater than 12 m. Three facies are found in the Lawrencetown Till. The predominant facies is the clay facies consisting of approximately 30% clay. This is overlain by a sandy facies comprised of approximately 50% sand up to 2 m in thickness that tends to thin toward drumlin apices (*cf.* Stea and Fowler, 1979). The sandy facies is incised by small (<2 m) cobbly gravel channels of stony facies. At one location on the west side of Lawlor Island a partially exposed channel greater than 10 m wide with bedded gravels is incised into the clay facies forming the largest outcrop of stony facies. Local sand and gravel lenses may be present within the clay facies.

A third till, the Beaver River Till, is found in a thin (<1 m) discontinuous sheet only on Devil's Island. This till is locally sourced (Stea and Fowler, 1979), contains clasts of Halifax Formation, and was deposited during the Scotian ice flow phase when ice flowed from a divide along the axis of Nova Scotia (Stea *et al.*, 1992) approximately 17-14 ka (Stea, 1995).

1.4.3 Shoreline Morphology

The morphology of drumlin shorelines on the Atlantic coast of Nova Scotia has been well documented (*e.g.* Barnes and Piper, 1978; Wang and Piper, 1982; Piper *et al.*, 1986; Sonnichsen, 1984; Taylor *et al.*, 1985). At McNab's Island the trend of drumlins is sub-parallel to both the direction of longest fetch (open to the Atlantic Ocean) and the direction from which storms may come. Headlands break up the coastline into discrete morphodynamic cells. Because of the morphologic arrangement of drumlins, sediment supplied from drumlin headlands and incident wave energy, which dynamically controls beach morphology, are segregated into separate embayments (Carter and Woodroffe, 1994; Forbes and Taylor, 1987; Carter *et al.*, 1990a).

Beaches may form either parallel (drift-aligned) or perpendicular (swash-aligned) to the dominant wave direction. In the study area most beaches are drift-aligned, thin, and backed by bluffs with varying rates of retreat. Coarse-clastic or gravel beaches are divided into shore-parallel zones consisting of an outer imbricate boulder or cobble frame, a zone of mixed sand, pebbles and cobbles termed the gravel sorting zone, and the most landward zone against the bluff toe consisting of possibly terraced beach gravels mixed with mud flow deposits from bluffs (*cf.* Bluck, 1967; Carter *et al.*, 1990a; Carter *et al.*, 1990b) (Figure 1.2). The highest part of the beach is termed the crest, and may be in contact with the bluff toe, or, in areas of abundant beach sediment, may form a ridge seaward of the toe. Seaward of the outer boulder frame is found a shoreface sand sheet which may extend to water depths of 10 to 20 m (Piper *et al.*, 1986; Hall, 1985).

1.4.4 Marine Geology

The Inner Scotian Shelf has been subdivided into a number of shore-parallel morphologic and seismic zones (Forbes *et al.*, 1991b; Stea *et al.*, 1994). Closest to shore is the Truncation Zone between 90 m water depth and the current shoreline, comprising the area of sea floor that was affected by transgression since the sea-level lowstand (Stea *et al.*, 1994).

The Truncation Zone is divided into four subzones. Of particular interest to coastal studies near Halifax are the Transition and Estuarine Subzones. The Transition

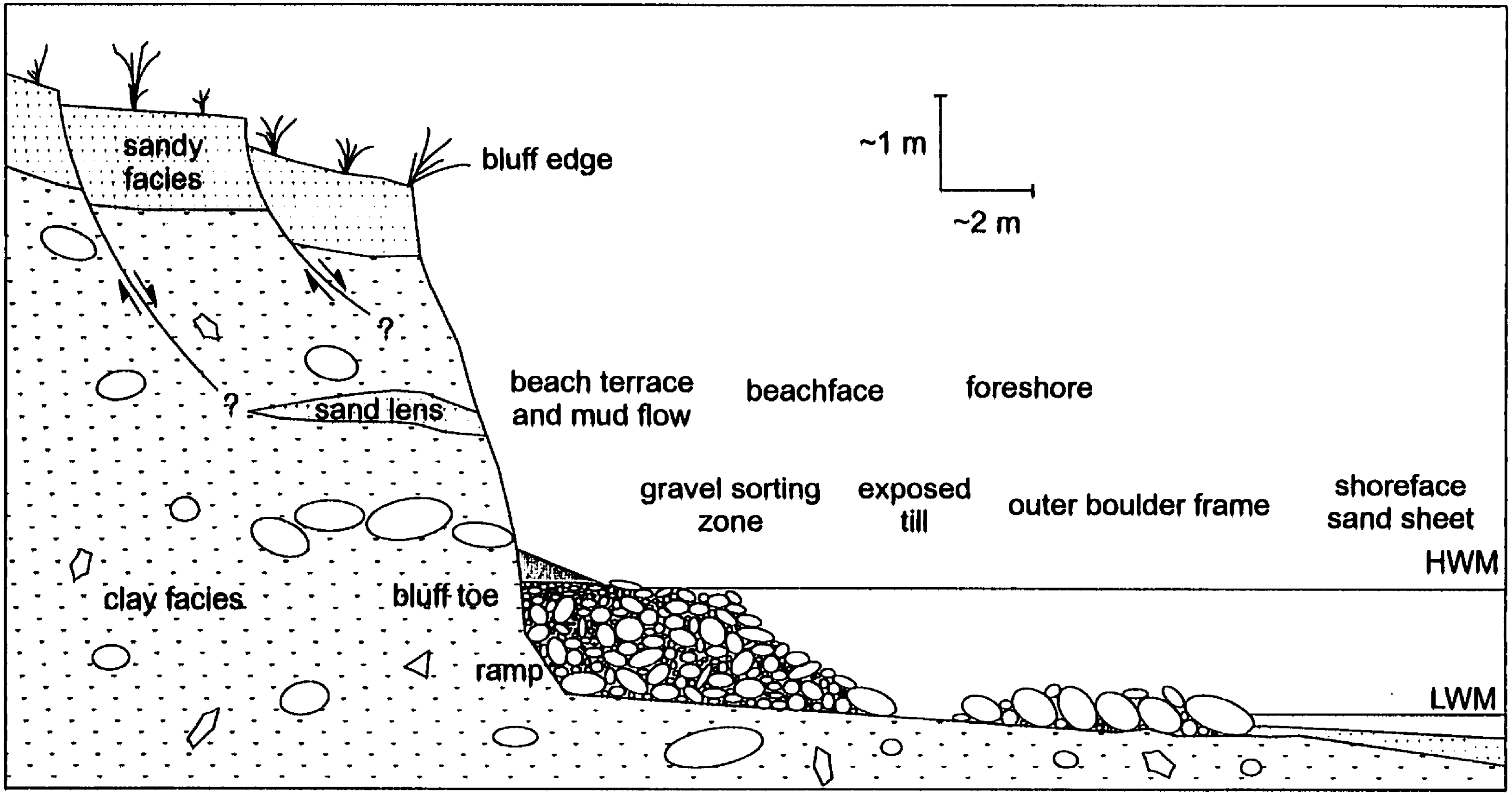


Figure 1.2 A schematic cross-section of a retreating drumlin bluff and gravel beach in the McNab's Island area. Not all features are necessarily present.

Subzone, found at depths from 75 to 65 m, is represented by a smooth, planar surface with limited sediment and records the previously mentioned last sea-level lowstand. The type section for this subzone is located approximately 12 km off McNab's Island (Stea *et al.*, 1994; G. Fader, pers. comm. 1999). The Estuarine Subzone, from depths of 50 m to the present shoreline consists of outcrops of estuarine materials with intervening gravel lag deposits (Forbes *et al.*, 1991b; Forbes and Boyd, 1989). It records the submergence during transgression of back-barrier estuarine deposits that formed in sheltered areas between drumlin headlands (Forbes *et al.*, 1991b). Sparse gravel ripples may also be present on the Inner Scotian Shelf near Halifax (Forbes and Boyd, 1987); these may move under storm waves to depths greater than 30 m (Forbes and Drapeau, 1989).

1.4.5 Historical Evolution

Several locations in the McNab's Island area have undergone rapid coastal change in historical times. Barrie Beach, Noonan's Beach, and Doyle Beach at various times after the mid-1800s were mined for sand and gravel and were submerged, while McCormick's Beach formed in Eastern Passage. The Thrumcaps, including Thrumcap Shoal, Big Thrumcap, Little Thrumcap, and Thrumcap Hook, have also undergone considerable change. Thrumcap Shoal and Little Thrumcap used to be drumlins but have been completely eroded and submerged, a process now occurring at Big Thrumcap. Thrumcap Hook is a gravel barrier beach that has been retreating since approximately 1920.

Chapter 2

Methods and Results

2.1 Introduction

Data were collected to interpret and measure coastal change at McNab's Island at a variety of time scales. Field data collected during a comprehensive monitoring period from 1997 to 1999 were supplemented with historical data from a variety of sources. Field data include till grain size and shear strength properties, till water content, bluff face erosion, foreshore erosion, bluff edge retreat, erosion of a submerged barrier beach and drumlin shoal, and environmental data including temperature, precipitation, well water level and temperature, winds, wave heights, and tidal heights. Historical data include charts, airphotos and wind, wave, and tidal height records.

Methods and results of data collection and analysis are presented in the following sections.

2.2 Survey Network

In November 1997 twenty survey lines were installed to measure bluff retreat on McNab's and Lawlor Islands (Figure 2.1, Appendix 1), consisting of one 1.5 m length of rebar, some with an aluminum numbered GSC survey cap, and one or more 0.5 m wood stakes closer to the bluff edge. At least one survey marker on each line was located using a Geotracer 2000 dual-phase differential or real-time kinematic (RTK) global positioning system (GPS) with horizontal and vertical field accuracy of approximately ±5 cm. Other survey markers under tree cover were located by measuring from RTK-GPS positions using Emery poles (Emery, 1961) with horizontal and vertical accuracy of approximately ±5 cm over distances less than 4 m.

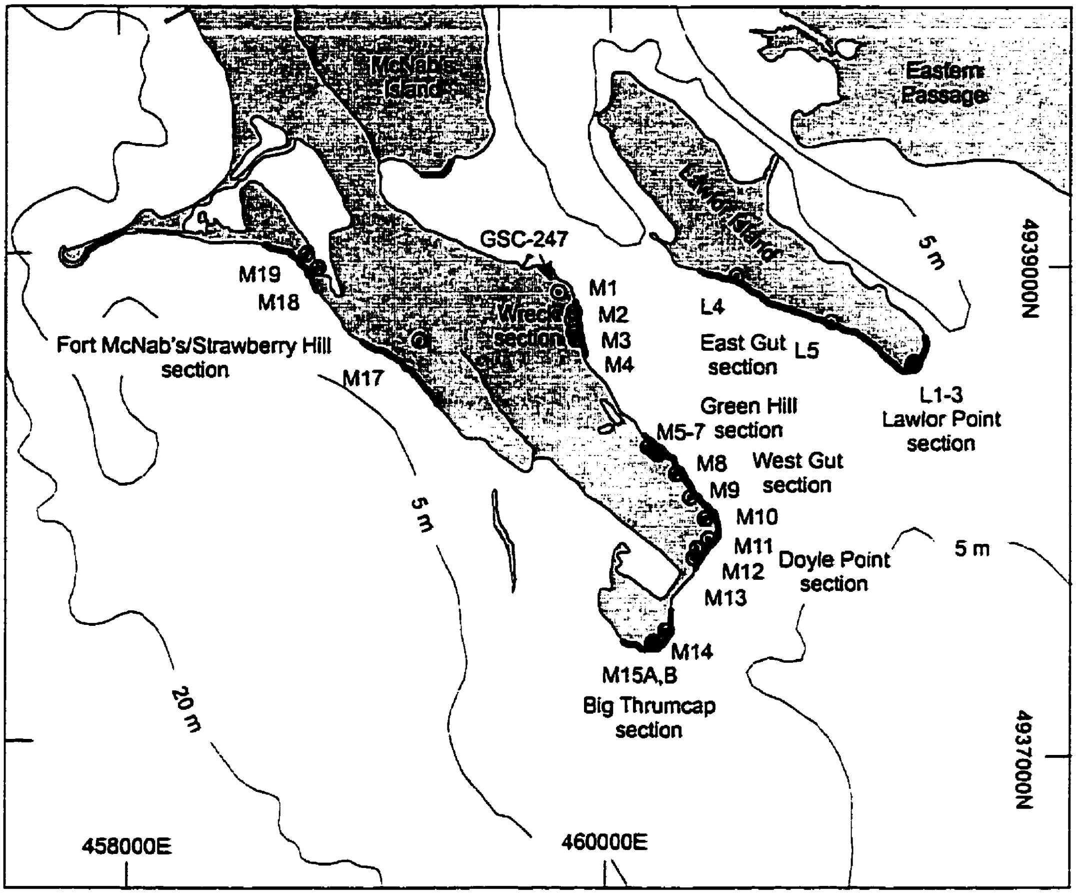


Figure 2.1 Map of part of the study area showing survey lines, section names, and 20 m and 5 m bathymetric contours. Heavy lines indicate eroding bluffs.

A combination of RTK-GPS and Emery pole measurements was necessary due to poor performance of the RTK system caused by suspected radio interference in the McNab's Island area. The Geotracer 2000 can be operated in post-processing mode which eliminates the need for radio communication between the rover and base station, however when using this option the system is slow to achieve precision mode (cm accuracy), data quality is not known until data are processed and elevations are not resolvable with current software. Additionally, regardless of the duration of GPS lock after startup or satellite loss, points collected within 1/2 hour of startup or loss are not always logged to the rover. RTK-GPS alone was used to collect profiles prior to June 1998.

The survey network was tied into the Nova Scotia Geodetic Benchmark System at two locations (NS-5719, below Fort Ives and NS-4354, 17th tee, Hartlen Point Golf Course). Back-calculation of the position of NS-4354 from NS-5719 through points on the survey network gives an uncertainty of 4 cm horizontally and 8 cm vertically. All positions are given as NAD83 (WGS84) UTM coordinates (Zone 20) relative to the 1975 NAD83 coordinates of NS-4354. All elevations are given as metres above geodetic datum.

2.3 Sampling and Laboratory Analyses

Samples were taken from the various facies of tills in the study area for three purposes: grain size analysis, remolded vane shear strength determination, and natural water content analysis.

Six samples of approximately 1 kg were taken in 1997 from McNab's Island, two from Lawlor Island, and three from Hartlen Point. These were divided roughly in two;

one half was used to determine grain size and the other to determine remolded vane shear strength. An additional sample was collected from each of McNab's and Lawlor Islands for grain size analysis in early 1998.

In the grain size analysis samples were dried at 90 °C, weighed, and wet-sieved to mud (<62 μm), sand (62 μm - 2 mm), and gravel (2 mm - 64 mm) fractions, each of which were dried and weighed to give percent by weight. The mud fraction was further separated to clay (<2 μm) and silt (2-62 μm) by hydrometer analysis (Holtz and Kovacs, 1981). The coarse fraction percentage (>64 mm) was determined by superimposing a 64 square grid on a ground level photograph of the sample site, estimating percent coverage of each square and averaging to give percent by weight (Kellerhals and Bray, 1971). Grain sizes of sampled facies are shown in Table 2.1 and show that the clay facies of the Lawrencetown Till is more clay-rich (20.1%) than the Hartlen Till which is of marginally higher silt content (35.3%). The Hartlen Till has higher percentages of coarse material and gravel (25.9%) and marginally less sand than the Lawrencetown Till clay facies. The sandy facies of the Lawrencetown Till is 73.2% sand and silt and has a higher percentage of gravel (17.2%) than the clay facies. The sand lens was determined to be 96.3% sand and silt. The stony facies has the highest percentage of coarse material and gravel (74.1%) and contains only 6.3% silt and clay.

The other portion of the grain size samples was used to determine the variation of shear strength with water content. Undrained remolded shear strength was measured using a laboratory vane shear device with miniature vane dimensions of 12.5 mm by 12.5 mm and a strain rate of 50°/minute. Samples were air-dried and pulverized using a mortar and pestle. Clasts that would interfere with testing (>~4 mm) were removed and

sample	facies	coarse (>64 mm)	gravel (2-64 mm)	weight percent sand (62 µm - 2mm)	mud (<62 µm)	silt (2 - 62 µm)	clay (<2 µm)
97-M1	clay	5.9	10.8	32.3	50.2	32.5	17.7
97-M2	sand lens	0.0	0.0	79.7	19.6	16.6	3.0
97-M3	sandy	1.8	12.4	44.3	41.4	31.7	9.8
97-M4	sandy	2.2	23.7	38.3	35.6	29.2	6.4
97-M5	clay	5.5	15.0	32.8	45.8	31.2	14.7
97-M6	clay	4.0	12.8	25.2	58.0	36.7	21.3
97-M6b	clay	14.0	11.5	22.6	52.0	32.9	19.1
98-M7	clay	4.2	8.5	33.1	53.7	32.9	20.8
97-L1	clay	5.3	10.8	31.9	51.5	32.1	19.4
97-L2	stony	46.4	27.7	19.4	6.3	5.1	1.2
98-L3	sandy	1.4	15.6	48.0	34.9	28.0	7.0
97-H1	clay	3.9	6.9	25.2	63.7	35.8	27.8
97-H2	Hartlen	9.9	17.2	23.7	49.0	34.2	14.8
97-H3	Hartlen	9.4	15.5	24.3	50.0	36.5	13.5
averages	clay	6.1	10.9	29.0	53.6	33.4	20.1
	sandy	1.8	17.2	43.6	37.3	29.6	7.7
	Hartlen	9.6	16.3	24.0	49.5	35.3	14.1

Table 2.1 Results of grain size analyses. M indicates samples from McNab's Island, L indicates Lawlor Island, and H indicates Hartlen Point. All samples are from facies of Lawrencetown Till except 97-H2 and 97-H3 which are from Hartlen Till. See Figure 2.5 for sample locations.

water was added in small increments until the sample was just moldable. A portion of the sample was uniformly packed into the test vessel, the vane inserted into the sample, and torque applied by the vane shear device until failure. Increments of stress and strain were automatically recorded on a laptop computer and the degrees of stress calculated from:

$$\text{stress}^{\circ} = \frac{180}{256}(\text{stress increment} - \text{strain increment}) \tag{1}$$

Torque is then calculated as:

$$\tau = \text{stress}^{\text{O}} \times \text{k} \tag{2}$$

where k is the spring constant equal to 0.0176 and 0.0098 for the two springs used. Peak undrained shear strength S_u is then given by:

$$S_u = \frac{\tau_{max}}{C} \tag{3}$$

where τ_{max} is peak torque and C is a constant depending on the shape and dimensions of the vane given by Lu and Bryant (1997):

$$C = \frac{\pi D^2 H(1 + D/3H)10^{-6}}{2} = 0.043 \quad m^3 \tag{4}$$

where D and H are the width and height of the vane.

After peak shear strength was reached the sample was removed from the vessel to determine its water content by weighing the wet sample, drying at 90 °C for greater than 24 hours, cooling in a desicator for greater than 24 hours, and reweighing. The percent water content w is given by:

$$w = \frac{M_w}{M_s} \times 100 \tag{5}$$

where M_w is the mass of water and M_s is the mass of solids in the sample (Holtz and Kovacs, 1981). Following removal of the sample for water content analysis another small amount of water was remolded into the remaining bulk sample and the shear test repeated. An average of eight tests were performed for each sample and the results from samples of the same facies were combined. It was found that the shear strength profiles of the Hartlen Till and the clay facies of the Lawrencetown Till were best fit by power curves, whereas the profiles of the sandy and stony facies were best fit by exponential curves. The sand lens was best fit by a series of three straight lines as shown in Figure 2.2.

The decrease in shear strength with increasing water content is not linear but occurs most rapidly over a critical range of water contents which differs for each till and facies. The critical range for the Hartlen Till is between approximately 11.5% and 14.5% water content whereas that for the Lawrencetown Till clay facies is slightly lower at 10-14%. The critical range of the sandy facies is approximately 4-8.5%. The sand lens has a remarkably different model and maintains a shear strength of 40 kPa to approximately 13.5% water content at which point it decreases to a value of 3-4 kPa.

Till samples collected at weekly to monthly intervals from November 1997 to May 1999 to determine the variability of natural water contents at nine different locations on McNab's and Lawlor Islands. Samples were also collected from exposed till foreshores. Approximately 40 g samples were taken from the external bluff surface (~2 cm depth) and from the internal fresh till (~10-15 cm depth) with a clean, dry hammer. Samples were wrapped in plastic kitchen wrap, sealed in small sample bags, and processed within a few days following the method of water content analysis described

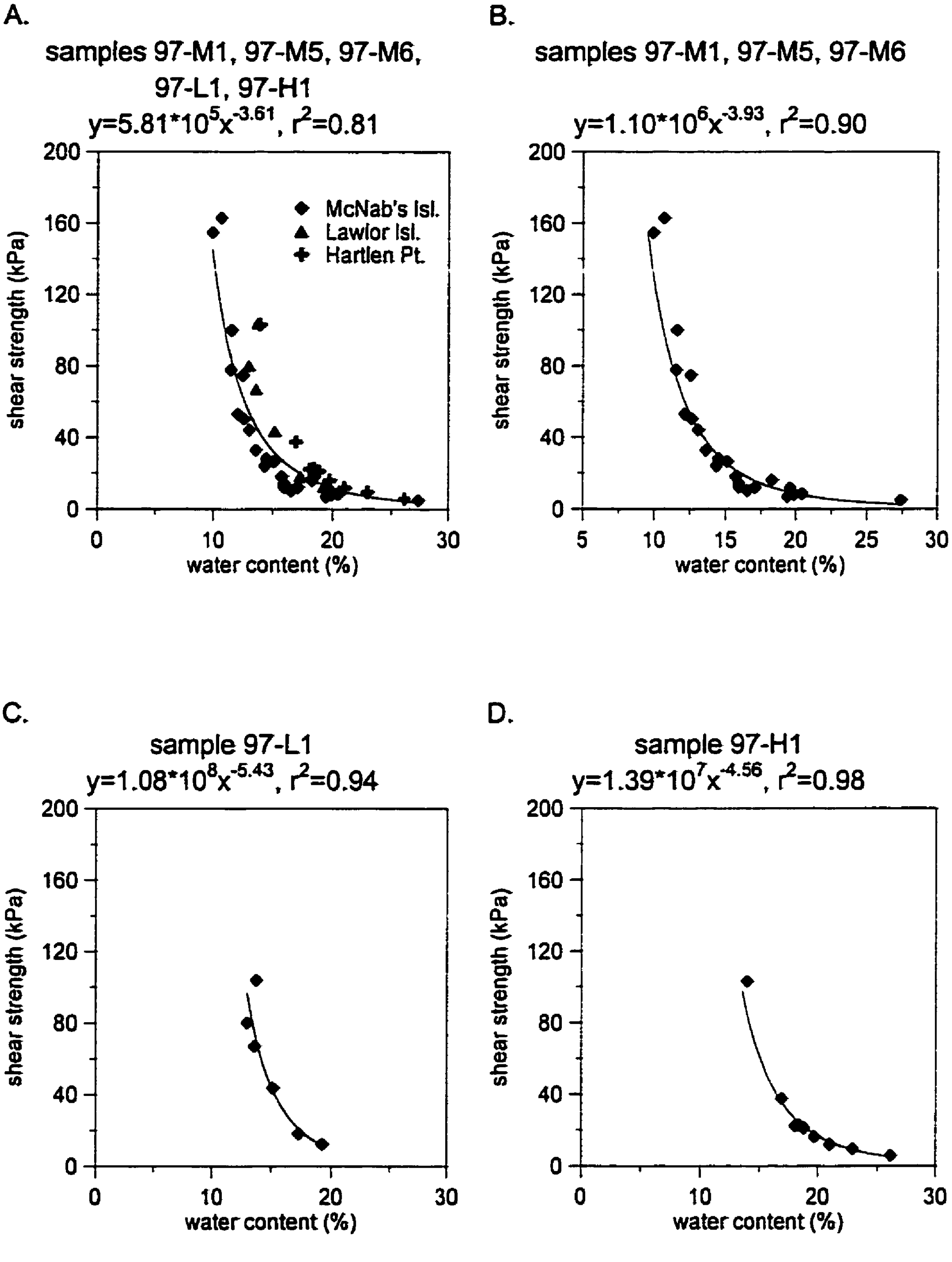


Figure 2.2 Shear strength models for the various tills and facies in the study area.
A) Lawrencetown Till clay facies at McNab's and Lawlor Islands and Hartlen Point
B) Clay facies on McNab's Island
C) Clay facies on Lawlor Island
D) Clay facies at Hartlen Point

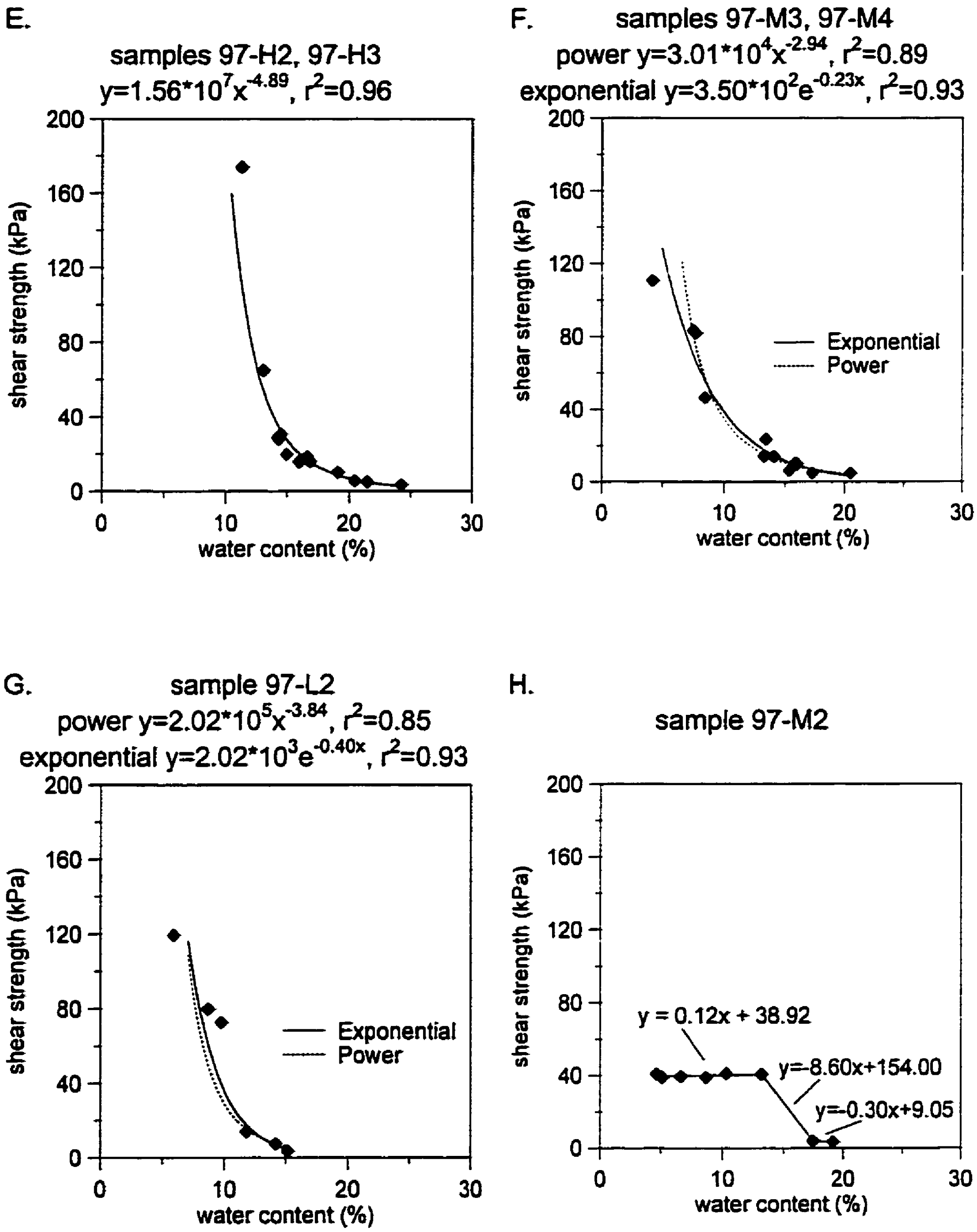


Figure 2.2 E) Hartlen Till at Hartlen Point
F) Sandy facies on McNab's Island
G) Stony facies on Lawlor Island
H) Sand Lens on McNab's Island

above. The results are shown in Figure 2.3 and data are given in Appendix B. Sample stations are named according to the approximate distance of the site from the nearest survey line. For example M5+5 is five metres towards line M6 from line M5, and M15A-25 is approximately 25 metres towards M14 from M15A.

Internal water content of the clay facies varies from 3.0 to 22.9% and tends to be at a maximum in February and March and at a minimum in August. External water content varies from 1.2 to 20.5% and may vary at weekly to monthly frequencies above and below internal water contents. External water content of the clay facies may be above internal water content for extended periods during the winter. Internal water content of the sandy facies varies from 6.0 to 28.8% and, in contrast to the clay facies, is closely matched by external water content which varies from 3.1 to 38.6%. Minima in both external and internal water contents of the sandy facies occur in September or October and maxima occur in February or March. The sand lens had maximum and minimum water contents of 32.1 and 17.9% in November 1997 just prior to being eroded.

Shear strength calculated from measured water content using the model appropriate to each facies varies inversely with water contents (Figure 2.4). The shear strength of the Lawrencetown Till clay facies is calculated using the formula of the curve in Figure 2.2a, shear strength of the Hartlen Till is calculated from the curve in Figure 2.2e, that of the sandy facies is calculated from the curve 2.2f, and the curve for the sand lens is calculated from the curve in Figure 2.2h. The stony facies has been excluded from this and further shear strength analyses because, as a clast-supported glaciofluvial deposit with little silt and clay, its failure behaviour in outcrop is controlled by coarse particle

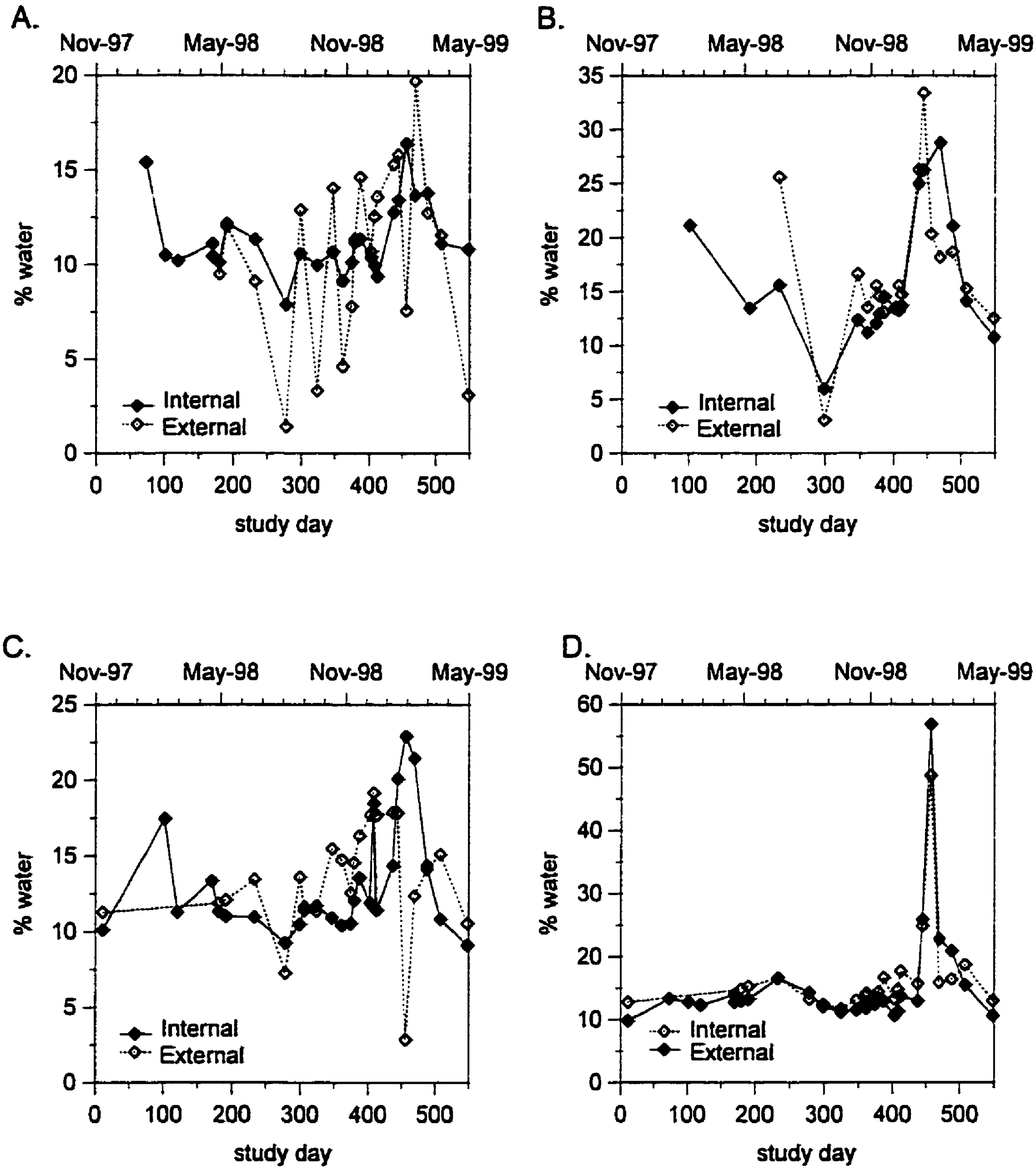


Figure 2.3 Internal and external water contents measured during the monitoring period.

A) M1+1, clay facies
B) M2+10, sandy facies
C) M5+5, clay facies
D) M9+10, sandy facies

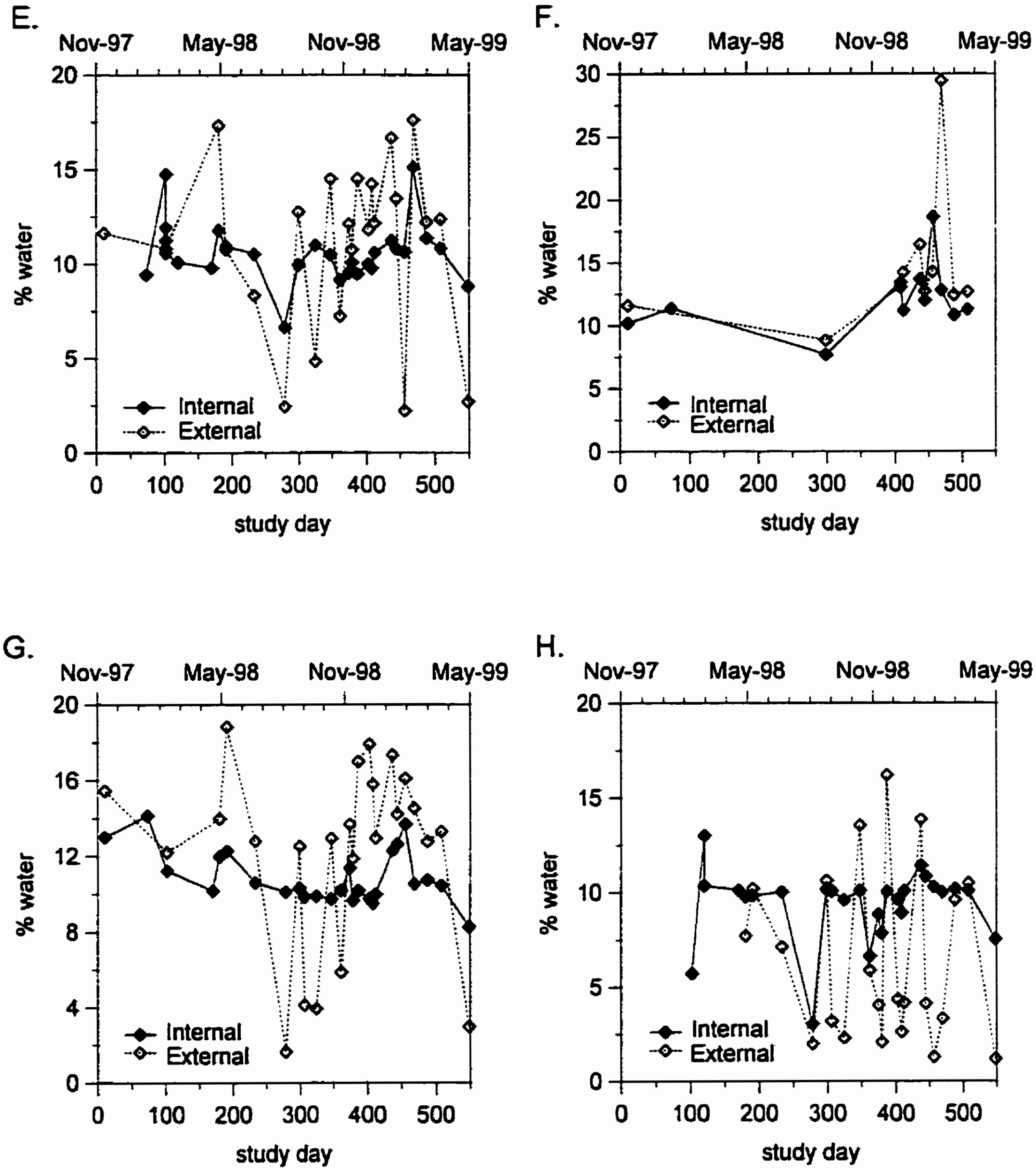


Figure 2.3 E) M10+50, clay facies
F) M11+1, sandy facies
G) M14+1, clay facies
H) M15A-25, clay facies

I.

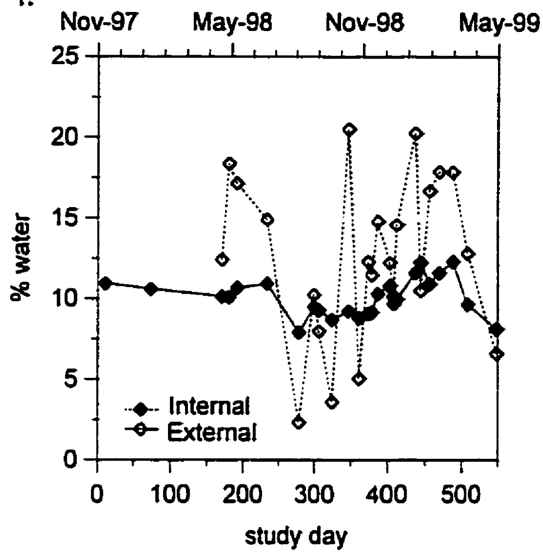


Figure 2.3 I) L4+40, clay facies

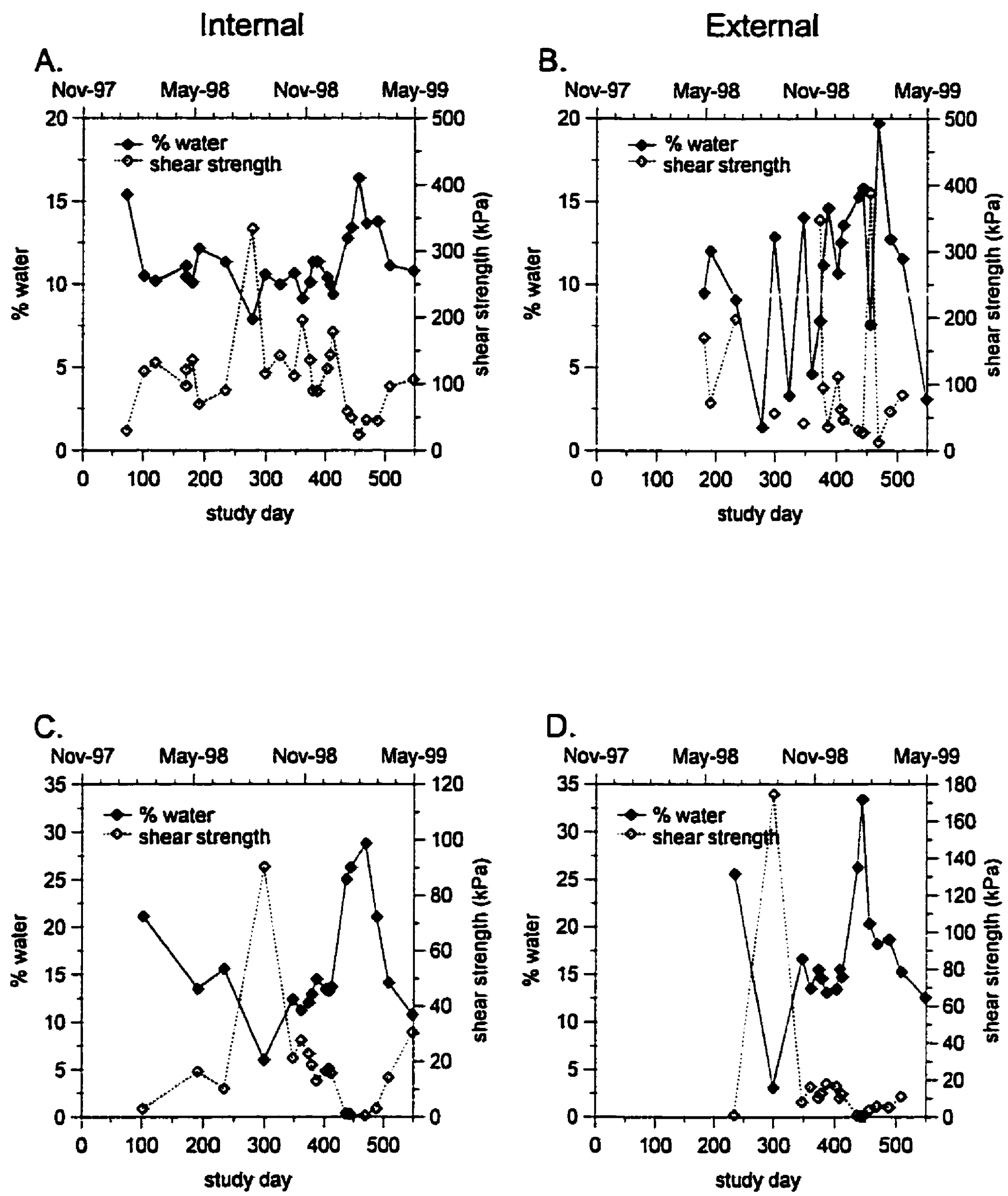


Figure 2.4 Natural internal and external water contents measured during the monitoring period and shear strengths modelled from water content using the model appropriate to each facies. Broken lines indicate values greater than 1000 kPa.

A) M1+1, clay facies, internal water contents
B) M1+1, clay facies, external water contents
C) M2+10, sandy facies, internal water contents
D) M2+10, sandy facies, external water contents

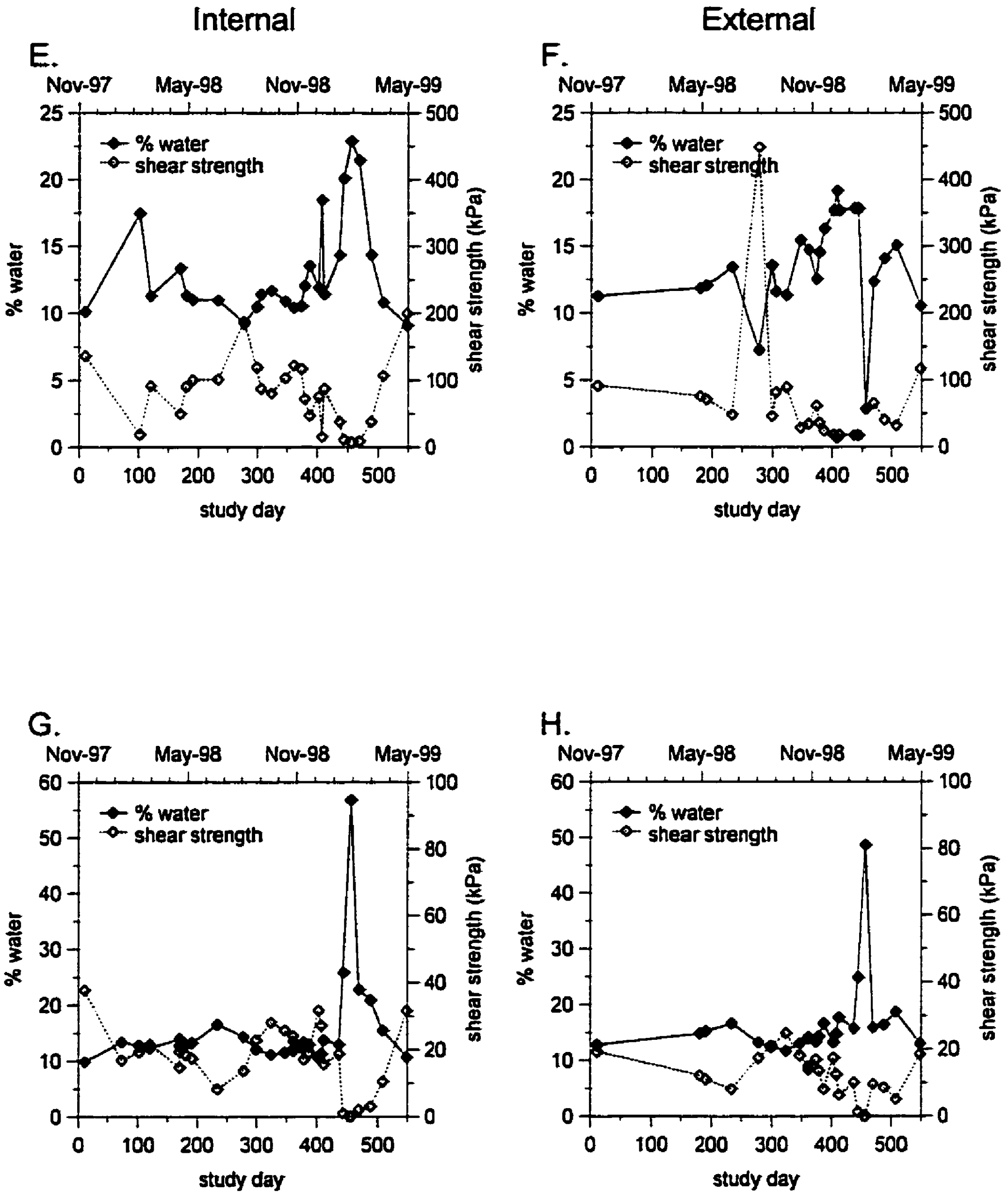


Figure 2.4 E) M5+5, clay facies, internal water contents
F) M5+5, clay facies, external water contents
G) M9+10, sandy facies, internal water contents
H) M9+10, sandy facies, external water contents

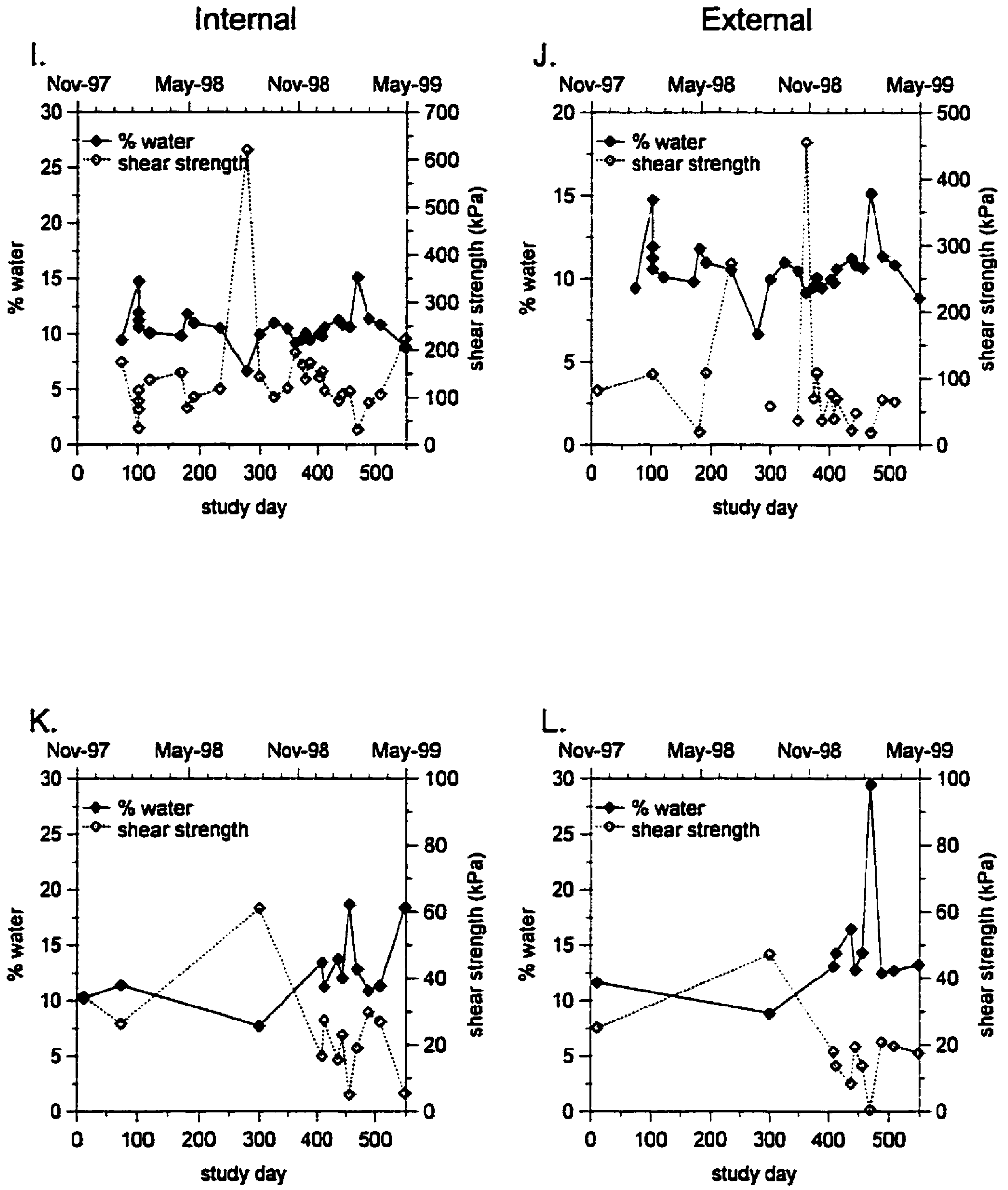


Figure 2.4 I) M10+50, clay facies, internal water contents
J) M10+50, clay facies, external water contents
K) M11+1, sandy facies, internal water contents
L) M11+1, sandy facies, external water contents

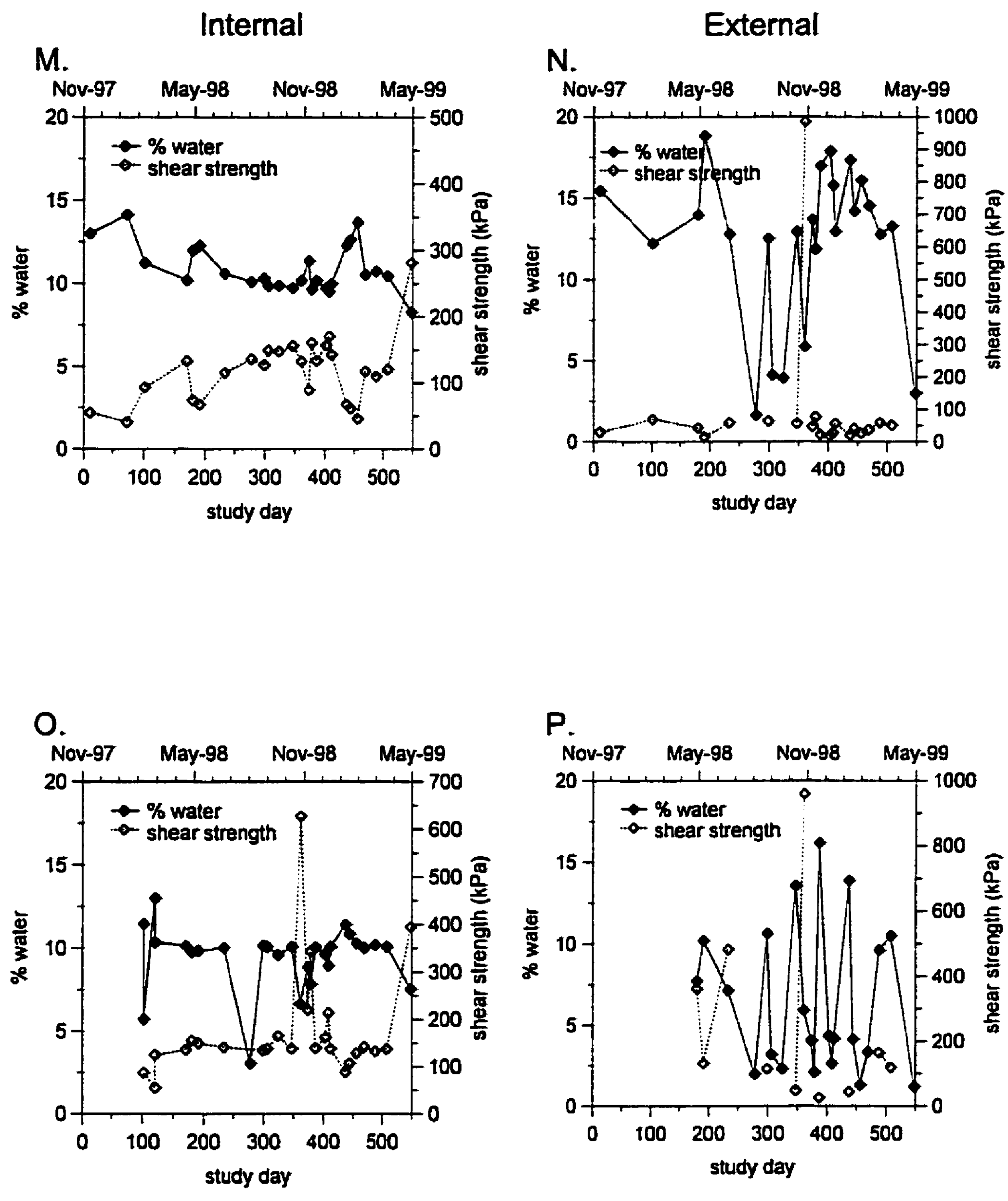


Figure 2.4 M) M14+1, clay facies, internal water contents
N) M14+1, clay facies, external water contents
O) M15A-25, clay facies, internal water contents
P) M15A-25, clay facies, external water contents

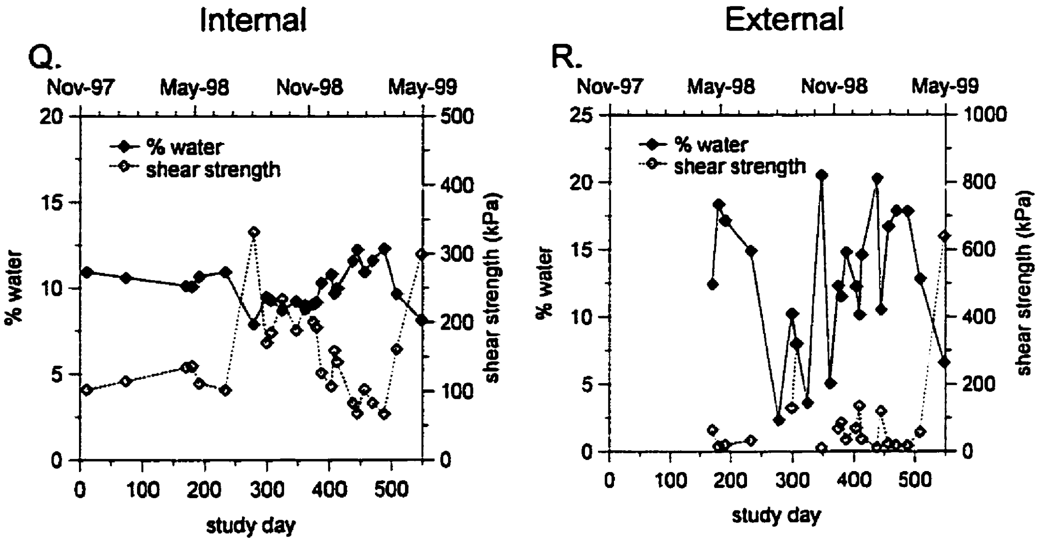


Figure 2.4 Q) L4+40, clay facies, internal water contents
R) L4+40, clay facies, external water contents

arrangement rather than the shear strength of the sparse and relatively non-cohesive matrix (Nash, 1987).

Calculated internal shear strength of the clay facies ranges from 7 kPa to 10,604 kPa while external shear strength ranges from 11 kPa to over 313,058 kPa. Shear strength values higher than 1000 kPa are not plotted in Figure 2.4. Internal shear strength of the sandy facies ranges from 0 to approximately 90 kPa while external shear strength ranges from approximately 0 to 175 kPa. One limitation of the approach to calculating shear strengths taken here is that, due to the steep slopes of the power curves at low water contents, extremely high shear strength values are calculated. External water content of the clay facies tends to be lowest and is therefore most susceptible to overestimation. Shear strengths calculated from water contents below the laboratory testing range (9.9-27.4% for the clay facies and 4.1-20.5%, 5.9-15.1% and 4.6-19.1% for the sandy and stony facies and sand lens), should be interpreted with caution.

Data in Figure 2.4 are summarized in Table 2.2 using the 10th, 50th, and 90th percentiles of the measured natural water content (w_{10}, w_{50}, and w_{90}) and calculated shear strength (S_{u10}, S_{u50}, and S_{u90}) distributions. At natural water contents, highest shear strengths are consistently displayed by the clay facies at station M15A-25 and the lowest are consistently in the sandy facies at M2+10. The lowest clay facies shear strengths occur at M5+5; those at M1+1 are slightly higher. Of stations M14+1 and M10+50 the lowest shear strengths are measured at M14+1 at low and high water contents and at M10+50 at moderate water contents. L4+40 displays higher shear strengths at all natural water contents than these two stations. Outcrops of clay facies on the foreshore in the study area show lower shear strength at natural water contents than the clay facies in

McNab's and Lawlor Islands Samples

A.

water content	facies	n internal	n external	σ_w internal	σ_w external	w_{10} internal	w_{10} external	w_{50} internal	w_{50} external	w_{90} internal	w_{90} external
M1+1	clay	26	21	1.89	4.56	9.67	3.32	10.74	11.56	13.73	15.29
M2+10	sandy	18	17	5.88	6.49	11.06	12.85	13.57	15.52	25.37	25.87
M5+5	clay	26	23	3.73	3.63	10.25	10.69	11.42	13.59	19.27	17.79
M9+10	sandy	28	23	8.74	7.35	10.96	12.82	12.88	14.70	21.41	18.47
M10+50	clay	29	23	1.56	4.40	9.38	3.12	10.52	12.12	11.82	16.23
M11+1	sandy	12	11	3.03	5.06	10.27	11.60	11.69	13.07	17.89	16.45
M14+1	clay	26	24	1.39	4.80	9.68	3.97	10.37	13.11	12.81	17.22
M15A-25	clay	27	22	1.91	4.41	7.17	1.97	10.04	4.24	11.05	13.25
L4+40	clay	25	23	1.16	5.02	8.73	5.34	10.09	12.43	11.59	18.27
Clay		159	163	2.40	5.05	9.08	3.03	10.48	12.21	13.44	17.47
Sandy		58	51	7.14	6.70	10.71	12.44	12.92	14.56	21.60	24.81
Sand Lens	not	2	-	7.06	-	19.40	-	25.05	-	30.71	-
Foreshore	above	31	12	1.85	2.10	10.29	10.61	12.12	12.47	15.21	15.72

B.

shear strength	facies	n internal	n external	σ_{Su} internal	σ_{Su} external	S_{u90} internal	S_{u90} external	S_{u50} internal	S_{u50} external	S_{u10} internal	S_{u10} external
M1+1	clay	26	21	61.61	36122.80	160.77	7606.15	109.16	83.69	44.97	30.47
M2+10	sandy	18	17	19.65	39.31	28.44	18.98	16.09	10.32	1.11	0.99
M5+5	clay	26	23	49.87	2696.18	129.23	111.72	87.45	46.57	13.39	17.60
M9+10	sandy	28	23	9.24	6.11	29.16	19.06	18.79	12.43	2.76	5.31
M10+50	clay	29	23	100.04	8480.33	178.25	13335.83	117.51	70.56	77.13	25.21
M11+1	sandy	12	11	14.14	11.10	34.06	25.15	24.68	18.00	6.43	8.36
M14+1	clay	26	24	49.93	19944.58	158.63	3994.54	123.75	53.12	57.73	19.83
M15A-25	clay	27	22	1973.55	78859.12	487.05	50092.69	139.28	3143.27	98.87	53.88
L4+40	clay	25	23	66.55	5625.46	230.45	1477.81	136.51	64.41	82.76	16.02
Clay		159	163	835.19	37661.81	199.91	10659.52	119.23	68.58	48.48	18.82
Sandy		58	51	14.44	23.85	30.80	20.79	18.66	12.84	2.63	1.25
Sand Lens	not	2	-	2.12	-	3.23	-	1.53	-	-0.16	-
Foreshore	above	31	12	38.63	42.04	127.21	114.72	70.58	63.68	31.04	28.23

Table 2.2 Statistics of (A) till water content measured in the field and (B) till shear strength calculated from measured water content. Individual sample sites are given if applicable, as well as facies averages. See Figure 2.5 for sample sites.

bluffs.

An alternate method of comparison, appropriate where natural water content was not measured (*e.g.* Hartlen Point), uses the 10th, 50th, and 90th percentiles of all water content samples taken during approximately 550 days of natural water content sampling to calculate shear strength. Table 2.3 shows that the Hartlen Till has the highest shear strength of all facies in the study area at low and moderate water content but at high water content is of low shear strength similar to the Lawrencetown Till clay facies. The sandy facies is of much lower strength than the clay facies at all water contents, while the sand lens is of near constant strength except at high water contents.

2.4 Sub-Annual Erosion Monitoring Measurements

Bluff face erosion was measured at 4 locations (Figure 2.5) on McNab's and Lawlor Islands from November 1997 to May 1999 using three 0.75 m long rebar rods hammered horizontally into selected clay facies bluff faces at approximately 0.5 m, 1.0 m, and 1.5 m above the base of the bluff toe (Amin and Davidson-Arnott, 1995). Appropriate locations for this type of measurement have high retreat rates, near vertical bluff faces, relatively steep foreshore slopes with imbricate cobble or boulder frames and little beach gravel. Measurements were taken from the exposed end of the rebar rod to the bluff using a steel ruler. The amount of erosion that occurred is the difference between successive measurements and division by the time interval gives a rate of erosion. Measurement accuracy of the method is considered to be approximately ±0.1 cm; error is contributed by difficulty reaching upper rods and the accumulation of eroding till on the rods. A major source of error, particularly during the winter of 1997/98 when

All Samples				Lawrencetown Till						Hartlen Till	
	n=221	n=188		Clay		Sandy		Sand Lens			
	Internal	External		Internal	External	Internal	External	Internal	External	Internal	External
W_{10}	9.23	3.48	S_{u10}	188.38	6390.45	43.05	158.91	40.03	39.34	294.49	34749.24
W_{50}	10.92	12.93	S_{u50}	102.65	55.80	29.34	18.60	40.23	40.47	129.46	56.72
W_{90}	15.41	17.85	S_{u90}	29.58	17.39	10.59	6.08	21.46	3.69	24.02	11.71

Table 2.3 Shear strength calculated for the various facies of Lawrencetown Till and the Hartlen Till using the distribution of all water content samples collected from all facies during the monitoring period.

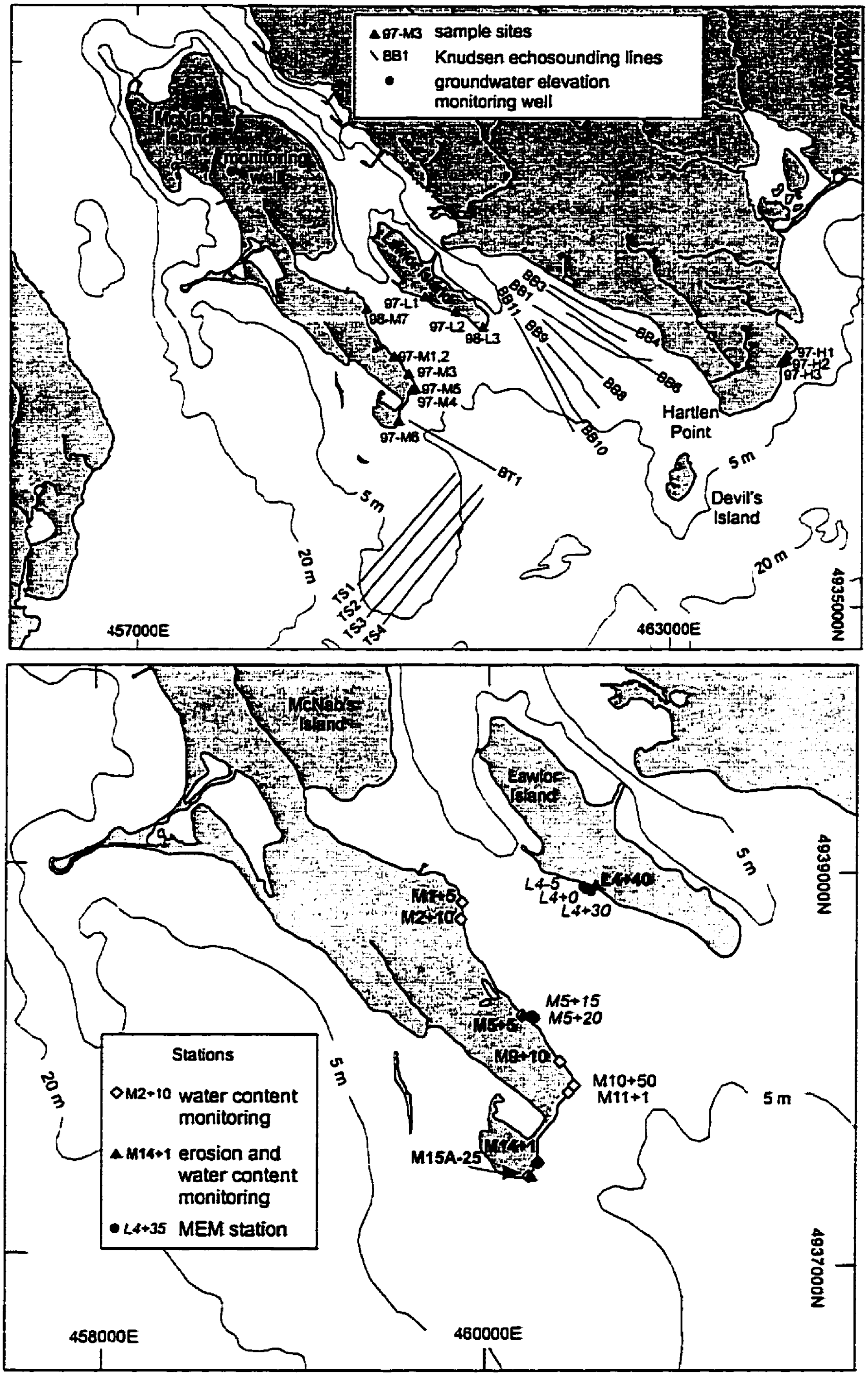


Figure 2.5 (Top) Map of study area showing sample sites of samples taken for grain size and shear strength analysis. Also shown are Knudsen echosounding lines and the location of the groundwater monitoring well at the McNab's Island teahouse. (Bottom) Map of southern McNab's Island showing water content, bluff erosion, and foreshore erosion monitoring stations.

rod lengths less than 0.5 m were used, was loss of rods as the bluff rapidly eroded during storm events. Rods were observed after storm events to be loosely in place when greater than one half the length was protruding from the bluff, therefore an erosion measurement of one half the rod length was used when rods were lost. This likely results in underestimation of retreat rate during extreme events in 1997/98. Results of bluff face erosion measurements are presented in Figure 2.6 and Appendix C.

Bluff face erosion rate is greatest in winter and reached a maximum at M14+1 of 11.44 m/a from January 28 to February 3, 1998 and 20.08 m/a between January 11 and 18, 1999. Other events had rates of 9.83 m/a from January 30 to February 12, 1999 and 9.13 m/a from March 3 to 23, 1999. At M15A-25 rates peaked at 8.64 m/a between February 3 and 28, 1998 and at 5.68 m/a between January 11 and 18, 1999. Station M5+5 had a peak of 17.89 m/a between February 3 and March 8, 1998 and another of 5.84 m/a between January 11 and 30, 1999. Station L4+40 had peaks of 9.70 m/a between February 10 and 17, 1998 and 6.15 m/a between February 12 and March 3, 1999. No clear relationship is seen between erosion rates at different elevations on the bluff face. Peaks in 1998 occur at all elevations while peaks in 1999 are, with the exception of M5+5, highest for the upper rod.

Measurements of foreshore erosion were made at two selected locations adjacent to two bluff face erosion monitoring stations (M5+5, L4+40). Appropriate locations for measuring foreshore erosion have exposed till below the bluff toe and ideally have little mobile coarse sediment. Three micro-erosion meter (MEM) stations were installed in exposures of till in the foreshore near M5+5 and L4+40. Using the micro-erosion meter as a template, at each station three 1 m lengths of zinc-plated steel rod 1 cm in diameter

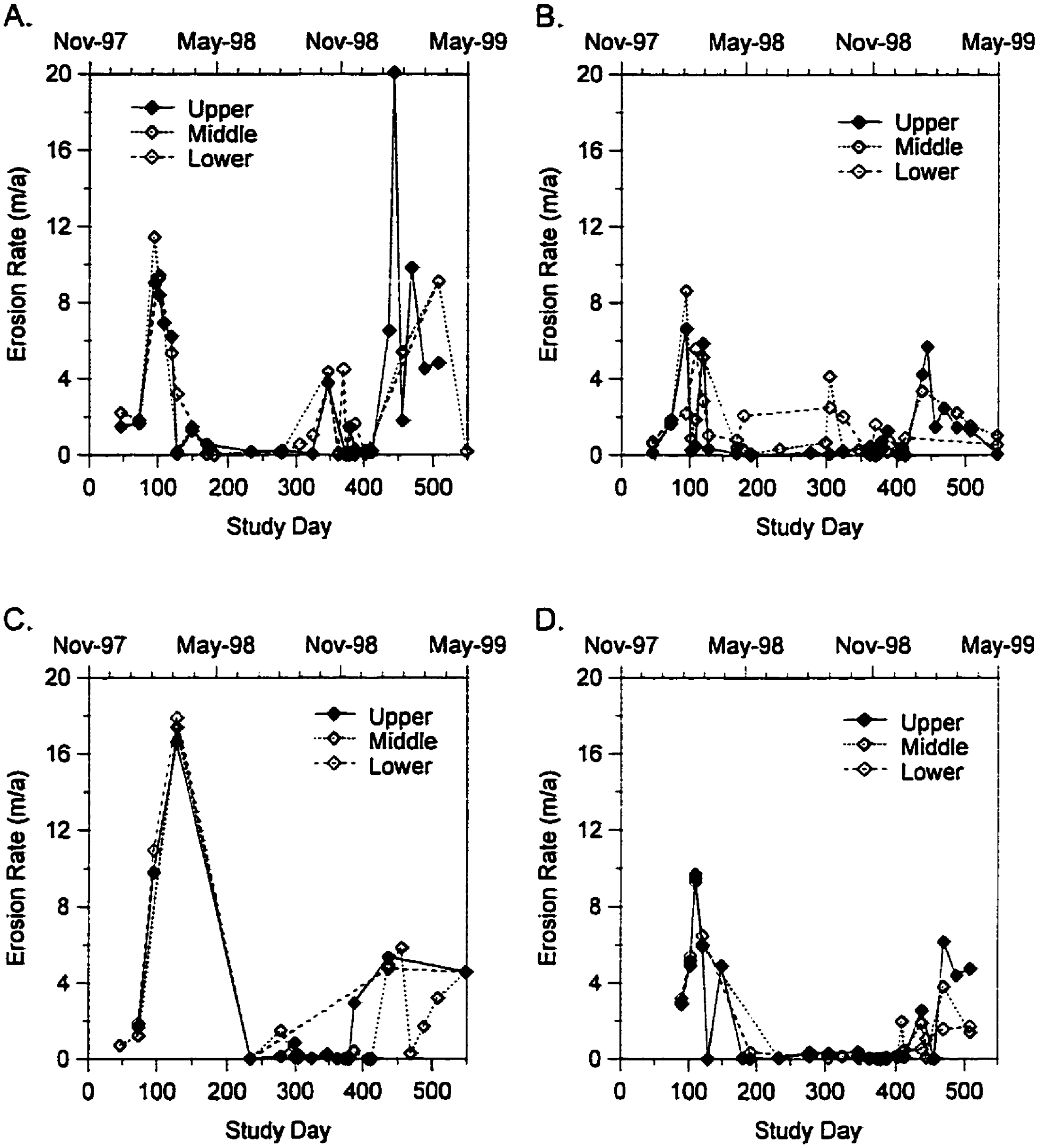


Figure 2.6 A) Bluff face erosion results from 3 rebar rods at M14+1. The upper rod is approximately 1.5 m above the base of the bluff toe, the middle is approximately 1 m and lower is approximately 0.5 m.
B) as in A but for M15A-25.
C) as in A but for M5+5.
D) as in A but for L4+40.

were hammered vertically into the exposed till at the corners of an equilateral triangle with sides 19 cm long, until approximately 15 cm of the rods showed above the till. The MEM was placed on top of the leveled rods, a plunger dropped to the till surface, and the distance from the top of the rods to the till surface read at the top of the plunger from a steel ruler. Measurements are made along the three sides of the triangle between the rods to avoid the influence of scour near the rods (Davidson-Arnott, 1986; Davidson-Arnott and Ollerhead, 1995).

The amount of erosion is the difference between successive measurements and a rate is obtained by division of the average of the positive erosion measurements made on each of the three sides of the triangle by the time interval between positive measurements. Although the measurement accuracy of this method is approximately ±0.05 cm, mobile sand, gravel, and cobbles frequently cover the till surface and result in negative measurements.

Results of micro-erosion meter measurements are shown in Figure 2.7. All three stations on McNab's Island were buried by infilling sand and gravel in November 1998 and have not since reappeared. Erosion meters on Lawlor Island remain visible but the foreshore surface has been frequently covered by sand and cobbles since November 1998. A maximum of 24.9 mm vertical foreshore erosion occurred at Lawlor Island station L4+30 between January 11, 1998 and January 18, 1999. Station L4-5 showed peaks of 30.6 and 2.67 mm between September 1 and 20, 1998 and September 20 and November 5, 1998 respectively. A maximum of 29.7 mm of foreshore erosion occurred at station M5+20 between May 10 and June 21, 1998.

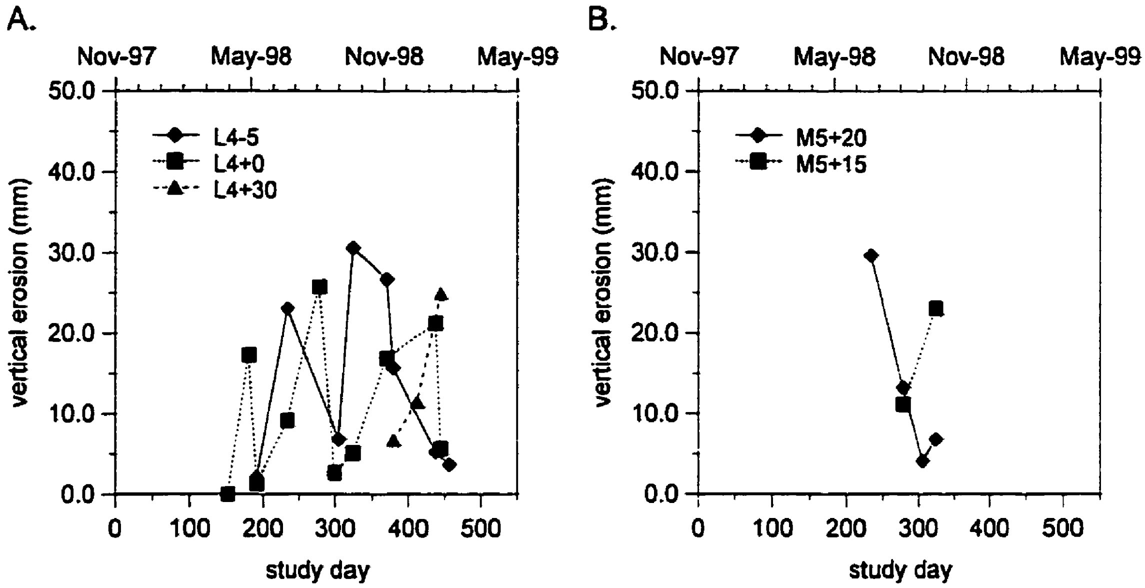


Figure 2.7 Results of foreshore erosion measurements using a micro-erosion meter. Negative values caused by sedimentation are not shown.
A) Lawlor Island stations.
B) McNab's Island stations. Sand deposition buried stations in November, 1998.

For both bluff face and foreshore erosion measurements, negative values were ignored and the time interval between measurements was taken to be the lapsed time since the last positive measurement. In this manner the effects of both the accumulation of material at monitoring stations and any clay expansion are removed.

2.5 Annual-Scale Retreat Measurements

Measurements of annual-scale coastal change collected include bluff profiles and measurements of bluff-edge retreat. These were made at each survey line at approximately 6 month to 1 year intervals starting in November 1997. The position of the bluff edge at the survey line was collected using RTK-GPS or the distance to the bluff edge was measured from a survey marker using Emery poles. Both techniques are considered accurate to ±5 cm, however additional uncertainty arises from choice of bluff edge position, especially where turf overhangs the bluff. Bluff edge retreat (X) is the difference between successive measurements to the bluff edge and error is therefore additive and equal to ±10 cm. Negative values of X measured in the field were discarded. Profiles were collected from a survey marker landward of the bluff edge, down the bluff to the water line (Figure 2.8). Elevations of survey markers were verified using predicted tidal elevation. Values were within 0.3 m over a 30-40 m long profile.

Lines M1, M5, M6, M7, M11, M14, and L4 showed marked change between 1998 and 1999 whereas lines M3, M4, M9, M13, and L5 were stable. Lines M2, M8, M10, and M12 are intermediate. Increasing beach elevations are seen at M5 to M7 whereas erosion of the beach prism is seen at M1 and M2. M11 and M12 show

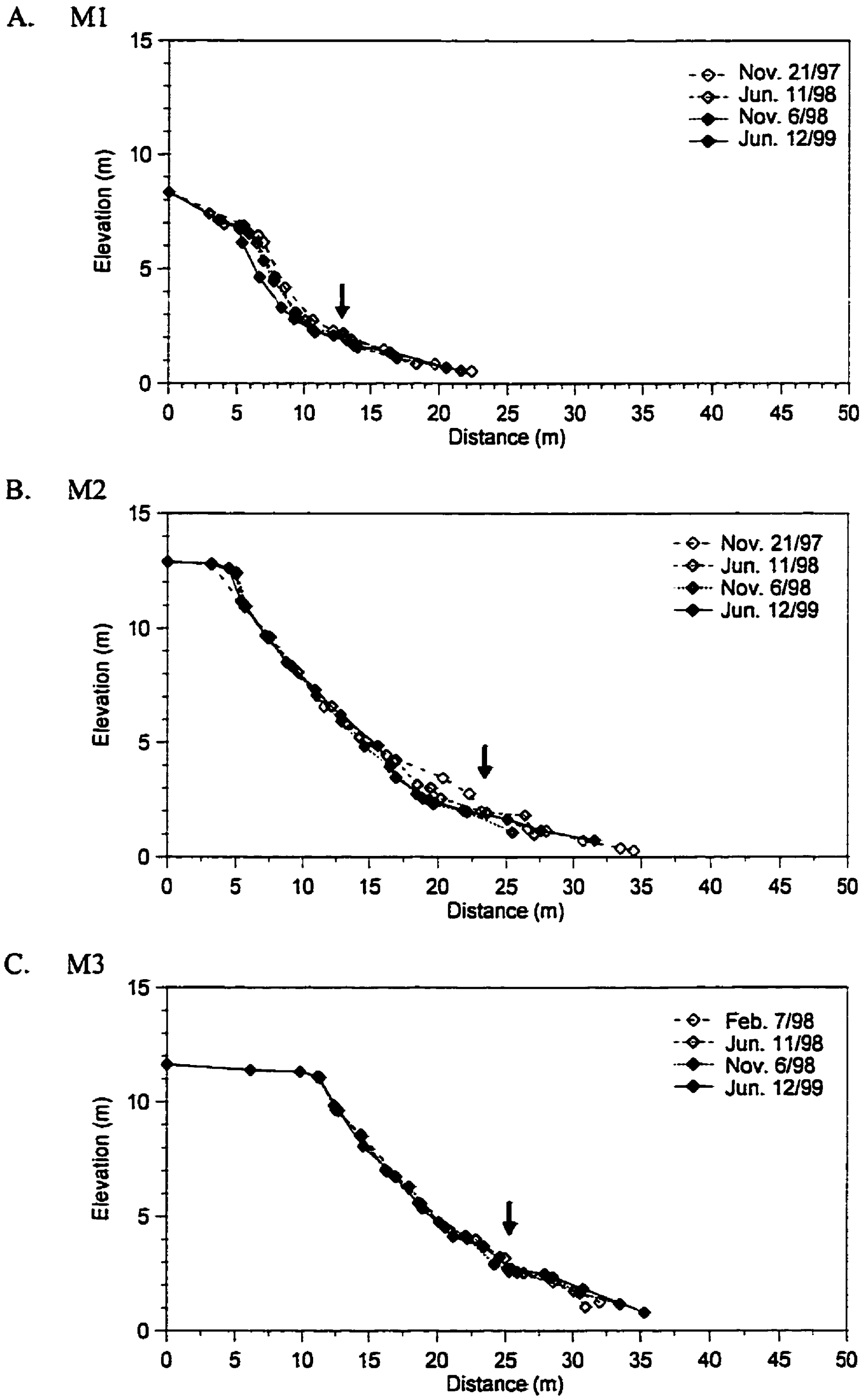
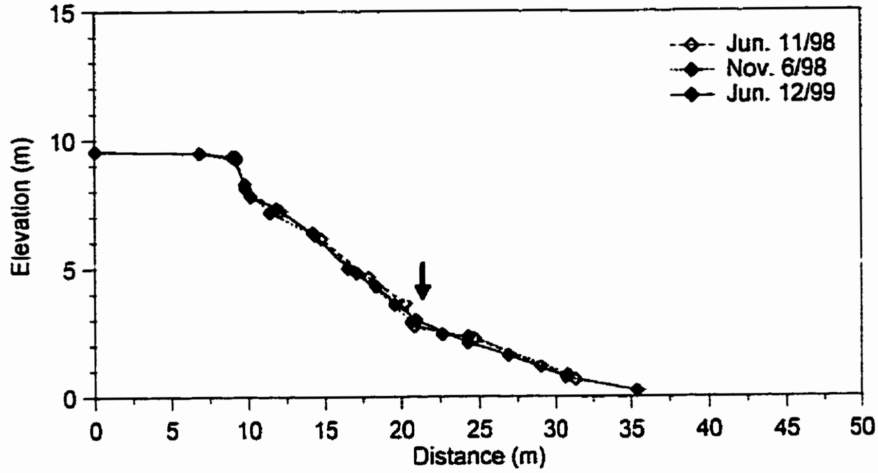
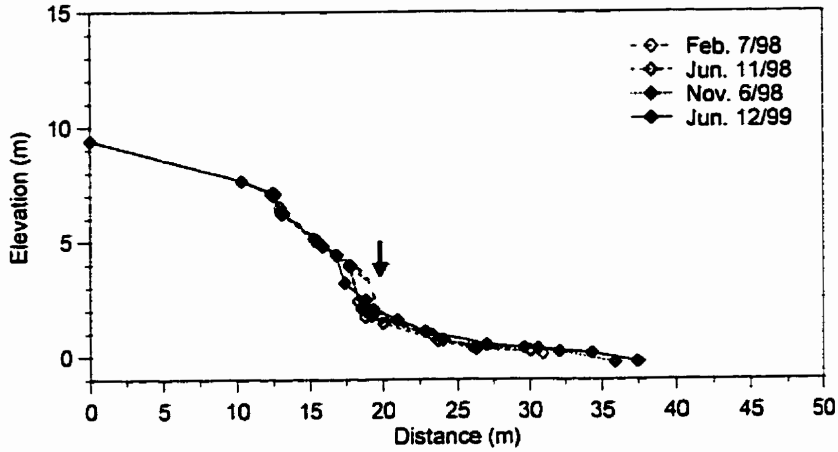


Figure 2.8 Bluff profiles collected along survey lines using RTK-GPS and Emery poles. Arrow indicates top of beach.

D. M4



E. M5



F. M6

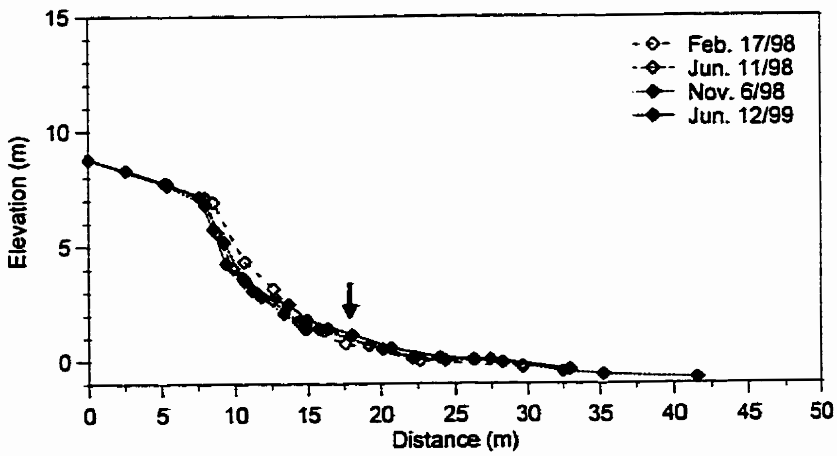


Figure 2.8 D-F

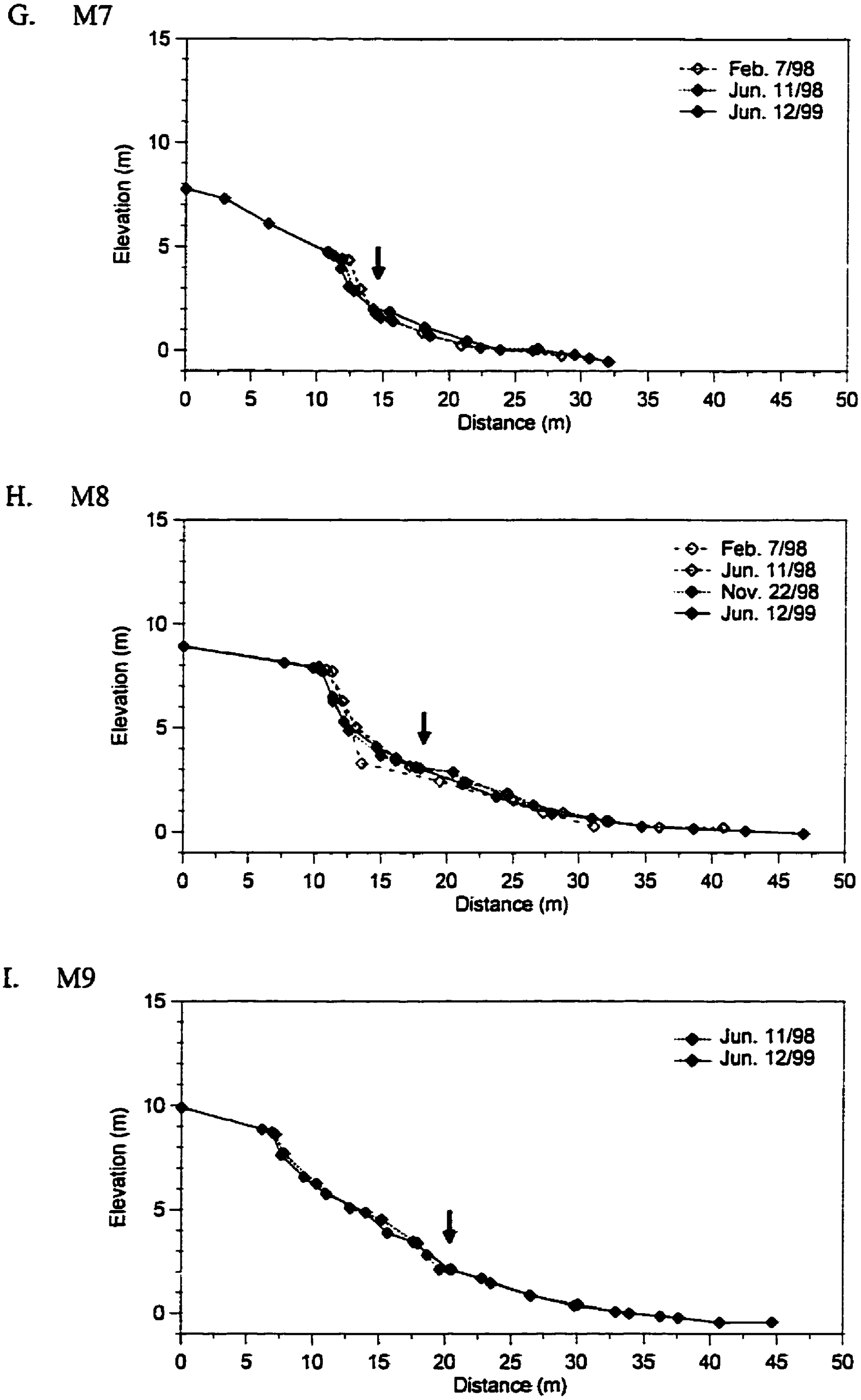
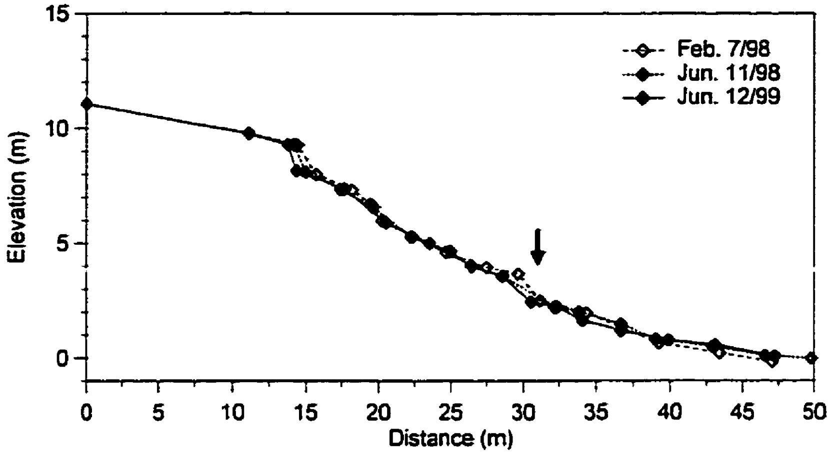
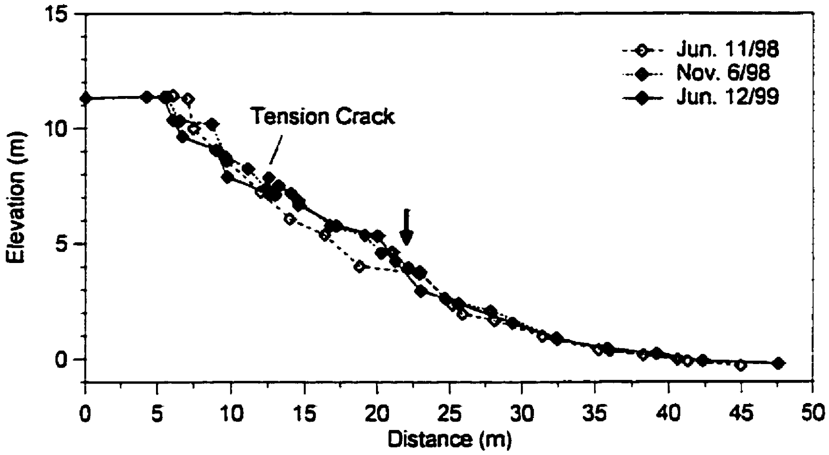

G. M7
Feb. 7/98
Jun. 11/98
Jun. 12/99
Elevation (m)
Distance (m)
H. M8
Feb. 7/98
Jun. 11/98
Nov. 22/98
Jun. 12/99
Elevation (m)
Distance (m)
I. M9
Jun. 11/98
Jun. 12/99
Elevation (m)
Distance (m)

Figure 2.8 G-I

J. M10



K. M11



L. M12

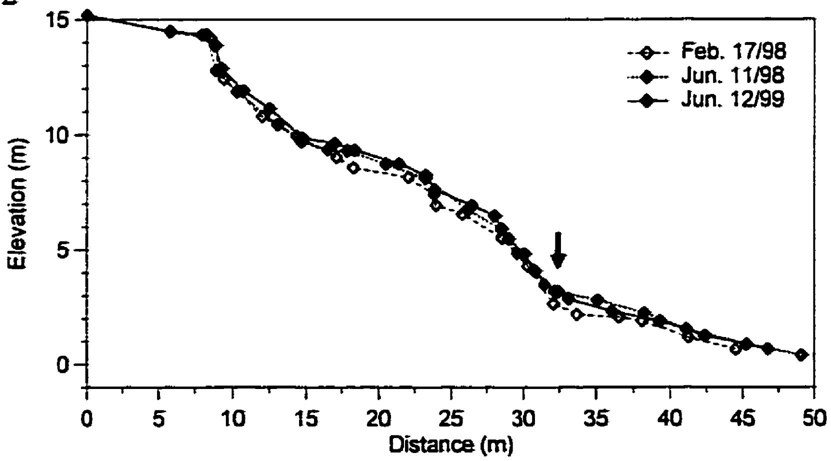
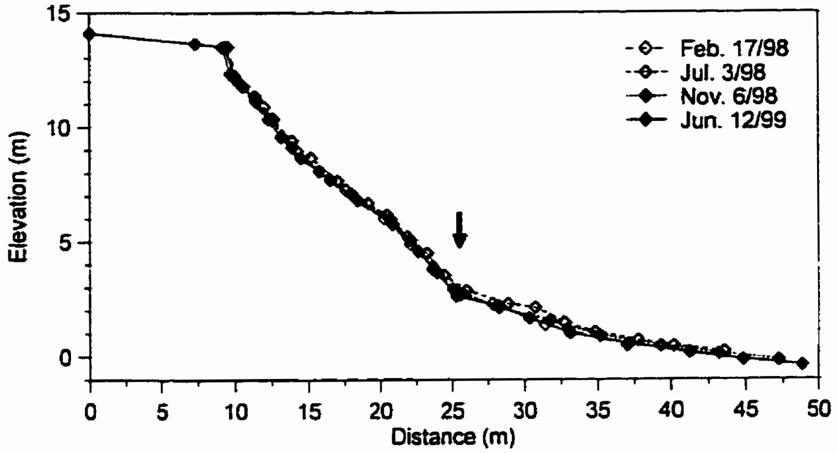
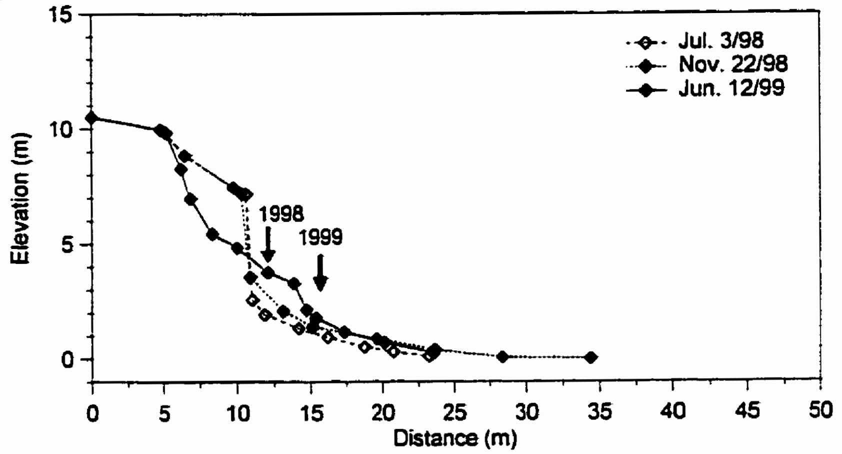


Figure 2.8 J-L

M. M13



N. M14



O. L1

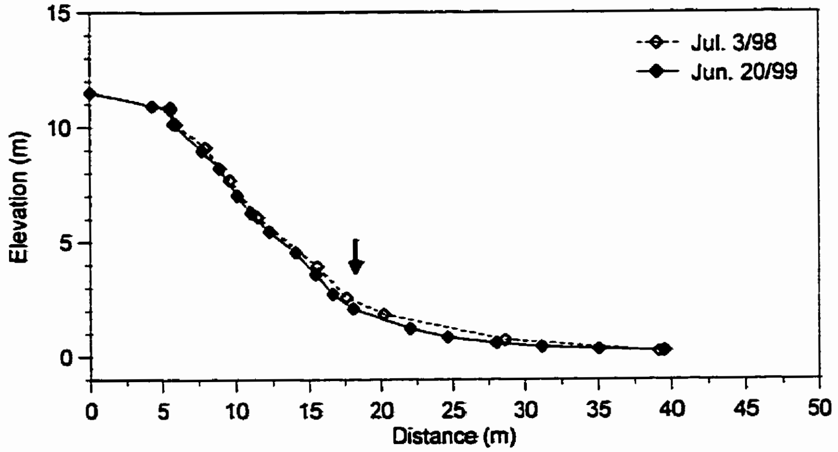
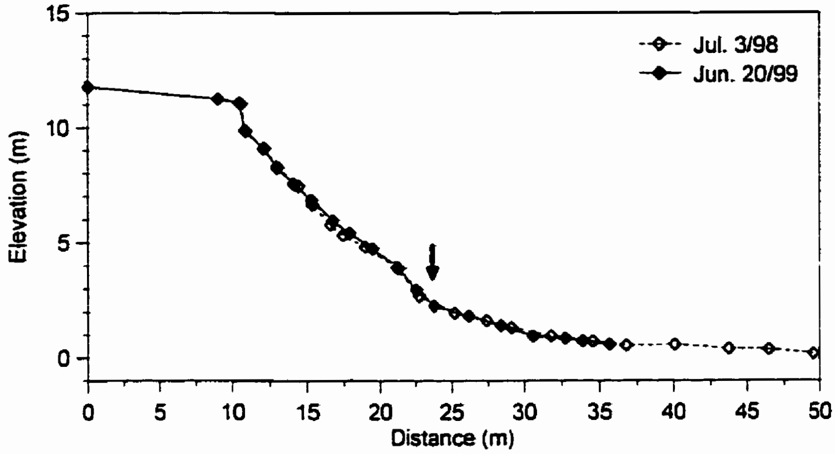
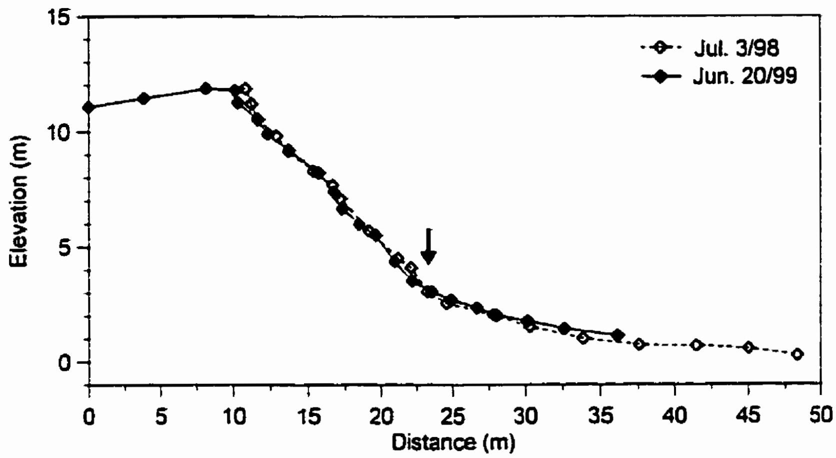


Figure 2.8 M-O

P. L2



Q. L3



R. L4

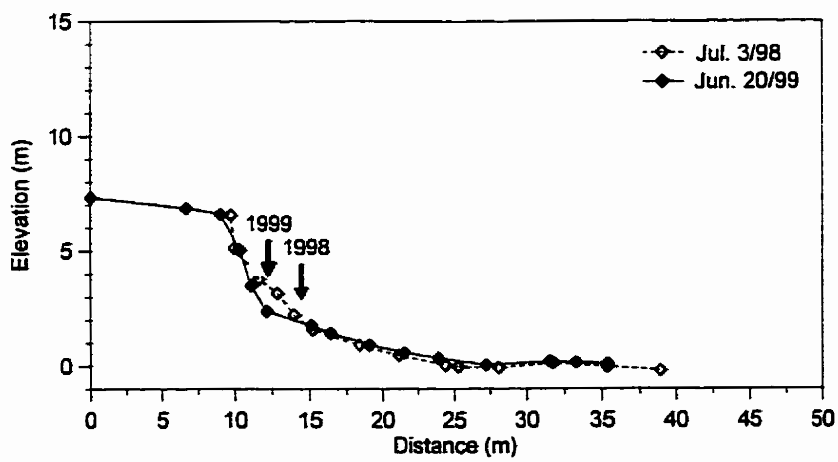


Figure 2.8 P-R

S. L5

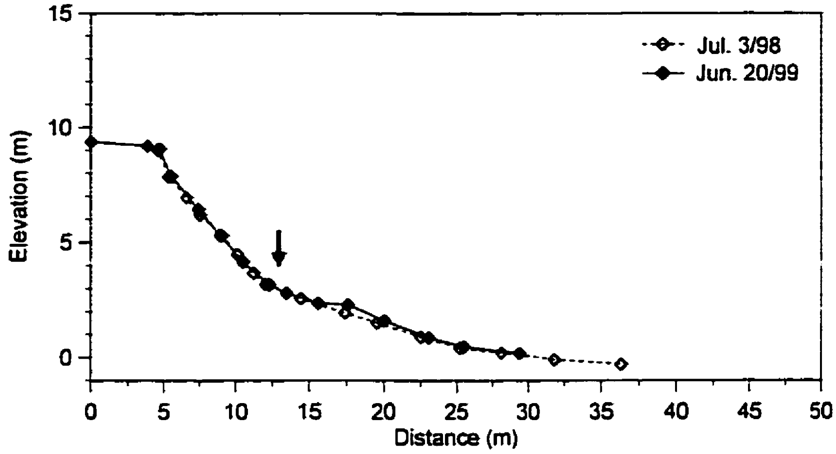


Figure 2.8 S

accumulation of material on slump blocks on the bluff face. Line M14 shows a slump at the bluff edge and colluvium at the bluff toe.

2.6 Decadal-Scale Retreat Measurements

Historical erosion of various source elements of the sediment budget was investigated using a lengthy historical record comprising airphotos at approximately 10 year intervals from 1934 and charts at irregular intervals from 1711.

Areas of prominent erosion shown by this data set include Big Thrumcap, Little Thrumcap, Thrumcap Hook, Doyle Point, 'Doyle' Beach, Barrie Beach, and Noonan's Beach. Deposition has occurred at Green Hill Cove, Lawlor Spit, McCormick's Beach, Maugher's Beach and Wreck Cove (Figures 1.1, 2.1).

Rectification of airphotos requires stable control points easily identifiable on airphotos. Suitable locations were positioned using RTK-GPS and used to rectify (by means of GRASS software) airphotos from 1934, 1945, 1954, 1966, 1982, 1992, and 1997 at scales of 1:5000 to 1:10,000 scanned at 400 d.p.i. Mosaics were constructed using the GRASS capability of registering one photo to another on-screen using a combination of GPS points and common points recognizable on each photo; however, root mean square (RMS) errors generated by this method were too large for detailed measurements. Low RMS errors (<3.5 m) were generated if small areas near the center of airphotos were rectified using 6 or more control points and a first order polynomial fit. Bluff edges were digitised from these low error images on-screen assisted by stereo interpretation of airphotos. The distance to the bluff edge from the position of a survey marker at each survey line was measured on-screen for each time interval between airphoto series. The amount of retreat (X) is the difference between two successive measurements.

The volume of sediments (V) delivered by bluff retreat was calculated using:

$$V = LHX \qquad\qquad X \geq 0 \qquad\qquad (6)$$

where L is the length of eroding bluff measured from scanned and rectified airphotos in GRASS, and H is the historic bluff height determined by extrapolating 1998 bluff top slopes measured in the field to historic bluff edge positions measured on airphotos, assuming constant 1998 beach heights. For the purposes of this calculation negative values of X measured from airphotos were treated as zero values.

Eroding bluff segments are located at survey lines and include, as much as possible, bluffs of the same height, composition, and retreat rate. The amounts of coarse material (>64 mm), gravel, sand and mud delivered from bluff retreat were calculated based on grain sizes of samples of the clay, sandy and stony facies, taken from each bluff segment, and the proportion of the different facies in each segment. Average facies grain size is used for bluff segments not sampled. The amount of sediment delivered by eroding bluffs is given in Figure 2.9 and Appendix D.

Total sediment volume delivered from the Wreck section (Figure 2.9) peaked at 21,100 m^3 between 1966 and 1982. Most sediment from the Wreck section was delivered from M2, M3, and M4; volume supplied from M1 was not significantly different from zero until 1992 when it began to increase. Sediment delivered from the Green Hill section was at a minimum between 1966 and 1982 and peaked between 1945 and 1954 and 1982 and 1992 when total volume of sediment is 1002 m^3 and 725 m^3 respectively. Volumes supplied at the three closely spaced lines at Green Hill are not significantly

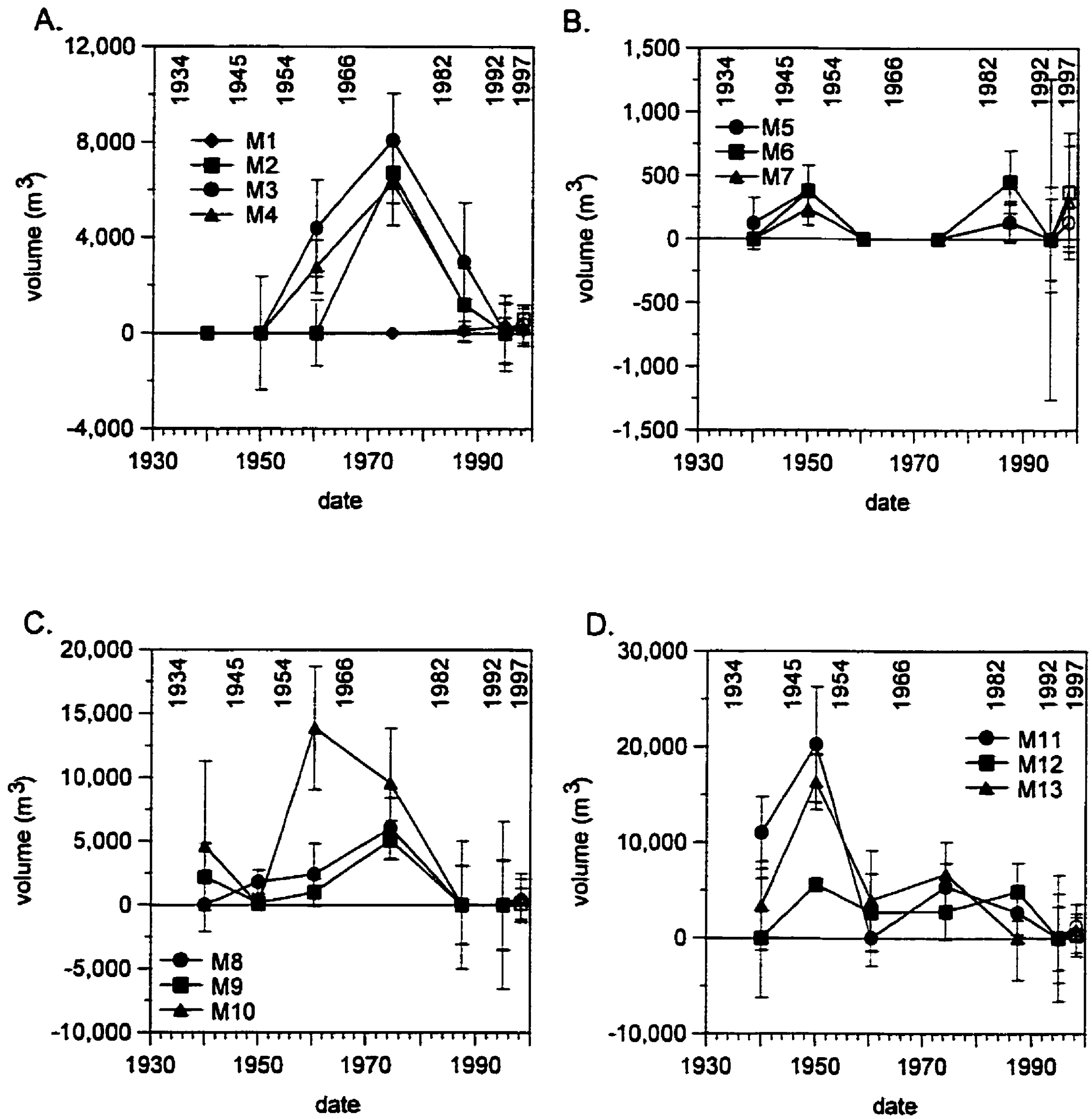


Figure 2.9 Sediment volumes delivered by bluff retreat. Closed symbols indicate measurements from airphotos and open symbols indicate field measurements. Numbers at the top of graphs refer to years of aerial photography. Error bars are calculated from Equations 8 and 9.

A) Wreck Section
B) Green Hill Section
C) West Gut Section
D) Doyle Section

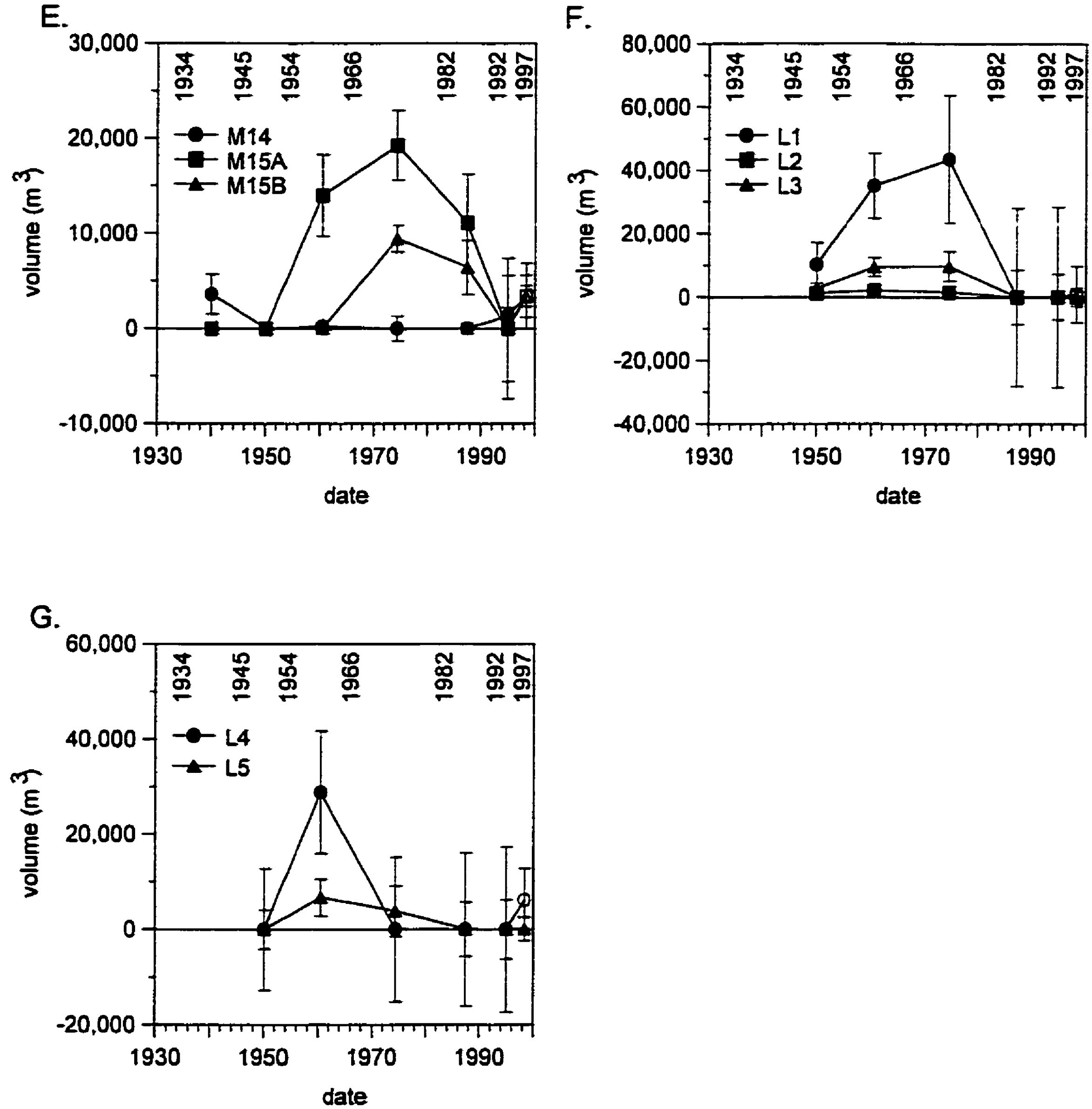


Figure 2.9 E) Big Thrumcap Section
F) Lawlor Point Section
G) East Gut Section

different from each other. Total volume delivered by Lines M8, M9, and M10 of the West Gut section peaked between 1954 and 1966 at 17,252 m^3. Significantly more sediment was delivered from M10 than M8 and M9 during this time, however volumes from M8 and M9 increased after 1966 and became not significantly different from M10. Volumes from these three stations decreased to 1992 and became not significantly different from zero. Volume delivered from Doyle Point reached a maximum between 1945 and 1954 at 42,120 m^3 with the greatest contribution coming from M11 and M13. Volume decreased to not significantly different from zero between 1954 and 1966, increased slightly to 1982 and then decreased again to zero. Volume delivered from Big Thrumcap reached a maximum between 1966 and 1982 at 28,695 m^3 with the greatest contribution from M15A, and decreased steadily to become not significantly different from zero between 1992 and 1997 at which time volume from M14 began to increase. Volumes delivered by the Lawlor Point section reached a maximum between 1966 and 1982 of 54,710 m^3 and then decreased to zero. Volume delivered by the East Gut section reached a maximum between 1954 and 1966 of 35,472 m^3 and then decreased to not significantly different from zero.

Error in sediment delivery volumes arises from volume measurement error and grain size analysis error. Because the loss of material during wet-sieving was less than 1%, and wet-sieving is effective at separating size classes, the bulk of the error is due to uncertainty in amount of retreat over a time period, uncertainty in bluff length, and uncertainty in bluff height.

Uncertainty in bluff height is difficult to quantify, but calculated heights are supported by airphoto interpretation. Bluffs at M1, 2, 3, 4, 5, and 8 were at different times calculated to have heights less than zero, that is, extrapolation of the slope to the 'bluff' edge indicated the bluffs were not present; examination of airphotos shows that at these times the drumlins were not yet experiencing wave attack and bluff height was therefore zero. Considering therefore that bluff heights appear consistent and uncertainty of bluff height is difficult to quantify, it may be assumed that most quantifiable error in the volume calculation arises from retreat and bluff length measurement error.

The average error of a measurement on a single airphoto is given by the RMS error of rectification so uncertainty in bluff length is equal to the RMS error (<3.5 m in this study). An additional source of uncertainty arises in the interpretation of bluff lengths which are chosen to be of uniform composition, amount of retreat and bluff height, and where low ends of bluffs are excluded. Interpretations were made using stereo airphotos and recent interpretations were field-checked.

When comparing two shoreline positions on two airphotos to measure amount of retreat (X), average retreat measurement error (E_X) over the area of rectification is given by:

$$E_X = \sqrt{(RMS_1)^2 + (RMS_2)^2}, \tag{7}$$

where RMS_1 and RMS_2 are the RMS errors of each airphoto. Typical values of error of the amount of retreat are less than 4 m but are often greater than the amount of retreat measured from airphotos, particularly if the time interval is short and retreat small.

Volume error (E_V) of airphoto measurements is therefore given by:

$$E_V = LH(E_X + RMS) \tag{8}$$

where RMS is the error of the photo used to measure bluff length.

Percentage volume errors obtained by this method are given in Table 2.4. Where retreat approaches the error of measurement, large percentage volume errors result. Long high bluffs have higher total error than short low bluffs.

Field measurements of retreat between 1997 and 1999 collected using Emery poles are more accurate than those made from airphotos and have error ±10 cm. As with historic retreat measurements, bluff lengths were measured from airphotos with error equal to the RMS error. Assuming again that most quantifiable error arises from the measurement error of retreat and bluff length, volume error of field measurements is given by:

$$E_V = LH(0.1 + RMS) \quad (9)$$

The total volume error depends mainly on bluff length where long bluffs have large errors. Percentage volume errors of field measurements, as is the case for airphoto measurements, depend on measured retreat. Values of E_v from field measurements are less than values from airphoto measurements.

Retreat rate (R) is calculated from:

$$R = \frac{X}{T} \quad (10)$$

where X is the measured retreat and T is the time interval between airphotos or field measurements. Error of decadal retreat rate measured from airphotos was evaluated in two ways. In the first method, a rejection method, a minimum-time requirement T_{min} is calculated from Dolan *et al.* (1991):

$$T_{min} = \frac{\sqrt{(RMS_1)^2 + (RMS_2)^2}}{R}. \quad (11)$$

line	1997-1999			1992-1997			1982-1992			1966-1982			1954-1966			1945-1954			1934-1945		
	total volume	total error	% error	total volume	total error	% error	total volume	total error	% error	total volume	total error	% error	total volume	total error	% error	total volume	total error	% error	total volume	total error	% error
M1	158	180	114	309	338	109	110	178	163	0	0	0	0	0	0	0	0	0	0	0	0
M2	592	610	103	0	1223	0	1177	1548	132	6689	1286	19	0	1377	0	0	2373	0	0	0	0
M3	386	787	204	0	1583	0	2967	2486	84	8052	1958	24	4372	2032	46	0	2369	0	0	0	0
M4	257	782	304	0	1280	0	1200	1534	128	6269	1786	28	2768	1107	40	0	0	0	0	0	0
M5	131	187	143	0	321	0	133	143	107	0	0	0	0	0	0	382	196	51	122	205	168
M6	371	468	126	0	1261	0	450	248	55	0	0	0	0	0	0	375	202	54	0	0	0
M7	291	446	153	0	413	0	136	161	118	0	0	0	0	0	0	237	133	56	0	0	0
M8	394	1664	423	0	3461	0	0	3043	0	5996	2389	40	2383	2429	102	1780	945	53	0	0	0
M9	122	1216	996	0	3557	0	0	3110	0	5057	1542	30	977	1068	109	157	139	89	2176	2634	121
M10	579	1901	328	0	6566	0	0	5011	0	9501	4320	45	13823	4821	35	0	0	0	4593	6700	146
M11	1239	1310	106	0	3317	0	2623	2323	89	5320	2461	46	0	2917	0	20083	6043	30	10909	3775	35
M12	326	1858	569	0	4644	0	4829	2995	62	2743	2924	107	2653	4046	153	5512	647	12	0	6241	0
M13	825	2741	332	0	6606	0	0	4373	0	6615	3392	51	3802	5235	134	16168	2884	18	3324	4643	140
M14	3406	1069	31	1334	854	64	0	550	0	0	1313	0	223	380	170	0	290	0	3605	2077	58
M15A	3407	3444	101	0	7377	0	11079	5132	46	19264	3699	19	13981	4302	31	0	0	0	0	0	0
M15B	3390	2205	65	0	5579	0	6402	2827	44	9423	1404	15	0	0	0	0	0	0	0	0	0
L1	894	8877	993	0	28407	0	0	28058	0	43330	20191	47	34943	10353	30	10163	6933	68	0	0	0
L2	42	346	828	0	1156	0	0	1183	0	1524	734	48	2043	613	30	1165	749	64	0	0	0
L3	67	2866	4257	0	7157	0	0	8522	0	9644	4631	48	9337	2962	32	2696	1641	61	0	0	0
L4	6124	6661	109	0	17316	0	0	16045	0	0	15138	0	28656	12882	45	0	12745	0	0	0	0
L5	82	2440	2980	0	6157	0	0	5687	0	3810	5288	139	6650	3848	58	0	4080	0	0	0	0
Total	23083	42059	182	1643	108573	6609	31104	95157	306	143238	74455	52	126712	60373	48	58759	42370	72	24728	26274	106
Mean	1099	2003	632	78	5170	8	1481	4531	49	6821	3545	34	6034	2875	48	2798	2018	26	1178	1251	32
σ	1563	2113	1030	288	6450	26	2758	6336	54	9387	4888	35	9400	3324	52	5552	3105	30	2580	2161	56

Table 2.4 Total volumes of sediment delivered by bluff retreat since 1934. Total and percent errors are also given. Zero values result when either bluff height or the amount of retreat X is zero. Negative values of retreat and retreat not significantly different from zero are treated as zero values. Large errors between the 1992 and 1997 airphotos results in numerous measurements not significantly different from zero.

Measurements are rejected if T_{min} is greater than the time interval between photos. The second method of error evaluation quantifies retreat rate error (E_R) measured on airphotos following:

$$E_R = \frac{\sqrt{(RMS_1)^2 + (RMS_2)^2}}{T} \qquad (12)$$

where T is the time interval between airphotos. Calculation of error bars by Equation 12 is used in this study because the minimum time requirement method reduces the number of data points and results in large interpolated retreat rates (Manson, 1999).

Large errors in airphoto measurements of R result from short airphoto intervals and large RMS errors. Error in field measurements of bluff retreat rate (E_R) is calculated simply as 0.1 m (Emery pole accuracy) divided by the time interval and are much smaller than E_R when R is measured from airphotos.

Historic and recent retreat rates for each survey line are given in Figure 2.10 and Appendix E. Retreat rates at the Wreck section reached a maximum of 2.07 m/a between 1966 and 1982 and decreased to a minimum between 1992 and 1997. Rates have not increased significantly since 1997. Rates at lines M2, M3, and M4 tend to be similar, while those at M1 are different and gradually increased to 1992. Negative values of retreat measured at M2 and M1 are significantly different from zero between 1945 and 1954 and result from an indistinct bluff edge. At the Green Hill section, retreat rate peaked between 1954 and 1945 at 1.35 m/a and decreased to not significantly different from zero between 1954 and 1966. A smaller peak of 1.01 m/a occurred between 1982 and 1992 followed by a decrease in rate to 1997 and a subsequent significant increase to 1.31 and 1.49 m/a at lines M5 and M6 respectively between 1997 and 1999. Retreat rates

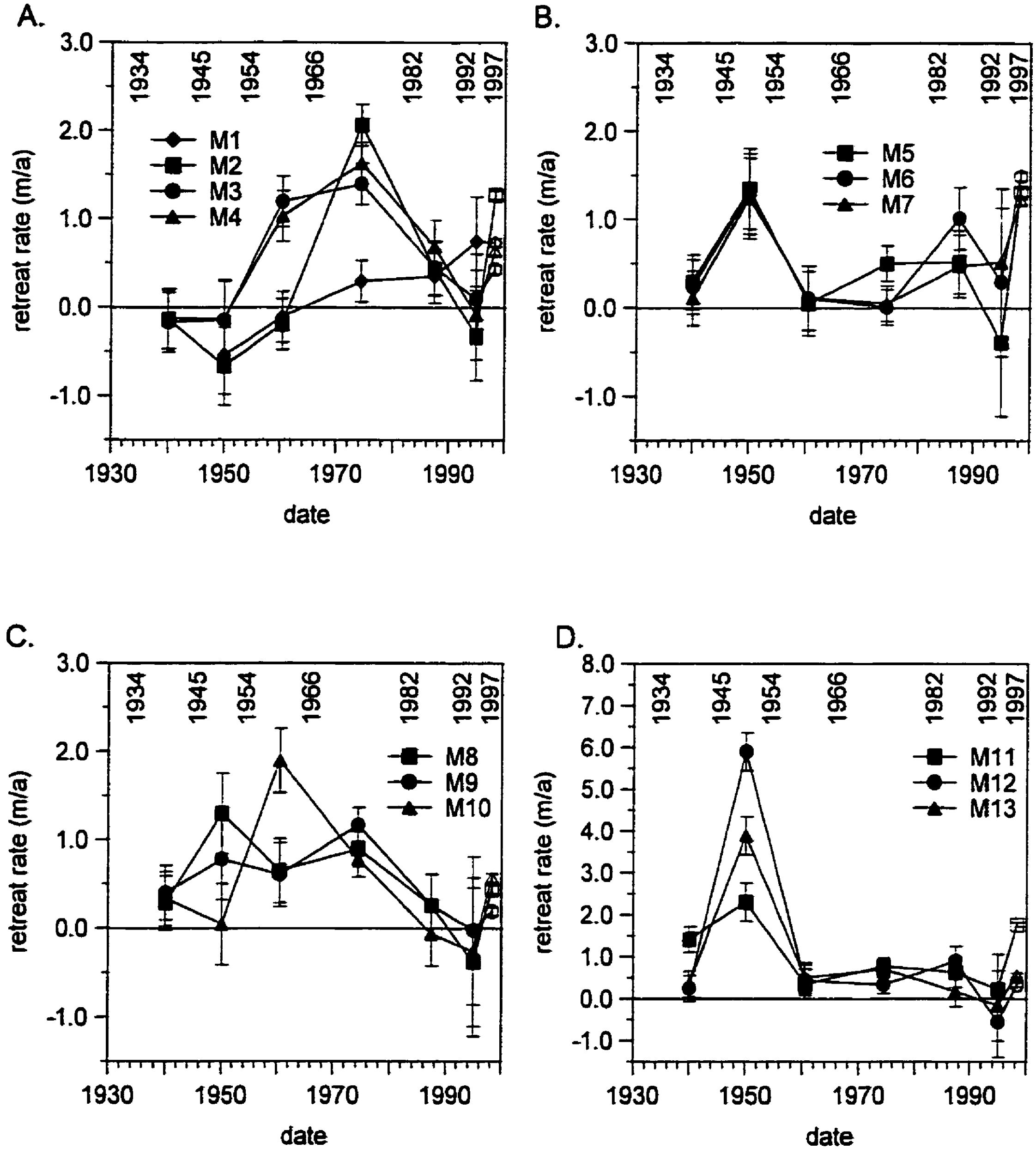


Figure 2.10 Retreat rates measured from airphotos from 1934 to 1997 (closed symbols) and fieldwork from 1997 to 1999 (open symbols). Numbers at the top of graphs refer to years of aerial photography. Error of measurements from airphotos are calculated from Equation 12.

A) Wreck Section

B) Green Hill Section

C) West Gut Section

D) Doyle Section

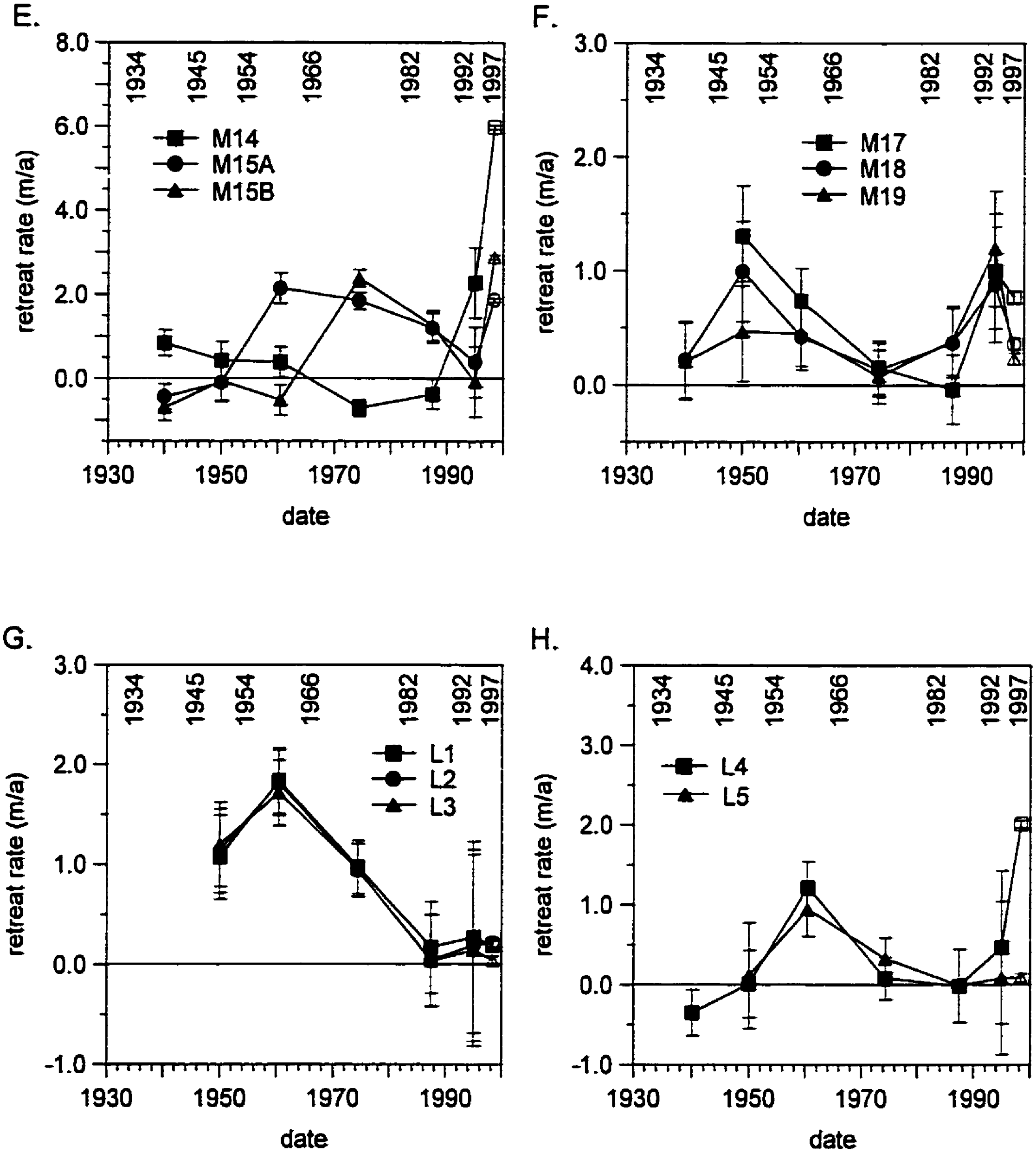


Figure 2.10 E) Big Thrumcap Section
F) Fort McNab's/Strawberry Hill Section
G) Lawlor Point Section
H) East Gut Section

at M5, M6, and M7 are similar to each other before 1966 and after 1997 but are variable between these dates. Retreat rates were low at the West Gut section between 1934 and 1945 and similar at M8, M9, and M10 but reached a maximum at M8 and M9 between 1945 and 1954 and at M10 between 1954 and 1966 reached 1.90 m/a. Rates were not significantly different from zero from 1982 to 1997 but have increased slightly after 1997. Retreat rate at Doyle Point reached a maximum between 1945 and 1954 of 5.90 m/a but decreased rapidly between 1954 and 1966. Only M11 has increased significantly since 1966. At Big Thrumcap retreat at lines M15A and B peaked between 1954 and 1966 and between 1966 and 1982 at 2.15 and 2.38 m/a respectively and decreased to not significantly different from zero between 1992 and 1997. Rates at M14 decreased from 1934 and became negative between 1966 and 1982 but show a strong increase to a maximum of 5.98 m/a between 1997 and 1999. Rates at M15A and B also increased significantly since 1992 to 1.86 and 2.88 m/a respectively. Retreat rates of lines at the Fort McNab's/Strawberry Hill section are not significantly different from each other since 1934 and show a decrease from a maximum between 1945 and 1954 of 1.31 m/a to not significantly different from zero between 1966 and 1982. Rates increased to 1997 to a maximum of 1.20 m/a at M19; a subsequent decrease between 1997 and 1999 is significant only for M19. Rates at Lawlor Point reached a maximum of 1.84 m/a between 1954 and 1966 and decreased to not significantly different from zero between 1982 and 1992. Rates have increased significantly since then only at L3. Retreat rates at the East Gut section peaked between 1954 and 1966 at 1.21 m/a and decreased to not significantly different from zero between 1966 and 1982. Lines M4 and M5 are similar to each other except between 1997 and 1999 when retreat at M4 increased to 3.01 m/a.

2.7 Measurements of Erosion of Offshore Features

Erosion over time of offshore features (shoals and submerged barrier beaches) was measured using a combination of echosounding in 1998 and 1999 and Canadian Hydrographic Service (CHS) field sheets containing a high density of historic echosoundings. 1998 and 1999 sounding profiles were collected using a Knudsen echosounder with both 200 kHz and 28 kHz transducers mounted on a 4.8 m Zodiac positioned using RTK-DGPS or a Garmin 45 GPS with differential control from Canadian Coast Guard radio beacons using a Magnavox MBX11 beacon receiver. Positioning accuracy of the Garmin/MBX11 system is approximately ±5-8 m.

The 200 kHz transducer is used for bottom detection while the 28 kHz transducer penetrates muddy sediments and can be used to identify these on traces. Soundings collected with the Knudsen echosounder are corrected for tides to 1987 chart datum and compared to historical soundings of Barrie Beach from a 1964 CHS fieldsheet and soundings of Thrumcap Shoal from 1950 and 1979 field sheets all corrected to 1987 chart datum and NAD83 horizontal datum. Horizontal corrections of historic soundings were made by correcting 4 points on each fieldsheet and recalculating the scale. The accuracy of these sources is not well defined and depends mainly on the navigation system being used. Positioning accuracy of ±5-10 m is possible. Sounding accuracies of both the Knudsen echosounder and the similar sounding systems used by CHS are approximately ±1 cm, however swell heave and Zodiac vessel parameters such as lift, squat, and pitch can introduce error. Eel grass is another potential source of inaccuracy when sounding sheltered sandy substrates as it is opaque to sonar at bottom detection frequencies. Barrie

Beach profiles are given in Figure 2.11, and Thrumcap Shoal profiles are given in Figure 2.12. All soundings are given in metres below 1987 chart datum which in 1999 is 0.8 m below geodetic datum.

1998 Barrie Beach profiles were collected by simultaneously recording RTK-GPS positions and soundings at 20 s to 1 min. intervals. Additional depths along profiles were obtained from echosounding traces and positions were interpolated. Results showed that up to 2 m vertical erosion of the submerged beach between 1964 and 1998 is accompanied by up to 1.5 m lowering and 50 m northwestward migration of the main crest. The smaller crest to the southeast was lowered by up to approximately 1 m with little migration. Negligible erosion over Cock's Comb, a bedrock shoal, is shown by Figure 2.12f, in which recent and historic profiles show remarkable similarity in form.

1999 Thrumcap Shoal profiles (Figure 2.12) were collected using the Garmin 45/MBX11 system and vertically corrected using measured tides. End points of profiles were converted from latitude and longitude to UTM coordinates and positions of soundings interpolated. 1950 and 1979 profiles tend to be similar and show marked vertical erosion (up to 3 m) only in shallow depths. Up to 3 m erosion occurred between 1979 and 1999 at depths greater than 3 m, but only up to 1 m of erosion has occurred at shallow depths.

The Knudsen echosounder was also used to identify other potential offshore sources of sediment (see also Figure 4.5) which were groundtruthed by SCUBA in 1998 and 1999 as hummocky estuarine or lagoonal sandy muds and relict barrier beach forms.

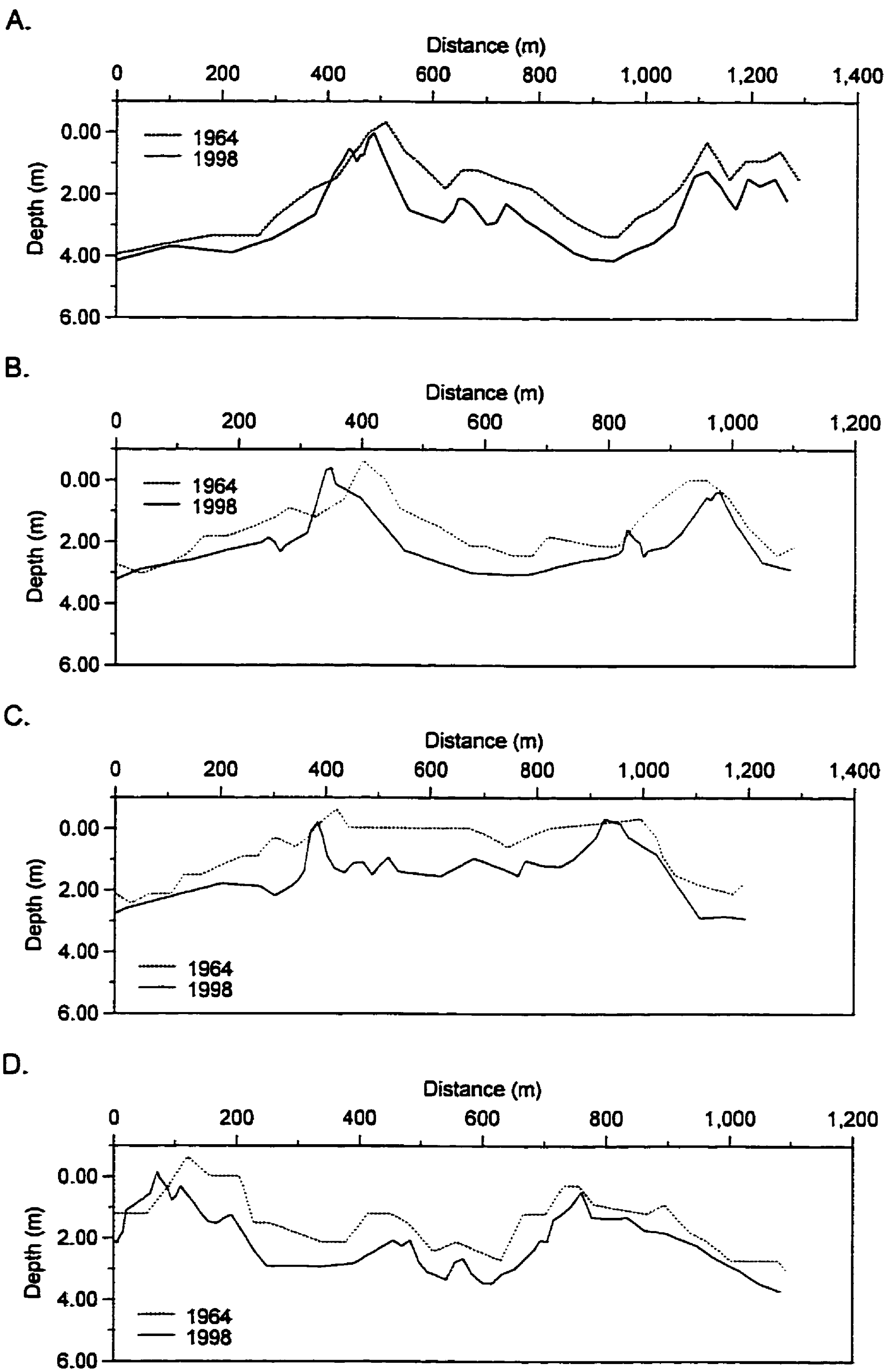


Figure 2.11 Knudsen echosounding profiles over Barrie Beach. Profile locations are given in Figure 2.5
A) BB1 B) BB3 C) BB4 D) BB6

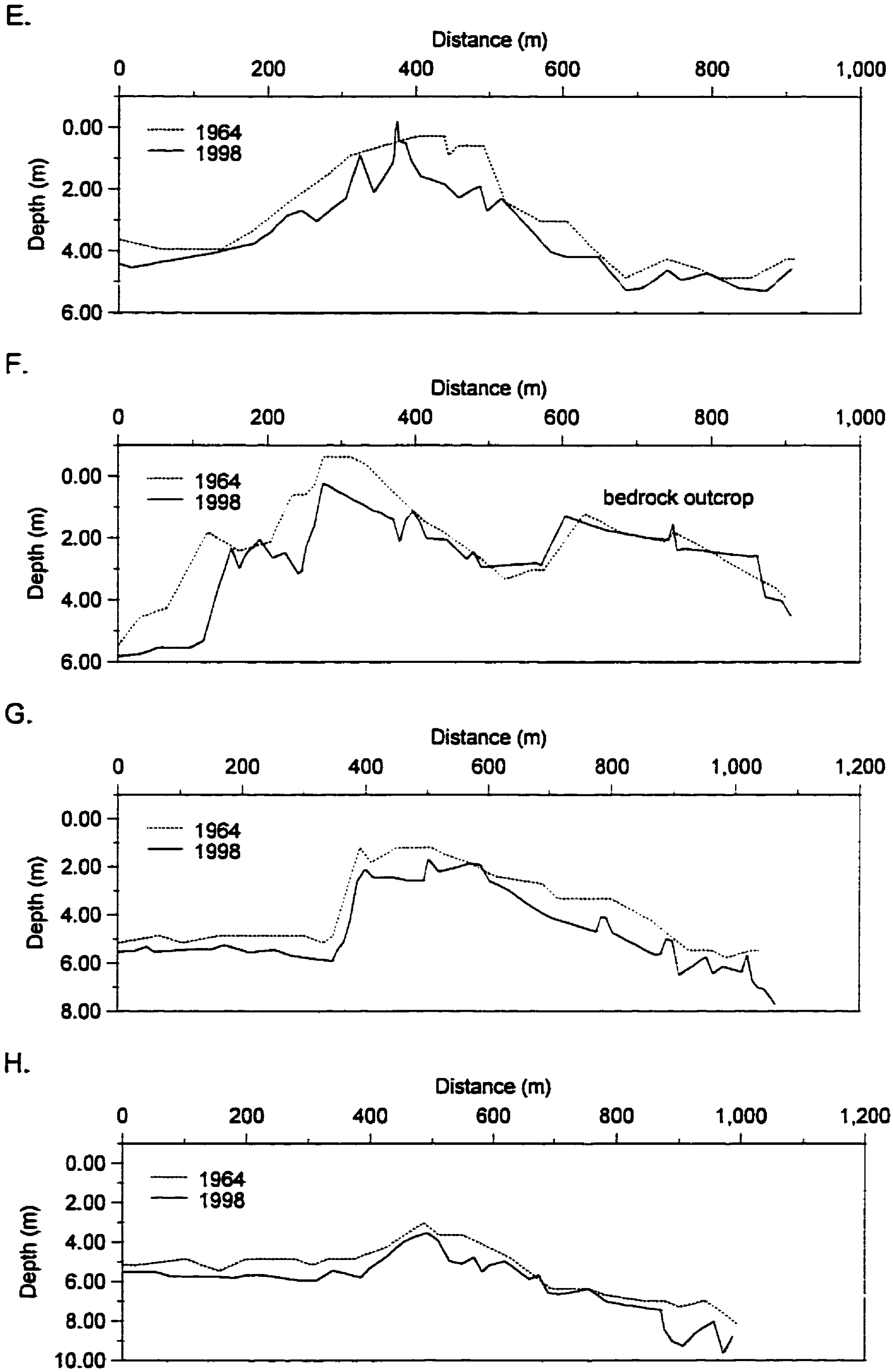


Figure 2.11 E) BB8 F) BB9
G) BB10 H) BB11

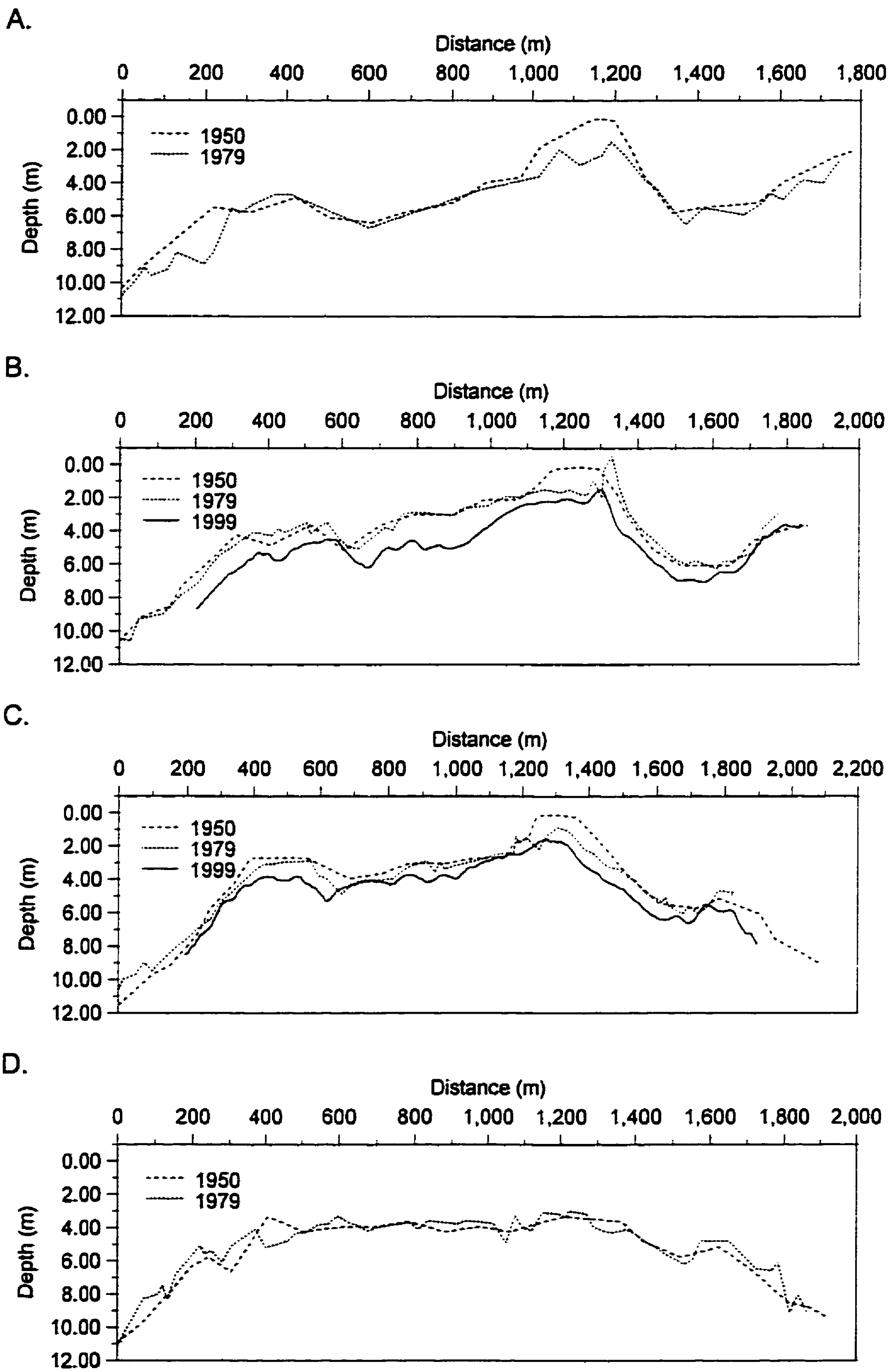


Figure 2.12 Knudsen echosounding profiles over Thrumcap Shoal. Profile locations are given in Figure 2.5
A) TS1 B) TS2 C) TS3 D) TS4

2.8 Environmental Data

Records of daily maximum and minimum temperature and precipitation and hourly wind speeds recorded at C.F.B. Shearwater (station 8205090) were obtained from the Atmospheric Environment Service (AES) of Environment Canada. Shearwater records were supplemented with data from Shearwater Autoport (station 8205091) and Citadel Hill (station 8205020). Precipitation and temperature data cover the monitoring period from 1997 to 1999 (Figure 2.13); wind data extend from 1953 to March 1999 (Figure 2.14).

Over 45 mm daily precipitation occurred 4 times during the monitoring period. On January 24, 1998, 52.2 mm of precipitation fell likely as mixed rain and snow when minimum and maximum temperatures on this day were -4.7 and 6.4 °C. 76.6 mm of rain fell on July 11, 1998 when minimum and maximum temperatures were 11.9 and 15.7 °C. 61.1 mm fell on October 11, 1998 when minimum and maximum temperatures were 9.1 and 12.7 °C. 48.1 mm of precipitation fell presumably as snow on February 18, 1999 when minimum and maximum temperatures were -6.5 and -1.6 °C.

Mean daily wind speeds show winter maxima and summer minima. Peak wind speeds were greater in the winter of 1997/98 than 1998/99. Mean daily wind speeds exceeded 35 km/h four times in 1997/98 and never in 1998/99. Northwesterly winds of speeds greater than 30 km/h were recorded for 32 hours on December 3, 1997, winds on January 14, 1998 were northwesterly greater than 30 km/h for 31 hours, and winds on January 21, 1998 were northerly greater than 30 km/h for 35 hours and greater than 50 km/h for 13 hours before veering northwesterly and diminishing. On February 25, 1998 easterly winds were greater than 30 km/h for 33 hours and greater than 50 km/h for 21

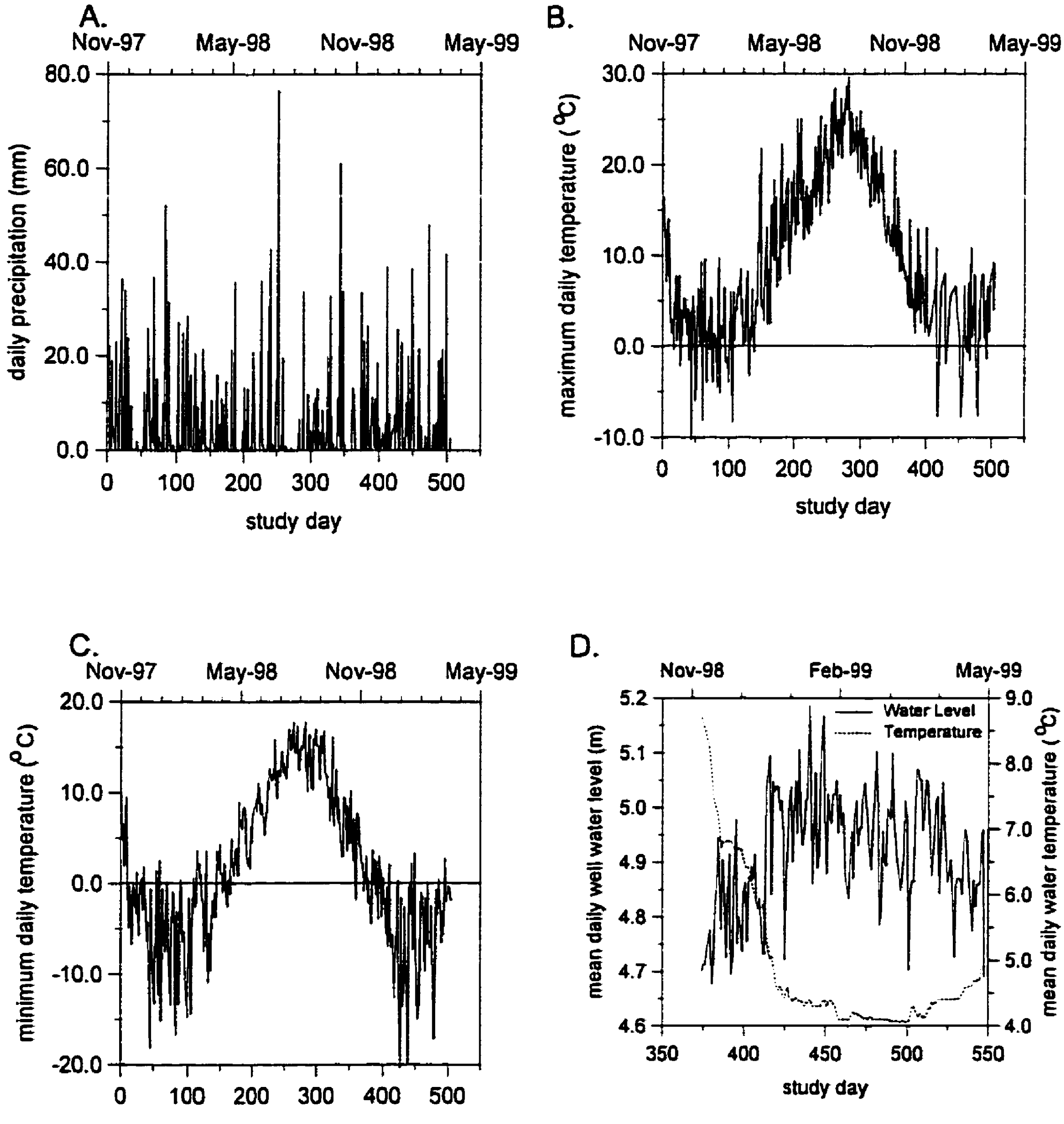


Figure 2.13 Environmental data during the monitoring period. Precipitation and temperature were measured at CFB Shearwater; well water level and temperature were measured at the teahouse well, McNab's Island (Figure 2.5).

A) Daily precipitation
B) Maximum daily temperature
C) Minimum daily temperature
D) Mean daily well water level and temperature

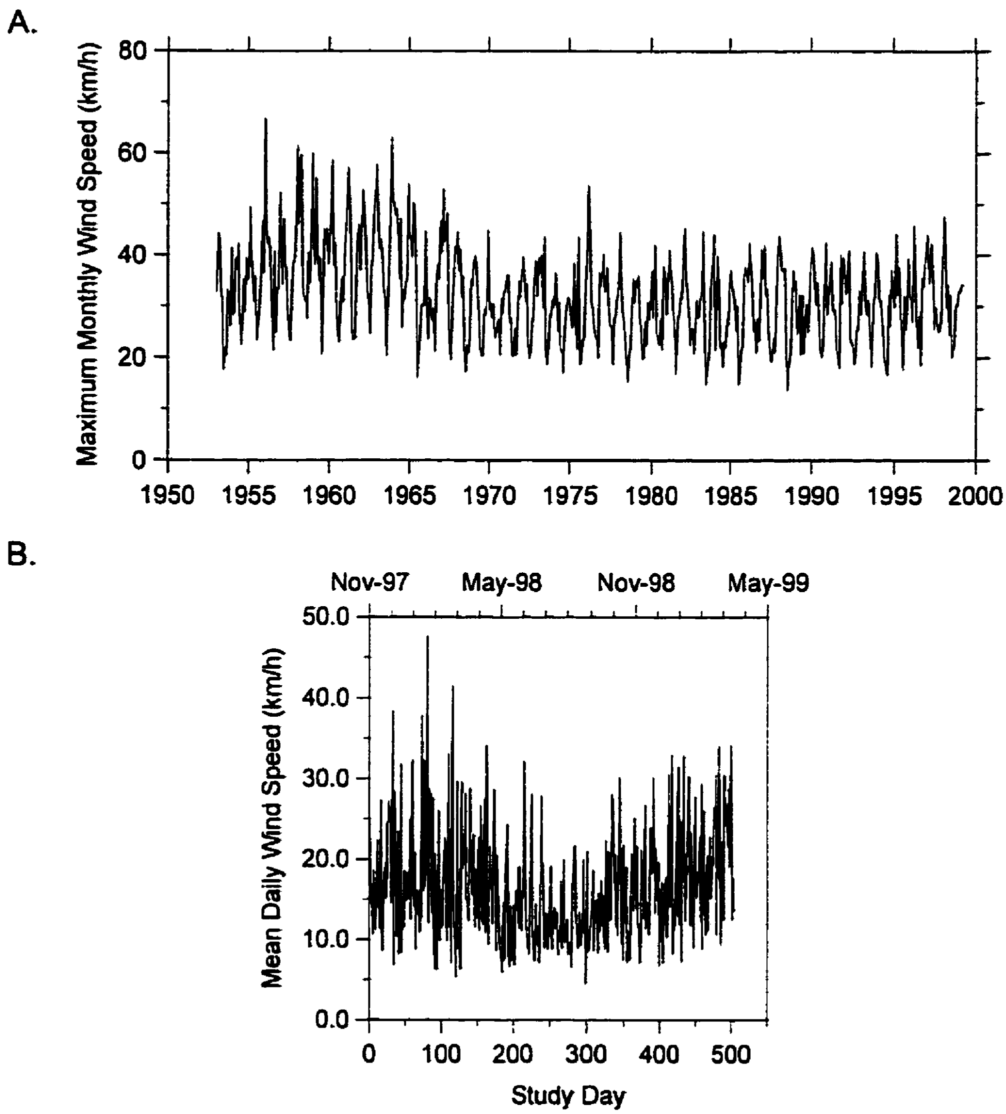


Figure 2.14 Wind speed measured at CFB Shearwater.
A) Maximum monthly wind speed since 1953.
B) Mean daily wind speed during the monitoring period.

hours. The four highest winds over the winter of 1998/99 were southerly switching to westerly greater than 30 km/h for 24 hours and greater than 50 km/h for 4 hours on December 22, 1998, and southeasterly switching to southwesterly greater than 30 km/h for 19 hours and greater than 50 km/h for 1 hour on January 9, 1999. Northwesterly winds on February 27, 1999 were greater than 30 km/h for 21 hours, and southwesterly veering to westerly winds were greater than 30 km/h for 39 hours and greater than 50 km/h for 5 hours on March 16, 1999. Wind storms appear to have been less intense but more numerous in winter 1998/99 than 1997/98.

Historic maximum monthly wind speeds show a period of storminess from 1956 to 1963 and a calm period to 1994. Storminess appears to have increased since 1994, however, maximum monthly wind speeds as low as those recorded in 1999 were last recorded in 1971. Important wind storms occurred on January 9, 1956, November 8, 1963, February 2, 1976, and February 25, 1998 (Table 2.5).

Hourly well water levels and temperatures were collected from November 1998 to May 1999 at 4.2 m depth in an abandoned 5 m deep stone-lined well on McNab's Island (Figure 2.5) using a Vemco Mini-Log recorder with depth and temperature resolution of 0.1 m and 0.1 °C (Figure 2.13). Water levels increased sharply in mid-December, reached a maximum of 5.19 m in mid-January and declined to May. Weekly oscillations of 0.3 to 0.4 m were common. Temperature decreased sharply from a maximum of 8.7 °C in November and more gently in December and January to a minimum of 4.1 °C in early March when it began to slowly rise.

Deep-water wave data measured since 1973 at the Shearwater wave-rider buoy located in 46 m water depth southeast of Osborne Head (44.54 °N, 63.46 °W) were

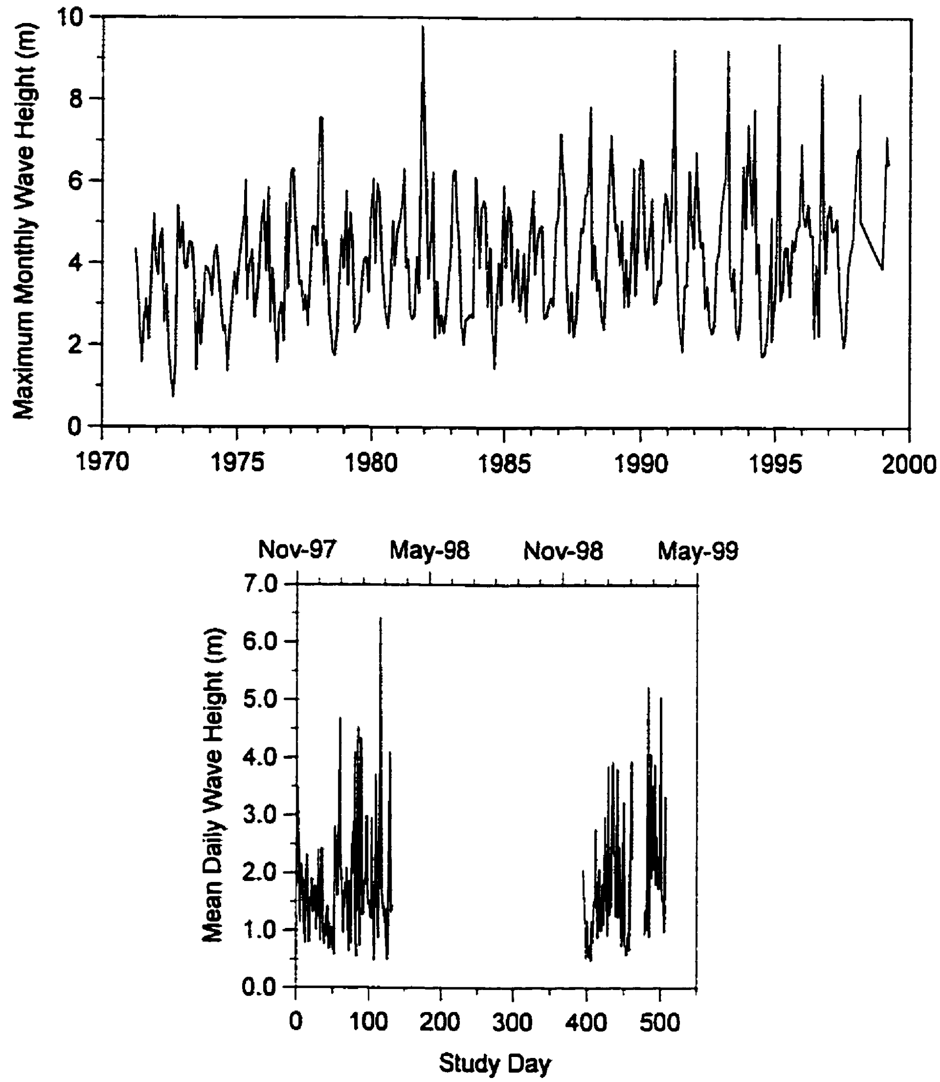
Date	Wind Speed (km/h)	Wind Direction	Wave Height (m)	Water Level (m)	Duration (hrs)	Area Affected
15/08/1635*	217	NE				SW Nova Scotia
1676*	hurricane					The Great Hurricane
1717*	gale?					New England
31/10/1723*	116-216	NE				New England, Nova Scotia?
03/11/1759*	storm					Halifax
25/09/1798*	gale	SE				Halifax/South Shore
13/11/1813*	gale					Nova Scotia
03/09/1821*	gale?					Long Island Hurricane
28/09/1831*	gale	SE-SW				Halifax
22/11/1851*	gale	SE				Halifax
24/12/1853*	storm	SE-SW				Halifax
02/08/1867*	gale	S				Halifax
04/10/1869*	gale			>2.5?		Bay of Fundy, Saxby Gale
04/09/1870*	110	SSE-SE				Halifax
24/08/1873*	storm				44	Halifax
07/09/1891*	gale?					Halifax
11/09/1954*	>50	SE		2.11	8	Hurricane Edna
09/01/1956	>70	NE		1.83	7	Halifax
30/12/1956*	>50	SW		2.17	9	South Shore
04/12/1958	>50	NE		2.14	10	Halifax
20/02/1963	>50	SW		2.08	4	Halifax
08/11/1963	>70	NE		1.90	11	Halifax
01/12/1964*	>50	SE		2.24	17	Halifax, 25 yr. storm
17/03/1974*	>30	SW	4.05	1.64	6	Hfx, Groundhog Day Storm
20/10/1974*	>30	W	3.08	2.32	7	Halifax
28/07/1975	>50	SW	4.33	2.16	4	Halifax
02/02/1976*	>50	S	5.88	2.21	26	Halifax
17/03/1976*	>50	SE	?	2.67	12	Halifax
09/11/1981	26	SW	9.82	1.75	1	Halifax
30/01/1990	>50	SE	6.52	2.56	8	Halifax
26/03/1991	28	N	9.25	1.67	1	Halifax
30/10/1991	>30	NE	6.28	2.26	47	Hfx, Hallowe'en Storm
14/03/1993	>50	S	9.23	2.06	10	Hfx, Storm of the Century
04/02/1995	>50	SW	9.39	2.20	9	Halifax
15/09/1996	>50	W	8.69	2.61	3	Halifax, Hurricane Hortense
25/02/1998	>50	E	8.17	2.38	21	Halifax

Table 2.5. List of important wind storms and wave events affecting the Maritime provinces and New England states giving wind speed, mean wind direction, maximum daily wave height, maximum daily tidal elevation and storm duration. Winds after 1953 are measured at CFB Shearwater, and waves after 1970 at the Shearwater wave-rider bouy. Asterix indicates storms compiled by DeIure (1983).

obtained from the Marine Environmental Data Service (MEDS) of the Department of Fisheries and Oceans (Figure 2.15). These data consist of significant wave heights and peak wave periods calculated from the wave spectrum determined from 20 minute water surface elevation records. Significant wave height is defined as four times the square root of the area under the variance spectrum of the water surface elevation and peak period is defined as the inverse of the frequency of the maximum variance. Quality control performed by MEDS was preserved during data processing; dubious and erroneous measurements were excluded. The accelerometer sensor on the wave buoy was inoperational from mid-March 1998 to mid-December 1998 and again in March and July 1999. Continuous wave records are invaluable in climate and coastal studies (e.g. Günther *et al.*, 1998; Forbes and Drapeau, 1989) and allow calibration of wave hindcast models (*e.g.* Amin and Davidson-Arnott, 1995). The wave record from Shearwater is unfortunately discontinuous and appears to be becoming more so; since the beginning of this study in November, 1997 the Shearwater wave buoy has been operative 51% of the time compared with a days operative average since 1970 of 89%.

Maximum monthly significant wave heights show maxima in winter and also in the early fall. Wave heights greater than 9 m were recorded once prior to 1990 and 3 times after. Smaller peaks were recorded in 1986 and 1987 and after 1996. Maximum daily significant wave height of 9.82 m was recorded on November 9, 1981, 9.25 m on March 26, 1991, 9.23 m on March 14, 1993, and 9.39 m on February 2, 1995. An early fall peak of 8.69 m was recorded on September 15, 1996. Mean daily significant wave heights greater than 5 m occurred twice in the winter of 1998/99 and once in 1997/98.

A.



B.

Figure 2.15 Deep water wave heights measured at the Shearwater wave rider buoy.
A) Maximum monthly wave height since 1970.
B) Mean daily wave height during the monitoring period. The accelerometer was inoperational for periods of 1998 and 1999.

Mean daily significant wave heights of 6.43 m occurred on February 25, 1998, 5.24 m on February 26, 1999, and 5.05 m on March 16, 1999.

Hourly sea level elevations recorded at the Halifax Harbour tide gauge from 1896 to 1905 and since 1920 were also obtained from MEDS. Measurements are corrected to 1987 chart datum. Data since 1996 are used to update the sea level curve for Halifax Harbour previously presented by Shaw *et al.* (1993) (Figure 2.16). Mean annual sea level has risen in a step-wise manner at rates of 0.8 mm/a to 8 mm/a with a cumulative rate since 1896 of 3.0 mm/a. Sea-level rise occurred rapidly between 1928 and 1970, very slowly after 1970 and in 1993 again began increasing rapidly. Maximum monthly water level since 1920 has maxima in winter which increase during rapid sea-level rise and decrease slightly after 1965. Major peaks since 1950 are 2.47 m on February 28, 1952, 2.63 m on November 12, 1961, 2.76 m on February 23, 1967, 2.67 m on March 17, 1976, 2.59 m on February 7, 1978, 2.65 m on January 29, 1979, 2.56 m on January 30, 1990, 2.53 m on December 21, 1995, and 2.61 m on September 14, 1996. Maximum daily water levels during the monitoring period appear highest during the winter of 1997/98 and show 4 peaks: 2.45 m on November 15, 1997, 2.44 m on December 30, 1997, and 2.38 m on February 25, 1998, and 2.3 m on December 30, 1998.

2.9 Climate Indices

The climate in the Maritime provinces may be controlled by two oscillation indices, the Southern Oscillation Index (SOI) (Figure 2.17) and the North Atlantic Oscillation Index (NAOI) (Figure 2.18). The SOI is defined as the difference of normalised monthly airpressures at sea level at Tahiti and Darwin, Australia. The NAOI

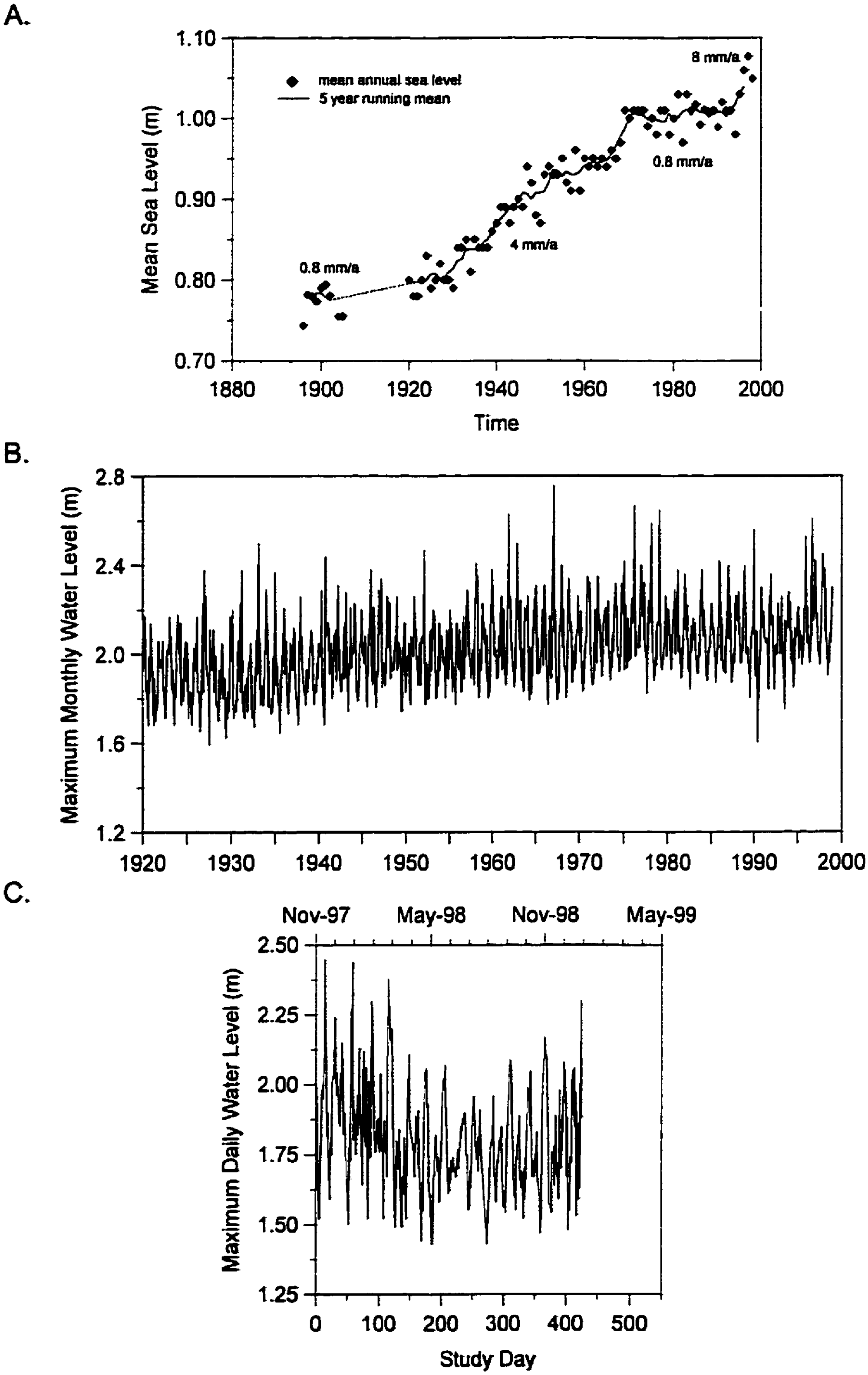


Figure 2.16 Water level measured at the Halifax Harbour tide gauge.
A) Mean annual sea-level since 1896 with rates of RSL rise.
B) Maximum monthly water levels since 1920.
C) Maximum daily water levels during the monitoring period.

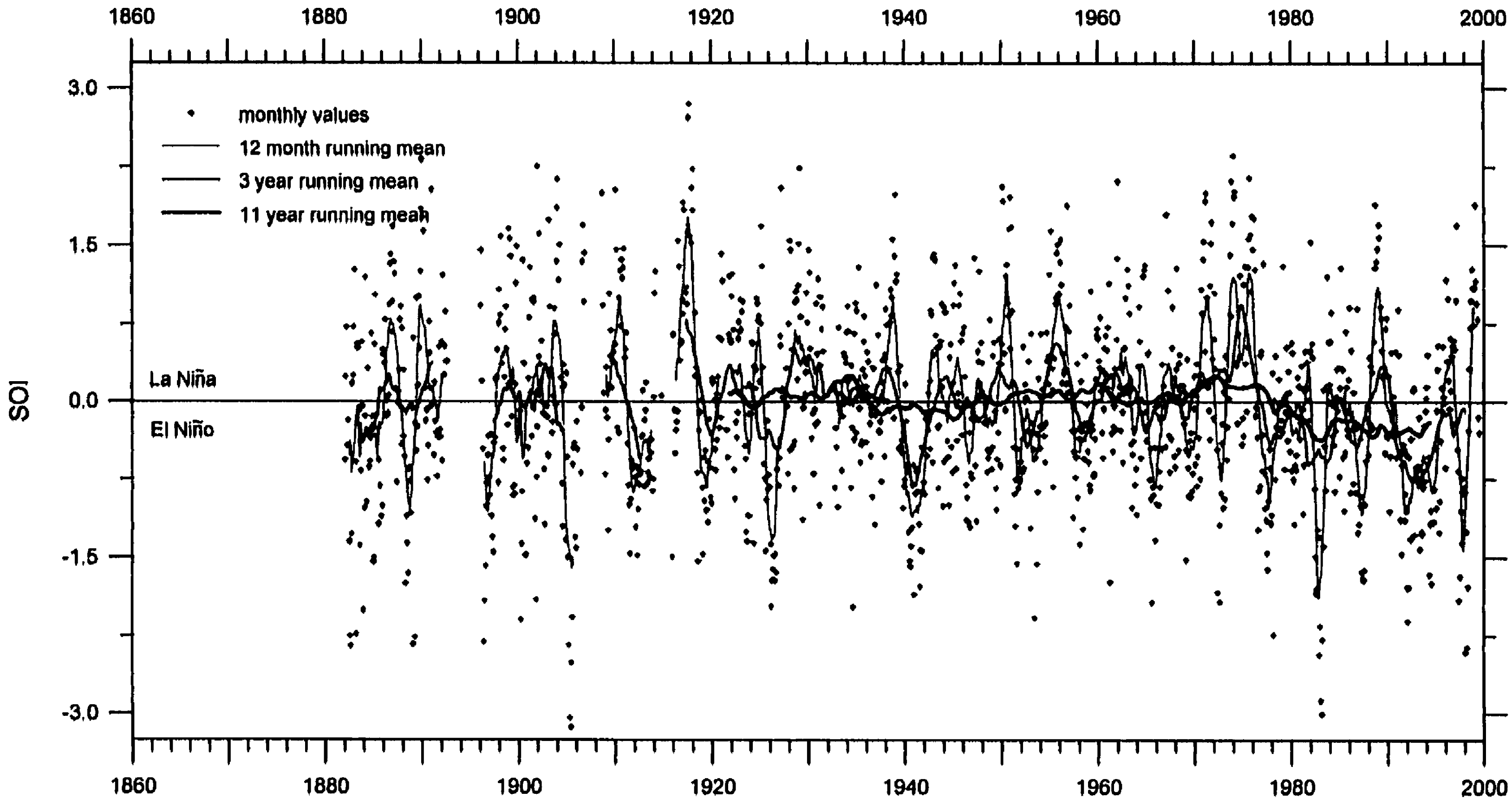


Figure 2.17 The Southern Oscillation Index (SOI) between 1881 and June 1999. The SOI is defined as the difference between normalised mean monthly sea level air pressures at Tahiti and Darwin. Monthly values, and the 12 month, 3 year, and 11 year running means are given. Air pressure at Tahiti is discontinuous prior to 1917. Source http://nic.fb4.noaa.gov/data/cddb/.

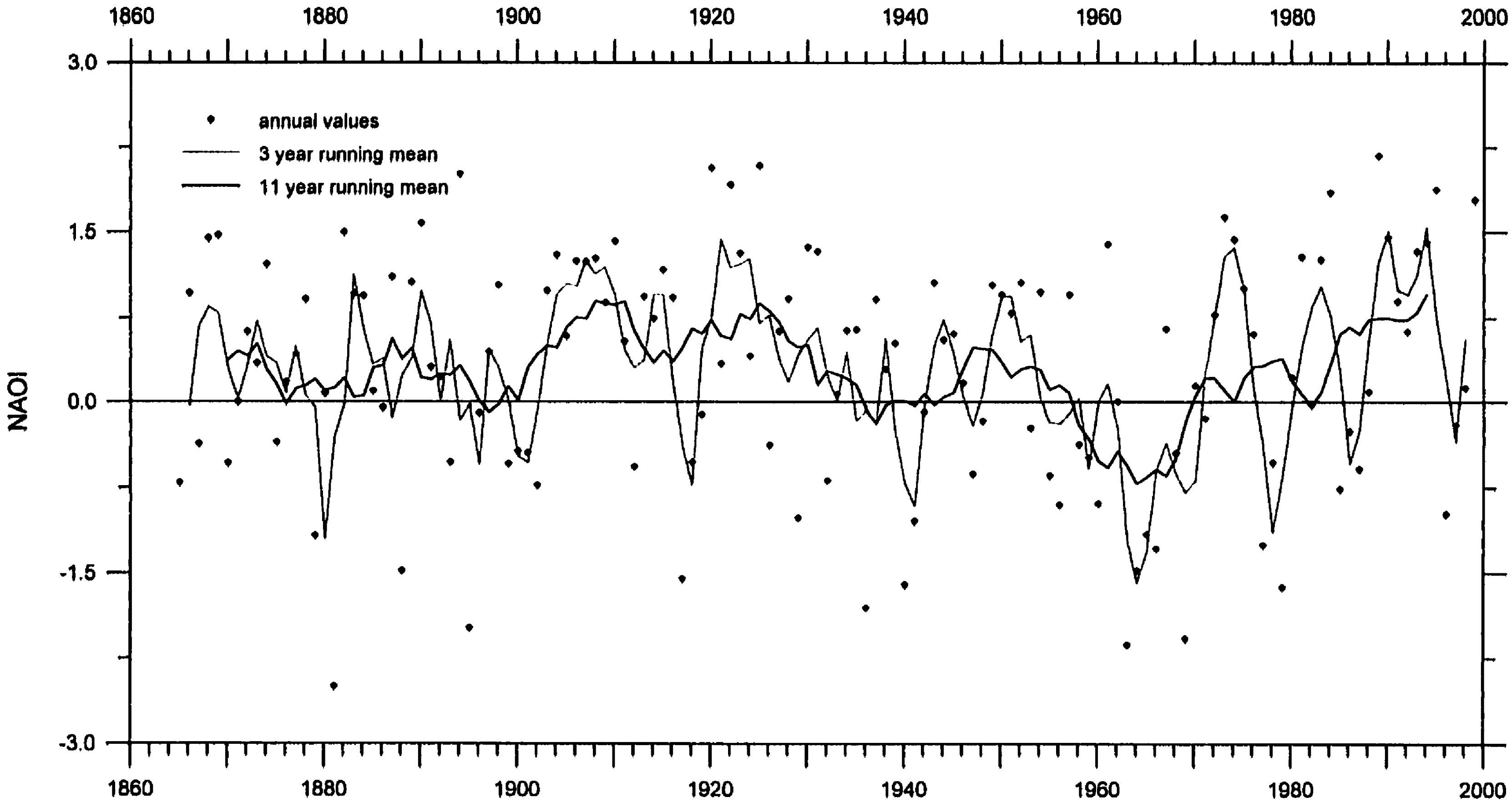


Figure 2.18 The North Atlantic Oscillation Index (NAOI) between 1864 and February, 1999. The NAOI is defined as the difference between normalised mean December, January, and February sea level air pressures at the Azores and Iceland. Annual values, and the 3 year and 11 year running means are given. Sources http://www.cru.uea.ac.uk/cru/data/nao.html; World Monthly Climatic Data, 1998-1999.

is defined as the difference between average normalised December to February monthly air pressures at sea level at Ponta Delgada (and Santa Maria), Azores, and Reykavik (and other stations), Iceland. Monthly values of the SOI and annual values of the NAOI were normalised using the mean and standard deviation of values from 1960 to 1990.

2.10 Conclusions

Methods used to collect field and historical data from a variety of sources are given and their accuracy discussed. Field results obtained by these methods are presented and include till grain size and shear strength properties, till water content, bluff face erosion, foreshore erosion, bluff edge retreat, erosion of a submerged barrier beach and drumlin shoal, and environmental data including temperature, precipitation, well water level and temperature, winds, wave heights, and tidal heights. Historical data include charts, airphotos and wind, wave, and tidal height records. Selected data and results are presented again and discussed in the following chapters. The sampling and laboratory analyses, sub-annual erosion measurements and annual retreat measurements are considered in Chapter 3; the decadal-scale historical chart and airphoto results and the echosounding data are further investigated in Chapter 4; and the environmental data and climate indices are discussed in Chapter 5 with reference to decadal-scale coastal change in the McNab's Island area.

Chapter 3

Annual and Sub-Annual Time Scales of Coastal Change

3.1 Introduction

Retreat of coastal bluffs occurs only if the bluffs are both eroded, delivering material to the upper beach, and if this material is subsequently removed from the bluff toe (Wilcock *et al.*, 1998). Retreat, an annual process at the bluff edge, and erosion, a sub-annual process affecting the bluff face, have been considered to be caused by an imbalance between an assailing force proportional to wave height at the bluff toe and a resisting force proportional to compressive strength of the bluff-forming material (Sunamura, 1977) whereby retreat or erosion occurs when the assailing force exceeds the resisting force.

Marine undercutting and debris removal is the product of the assailing side of the force imbalance. Elevated water levels and storm surges (Carter and Guy, 1988), relative wave strength (Wilcock *et al.*, 1998) and all of these (Amin and Davidson-Arnott, 1995) have been shown to increase bluff erosion rates by increasing the assailing force. Other research has focused on the erosion of cohesive till foreshores and nearshores as a control of the rate of bluff retreat (Davidson-Arnott and Askin, 1980; Kamphuis, 1987). Assuming an equilibrium profile under stable water levels, vertical lowering of the foreshore must accompany horizontal bluff retreat; high rates of foreshore lowering remove protective and dissipative foreshores and allow increased wave attack at the bluff toe, while low rates allow the development of protective ramps seaward of the bluff toe (Davidson-Arnott and Ollerhead, 1995). Rates of foreshore lowering decrease seaward of the bluff toe (Davidson-Arnott, 1986) and in flume tests rapidly increase when thin layers of moving sand are present (Skafel and Bishop, 1994).

The resisting force is controlled by properties of the bluff material. Significant properties of cohesive bluffs in glacial materials have been considered to be to bluff shear strength (Zeman, 1986; Kamphuis, 1987), stratigraphy (Eyles *et al.*, 1986; Jibson *et al.*, 1994) and groundwater flow (Leatherman, 1986).

Between the assailing and resisting forces, however, lie beaches which, like foreshores and ramps, absorb incident wave energy and can prevent both foreshore and bluff toe erosion. Beaches are particularly important on paraglacial coasts undergoing transgression because they are derived from the products of bluff erosion (Boyd *et al.*, 1987) and thus present mechanisms for morphodynamic feedback as beach development in front of an eroding bluff may slow erosion rates and the supply of beach-forming material (Carter and Orford, 1988; Forbes *et al.*, 1995a).

Locally, annual bluff retreat has been measured since 1973 at Hartlen Point (Taylor *et al.*, 1995). The only previous measurements that define the resisting force of the Hartlen and Lawrencetown Tills are grain sizes and Atterberg Limits (Neilsen, 1976; Podolak and Shilts, 1978); shorelines of McNab's Island have been investigated in a 1914 photographic survey by J. W. Goldthwaite of the GSC and in a M.Sc thesis on the behaviour of tar particles on Maugher's Beach (von Borstal, 1974). The assailing force has been investigated more closely; Carter *et al.* (1990a) show how bluff retreat downdrift of drumlin headlands is controlled by longshore gradients in wave height, the wave breaking angle and the dispersal of eroded material along the drumlin flank. The contributions of individual storms to increased rates of barrier beach retreat due to increased wave heights and storm surges has been shown by Taylor *et al.* (1997, 1999).

The purpose of this chapter is to investigate geographic, morphodynamic and temporal variability of sub-annual to annual bluff erosion and retreat in the study area to determine the relative importance of bluff and beach morphology and environmental forcing by storm events in contributing to bluff erosion. Results from approximately 550 days of monitoring of bluff top retreat, bluff face erosion, till water content and shear strength, precipitation, well water level, and measurements of wind speed and direction, deep water wave height, and water level are presented and discussed first by describing retreat processes at survey lines and second by detailed examination of sub-annual changes at selected monitoring sites.

3.2 Geographic and Morphodynamic Variability of The Study Area

Mechanisms and styles of bluff retreat and erosion vary both geographically and temporally. This section describes and attempts to explain the inter-site variability of bluff retreat and erosion in the study area. Geomorphology and morphodynamic processes are described at survey lines and monitoring sites. Bluff profiles along survey lines are shown in Figure 2.8, and locations are given in Figures 2.1 and 2.5. Descriptions and retreat rates are summarized in Table 3.1.

3.2.1 Wreck Section

The bluff at the Wreck section (M1, M2, M3, and M4) is formed predominantly in clay facies overlain by up to 1.2 m of sandy facies. The bluff at lines M3 and M4 is gently sloping and more vegetated than either M2 or M1. The bluff at M2 is high and

Section	Line	Cumul. Retreat 97-99 (m)	Retreat Rate 97-98 (m/a)	Retreat Rate 98-99 (m/a)	Retreat Rate 97-99 (m/a)	Stratigraphy	Aspect (deg.)	Bluff Face Slope (deg.)	Bluff Top Slope (deg.)	Bluff Elevation (m)	Beach Elevation (m)	Wave Angle (deg.)
Wreck	M1	1.79	0.79	1.34	1.15	0.2 m sandy facies over clay facies	90	38.4	17.2	6.7	2.26	90
	M2	1.98	2.59	0.54	1.27	1.2 m sandy facies over clay facies	88	34.2	3.4	12.4	2.46	95
	M3	1.00	0.23	0.87	0.64	0.75 m sandy facies over clay facies	77	30.5	2.8	11.2	2.71	96
	M4	0.67	0.78	0.24	0.43	0.75 m sandy facies over clay facies	63	27.9	1.3	9.2	2.99	99
Green Hill	M5	1.95	2.04	0.96	1.31	clay facies	57	43.8	16.6	3.9	2.02	110
	M6	2.21	3.40	0.56	1.49	clay facies formerly with sand lens	46	36.1	12.0	6.8	1.80	123
	M7	1.82	2.47	0.62	1.22	clay facies	31	41.0	15.8	4.3	1.98	127
West Gut	M8	0.66	0.45	0.44	0.44	0.4 m sandy facies over clay facies	67	33.0	6.1	7.8	3.09	125
	M9	0.28	0.14	0.21	0.19	0.8 m sandy facies over clay facies	51	26.1	9.7	7.8	2.11	118
	M10	0.85	0.80	0.46	0.57	1.3 m sandy facies over clay facies	54	22.2	7.3	9.3	2.44	119
Doyle Pt.	M11	2.69	0.31	2.48	1.77	1.1 m sandy facies over clay facies, inclusions of stony facies	119	25.7	-0.3	11.3	2.94	96
	M12	0.44	0.41	0.29	0.33	1.2 m sandy facies over clay facies	126	24.5	6.1	13.6	2.85	90
	M13	0.84	1.19	0.20	0.56	1.0 m sandy facies over clay facies	117	34.0	3.7	13.5	2.64	101
Big Thrumcap	M14	8.89	6.27	5.81	5.98	clay facies	94	50.2	17.8	7.1	1.39	111
	M15A	2.76	3.85	0.70	1.86	0.1 m sandy facies over clay facies	160	36.5	8.3	12.7	0.94	85
	M15B	4.29	4.75	1.80	2.88	0.1 m sandy facies over clay facies	179	46.9	2.5	12.7	1.35	80
Fort McNab's/ Strawberry Hill	M17	1.06	0.86	0.61	0.77	1.3 m sandy facies over clay facies	215	>40	-6.5	12?	?	90
	M18	0.50	0.55	0.02	0.36	0.6 m sandy facies over clay facies	232	>60	complex	8?	?	66
	M19	0.31	0.33	0.02	0.23	0.8 m sandy facies over 8 m clay facies over Hartlen Till	222	>40	-10.2	10?	?	84
Lawlor Pt.	L1	0.30	0.85	0.05	0.19	1.5 m sandy facies over clay facies	144	34.9	7.2	10.9	2.08	68
	L2	0.36	0.43	0.13	0.22	1.0 m sandy facies over clay facies	134	33.6	3.7	11.0	2.25	87
	L3	0.07	-	-	0.04	1.2 m sandy facies over clay facies	134	33.1	-3.5	11.1	3.05	81
East Gut	L4	2.74	8.9	0.51	2.01	0.2 m sandy facies over clay facies	200	53.2	4.7	6.5	2.37	73
	L5	0.10	-	0.09	-	stony facies	194	35.6	3.7	9.0	2.79	61

Station	Cumul. Erosion (m)	Erosion Rate 97-99 (m/a)	Aspect (deg.)	Mean w%	Mean S_u (kPa)	Beach Elevation (m)	Wave Angle (deg.)
M14+1	2.08	3.42	94	10.37	123.75	1.39	111
M15A-25	1.10	1.39	132	10.04	139.28	1.86	90
M5+5	1.74	2.45	57	11.42	87.45	2.02	110
L4+40	1.32	1.74	200	10.09	136.51	2.46	69

Table 3.1. Retreat rates, stratigraphy and bluff and beach characteristics at survey lines and monitoring stations.

steep capped by a 1.2 m thickness of sandy facies. M1 is a low bluff with a steep bluff top slope; the line is located on a formerly east-facing erosional slope that became inactive and was revegetated between 1934 and 1945 and became active again after 1966. The beach fronting the Wreck section is predominantly swash aligned (Figure 3.1) and gravelly. Although variable, grain size of beach sediment tends to increase to M3 and M4 where a 0.5 ha accumulation of boulders (b-axis ≤ 1.3 m) is present and where an upper beach terrace frequently develops. Development of beach cusps with wavelengths of 1-2 m is common when the terrace is present and swash-aligned. Till is frequently exposed between the gravel beach and outer boulder frame at M1; terrace development is less common at this site.

Retreat is high at M2, despite a relatively high beach, due to the sandy facies from which groundwater seepage flows down the bluff face. Groundwater can accumulate in the sandy facies during below-freezing temperatures. Water content measured over the winter of 1998/99 shows a peak in late January (Figure 3.2) but is otherwise relatively constant with similar internal and external values and shows weak correlation to precipitation events. Well water level (a proxy for hydraulic head) shows no apparent correlation to precipitation events but, like precipitation, it has a winter maximum. This lack of correlation is due to a delay between precipitation entering the groundwater flow and reaching the monitoring well and also due to delayed runoff when precipitation falls as snow. The peak in the sandy facies water content, however, is correlated with a precipitation event that occurred in late January 1999 while temperatures were above freezing. Temperature then fell below freezing for approximately 1 week and trapped water as it percolated through the sandy facies allowing high water contents to build up at

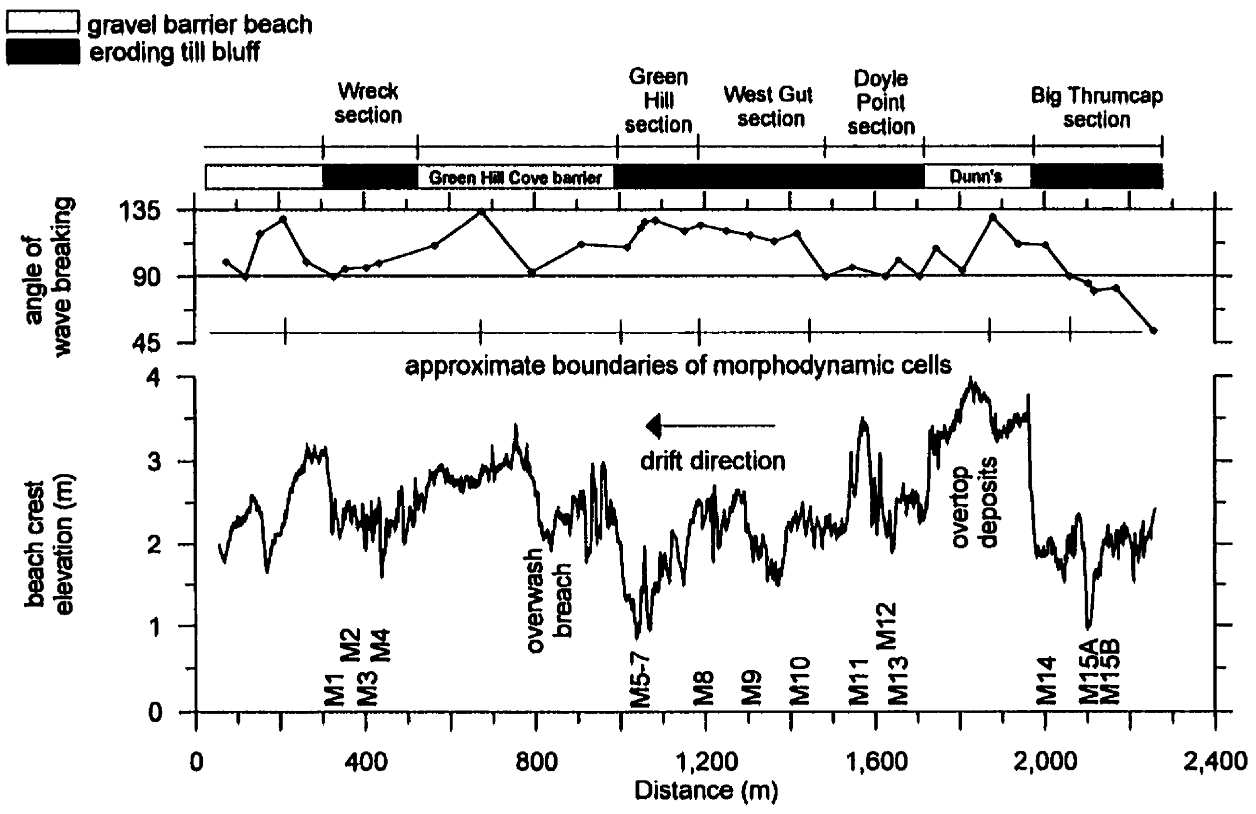


Figure 3.1 Beach crest and bluff toe elevations from Wreck Cove to Big Thrumcap, February, 1998 with survey line locations. Upper graph shows wave breaking angle where 90^{o} represents shore-normal wave breaking and swash-alignment. Ticks at top indicate sections described. Approximate boundaries of morphodynamic cells are also shown. Wave breaking angle was measured from 1997 airphotos showing waves from the south with deep water period of 10.5 s and height of 2.1 m

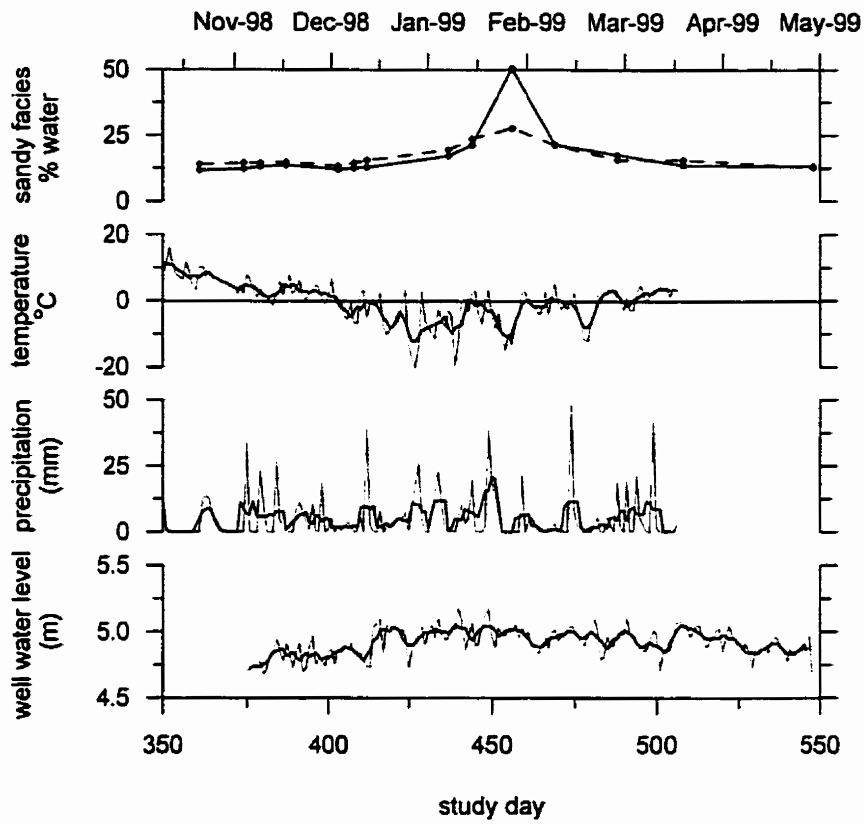


Figure 3.2 Average daily well water level, total daily precipitation, mean daily temperature, and average external (dashed line) and internal (solid line) water content (%) of the sandy facies (M2+10, M9+50, M11+1) from mid-October, 1998 to mid-March, 1999. 5 day running means of well water level, precipitation, and temperature are shown by dark lines.

the bluff face. Following increasing daily temperatures the ice melted and water content in the sandy facies rapidly increased promoting slumping of the bluff edge and contributing most of the retreat that occurred over the winter of 1998/99.

To summarize, the Wreck section (M1, M2, M3, M4) has both rapidly and slowly retreating lines. M1 and M2 represent moderate to rapidly retreating bluffs formed in clay facies. The sandy facies is approximately 1 m thick at M2 and contributes to retreat at this site. Groundwater accumulates in the sandy facies during periods of below freezing temperatures and, when it melts, greatly increases the water content which lowers shear strength and causes failure. M1 is at a low bluff with a steep bluff top slope and has recently been reactivated after a long period of stability. M3 and M4 are partially vegetated and retreat slowly. This section is predominantly swash-aligned and a gravel terrace may develop in front of the bluff toe. Beach cusps may form in the terrace.

3.2.2 Green Hill Section

The drift-aligned Green Hill section (lines M5, M6, and M7) comprises a low and short (~120 m) bluff formed in clay facies with a steep bluff top slope. The bluff was vegetated in 1992 but the eroding face was observed to grow in both height and length between 1997 and 1999, from approximately 1.5 m high and 30 m long to 5.5 m high and 120 m long. Most retreat at M6 occurred during the winter of 1997/98 (1.65 m at 4.15 m/a) as a sand lens 0.8 m above the bluff toe eroded. The process of retreat was similar to that described at M2: the sand lens accumulated water as ice during a period of low temperatures and when temperatures rose water content reached 35%, shear strength dropped to zero, and rapid retreat occurred. A colluvial wedge that developed at the bluff toe following collapse of the bluff edge above the eroded sand lens persisted through the winter of 1998/99. M7 showed a similar pattern of initially rapid retreat during the winter of 1997/98 followed by slowing as the elevation of the pebbly gravel foreshore increased by about 0.25 m and the beach crest elevation (at the bluff toe) increased approximately 0.15 m (Figure 2.8). Significant areas of the till foreshore were exposed between M5 and M6 during the winter of 1997/98 but were covered, similar to M7, as 0.25 m of pebbly gravel was added to the lower beachface in November 1998 and remained through the winter of 1998/99. Bluff face erosion measurements at M5+5 and bluff edge retreat measurements at M5 both show a significant decrease in erosion from 1997/98 to 1998/99 (Table 3.1).

To summarize, the Green Hill section (M5, M6, M7) is a rapidly retreating site with a low bluff formed in clay facies with sparse protecting beach sediment. The bluff top is steep with active seepage. The bluff has recently been reactivated and retreat and erosion occurred initially rapidly over the winter of 1997 and 1998 but have since slowed. Erosion of a saturated sand lens in the bluff in 1997 may have contributed to rapid retreat then, and the beach also prograded and increased in elevation during the monitoring period resulting in slower retreat in 1998 and 1999. Exposures of till in the foreshore were buried by beach development in 1998. The section is strongly drift-aligned.

3.2.3 West Gut Section

The West Gut section (lines M8, M9, and M10) is characterised by gently sloping high bluffs along a drumlin flank. A well-developed strongly drift-aligned pebble cobble beach is stranded (*i.e.* in continuous contact with the bluff toe with no intervening lagoon) reaching elevations of approximately 3 m (Figure 3.1) where terraces form a beach crest seaward of the bluff toe. Bluffs are comprised of clay facies overlain by a

0.4-1.3 m thickness of sandy facies. Bluff faces at M9 and M10 are partially vegetated, wet, and subject to sandy fluidized flows which frequently reach the upper beach terrace. A flow channel with levees is well developed at M10 where winter ice collects in the channel. M8 is similar to lines at the Green Hill section and is unvegetated, steep and comprised predominantly of clay facies but has lower retreat rates and a much higher fronting beach. Retreat rates are low at M8, M9 and M10 and did not change significantly over the monitoring period (Table 3.1).

In summary, the bluff at the West Gut section is gently sloping and formed in clay facies overlain by up to 1.3 m of sandy facies. Sandy fluidized flows travel down channels and deposit sediment on a locally well-developed beach terrace. Even where the terrace is not developed the beach is high. Bluffs are partially vegetated and retreat slowly though a wave-cut scarp is observed in colluvium at the beach terrace.

3.2.4 East Gut Section

The East Gut section (L4 and L5), across Drake's Gut from the West Gut section, is characterised by a long, low bluff predominantly in the clay facies with a 140 m section of stony facies to the southeast. The sandy facies may be present overlying the clay facies in thicknesses up to 0.5 m grading laterally to small lenses of stony facies. The bluff face at L4 is steep with a gentle bluff-top slope. A 2 m long and 1.5 m deep slump occurred in the sandy facies at the bluff top just prior to March 29, 1998 resulting in a wedge of low strength colluvium on the upper beach which was mostly eroded during the winter of 1998/99. The failure has continued to propagate laterally and landwards. The cobble gravel beach at L4 is relatively high and periodically has a short-lived terrace. The outer boulder frame has common narrow shore-parallel gaps between the beachface and the top of the boulder frame which expose till in the foreshore. Three micro-erosion meter stations were installed in these gaps, however, as at the Green Hill section, results are limited by infilling of sand, pebbles and cobbles after November, 1998. A bluff erosion monitoring station was also installed at L4 but was moved 40 m southeast to L4+40 following slumping at L4. The bluff at the monitoring station is similar to L4; it is low, steep, planar, formed in clay facies overlain by 0.2 m of sandy facies, and contains thin beds of laminated silt.

The bluff at L5 is moderately steeply sloping, of intermediate height and formed in the stony facies. The clay facies likely forms the foreshore substrate but is not visible beneath a high drift-aligned pebble cobble beach with a well-developed outer boulder frame. Boulders are common on the bluff face. Retreat occurs slowly in the stony facies through face-parallel slipping and by toppling of individual boulders.

To summarize, the bluff at L4 is low, rapidly retreating and composed of clay facies. Exposures of till are common in the foreshore although immediately in front of the bluff a high gravel terrace can develop. Similar to the Green Hill section, sand and gravel partially infilled foreshore gaps in 1998. A typical failure in the sandy facies occurred in March 1998 near L4+40. The bluff at L5 is composed of stony facies, has a well-developed beach with a permanent terrace and is slowly retreating. The section is strongly drift-aligned with a well-developed outer boulder frame.

3.2.5 Lawlor Point Section

The Lawlor Point section (L1, L2, and L3) is a narrow eroding promontory with a rounded headland consisting of a bluff in clay facies overlain by 1.0 to 1.5 m of sandy facies. The bluff top slope is gentle with a 0.3 m scarp between 20 and 30 m landward of the current bluff edge. The bluff profile is convex becoming steep at the bluff toe. The upper bluff is partially covered by grassy vegetation. Rills are present and focus small debris flows to the moderately high beach. A boulder frame is well developed seaward of the gravel beach and an extensive lag covered-shore platform extends south of this.

3.2.6 Doyle Point Section

The bluff at Doyle Point (M11, M12 and M13) is morphologically variable. M11 and M12 are located at a 75 m long vegetated deep-seated rotational slump block that formed after 1945. Several smaller stacked rotational slumps are located southeast of M11 and form the bluff at the west side of Doyle Point. Retreat rates are highest at M11 due to continuing slumping of the 1.1 m sandy facies in the most landward scarp since July 1998. A shallow flow originating at the slope break of a wave-cut scarp in the clay facies 12 m northeast of M11 was likely triggered by a 76.6 mm precipitation event on July 11, 1998, as no high winds or waves are recorded at this time and beach height was at a maximum with a well-developed, approximately 3.2 m high, seasonal, cobble terrace fronting the wave-cut scarp. Following this failure, sub-parallel tension cracks propagated 30 m southwest past M11 towards M12 along the slump block. These continued to widen during the winter of 1998/99 and were infilled with muddy sand eroded from the landward scarp at M11. The tension cracks appear to have migrated approximately 0.5 m seaward with the slump block, while the surface of the slump block increased in elevation up to 1.25 m due to deposition of material from the landward migrating scarp at M11. The same process was observed at M12 where 0.5 m of deposition occurred during the winter of 1998/99. While it is normal for slow movement to occur along existing rotational failure planes and tension cracks in deep-seated failures in coastal bluffs, this is theoretically accompanied by lowering of the slump block surface (*e.g.* Terzaghi, 1943; Richards and Lorriman, 1987). The long-term movement of the slump block at M11 and M12 probably follows this model, however the short-term evolution of the slope may be characterised by episodic deposition causing loading of the slump block and episodic movement along failure planes. Ponding of runoff on the surface of the block also likely contributes to the episodic nature of rotational failure as shear strength along failure planes and tension cracks is reduced; flow of water down tension cracks is observed at M12. Flowing water redistributes material over the surface of the slump block contributing to deposition at M12, despite slow retreat at this line.

M13 is different from both M11 and M12 and is a convex, unvegetated bluff becoming steeper at the bluff toe. Despite its apparently exposed location little retreat occurred at this line during the monitoring period. A shore platform with residual boulder frame to the immediate southwest causes refraction and dissipation of incident waves (Figure 3.3) and may offer this site some protection during storms. Beach elevation is only moderate at this site and the bluff is high. The bluff top slope is gentle without tension cracks.

In summary, the Doyle Point section (M11, M12, M13) is predominantly swash-aligned with a well-developed beach. The bluff is formed in clay facies mantled by up to approximately 1.5 m of sandy facies. At M11 and M12, a vegetated rotational slump block is present. A precipitation event in July 1998 caused a failure to the northeast of M11 and tension cracks formed in the slump block and propagated southwest towards M12. Lubrication of failure planes by water is likely important given the relationship of

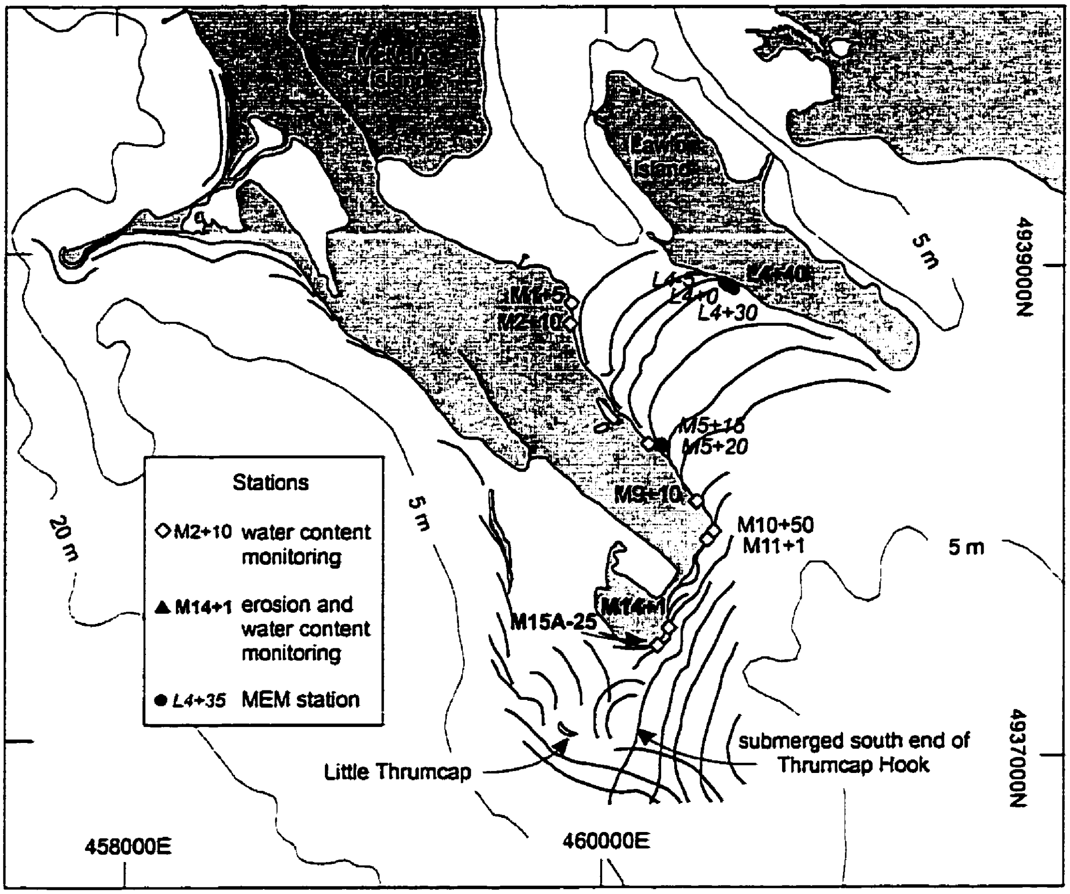


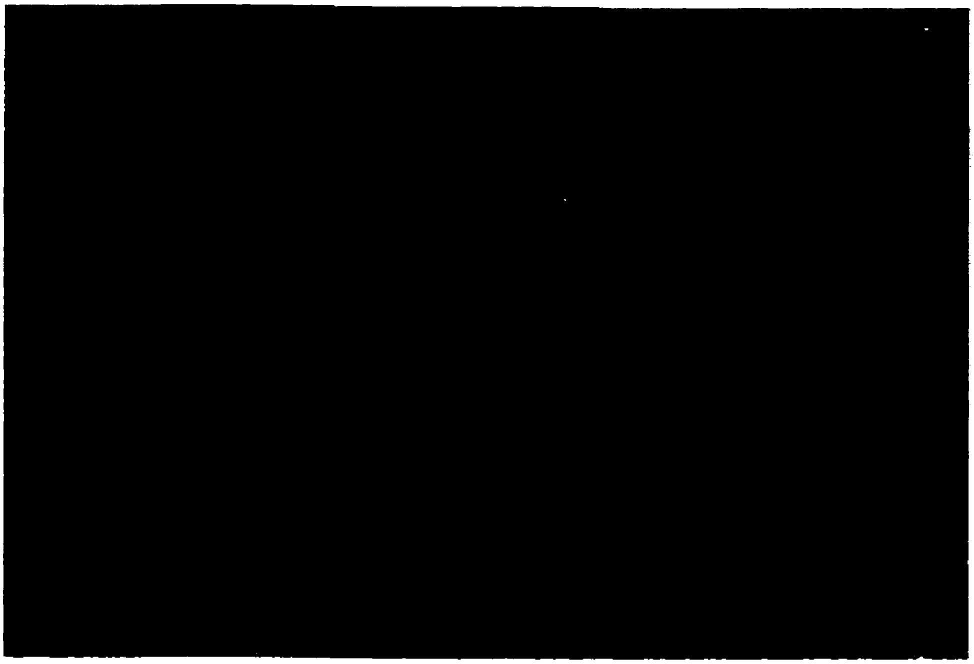
Figure 3.3 Large scale map of southern McNab's Island and Lawlor Island showing water content, bluff face erosion, and micro-erosion meter (MEM) stations. Also shown are the refraction of nearshore waves from 1997 air photos. Deep water waves are from the south with peak period of 10.5 s and a significant height of 2.1 m. Stations are named according to their distance from the nearest survey line. For example, M5+5 is ~5 metres towards M6 from M5, and M15A-25 is ~25 m towards M14 from M15A.

till shear strength to water content and loading of the block by sediment delivered by retreat of the landward scarp may cause episodic movement. M13 is a high, steep, slowly retreating bluff with a low fronting beach but well-developed shore platform.

3.2.7 Big Thrumcap Section

The Big Thrumcap section consists of three lines (M14, M15A, and M15B) at a well-defined remnant drumlin headland. Profiles were collected only at M14 as bluffs at M15A and B are too steep and high. Approximately 30 m long rotational slump blocks subject to wave attack are present between M14 and M15A and also at M15A. A drift-divide (Carter *et al.*, 1990b) which occurs between M14 and M15A is characterised by a high beach consisting of a boulder frame (b-axis ≤ 1.5 m) 1-2 clasts thick to the bluff toe with little interstitial pebbles or cobbles. Beach height decreases toward M14 and M15A, and then increases away from the headland (Figure 3.1).

M14 is a rapidly retreating east-facing low bluff with a steep bluff-top slope with common tension cracks. A boulder frame is absent at the bluff toe and also in places near the low tide line; till is commonly exposed but may be covered by an ephemeral thin sandy gravel beach. Foreshore erosion is evidenced by hummocky topography (up to 0.3 m relief) in exposed till in the foreshore and by an oblique, laterally migrating, 0.5 m high scarp in the ramp at the bluff toe (Figure 3.4). Oblique foreshore scarps are also observed at M4 and M15A but are protected by the boulder frame at these locations and do not rapidly migrate. At M14 the scarp developed in February 1998 originally as a 0.8 m wide and 0.3 m deep crescentic gravel-filled hollow in the ramp which grew and migrated approximately 30 m northeast before the scarp was smoothed and destroyed by wave activity in March 1999. Approximately 0.5 m of almost instantaneous vertical erosion



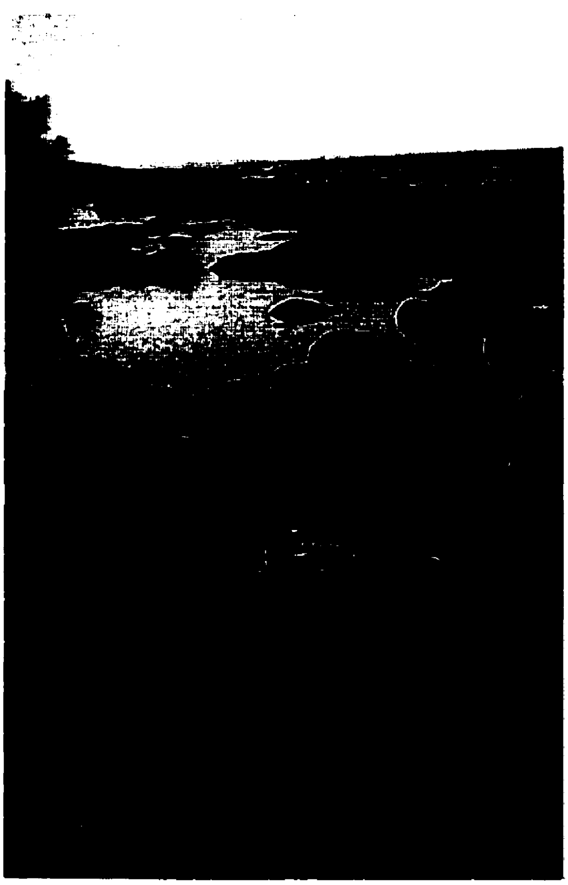


Figure 3.4 Features formed in till foreshores. (Top) Oblique foreshore scarp near M14. The boulder in the left foreground is approximately 0.4 m in diameter. (Bottom) Shore-parallel gaps between the lower beachface and the top of the boulder frame at L4+40. The MEM, shown in measurement position, is 24 cm in diameter.

occurred as this feature migrated downdrift removing the ramp and formed a high angle junction between the foreshore and bluff toe.

Failures at M14 usually were small where intact turf and till topple from the bluff edge, although they also occurred as slumps over longer lengths of the bluff. One example occurred along a 5 m length of bluff after a precipitation event of 61.1 mm on October 11, 1998, coincident with mean daily wind speeds of 30 km/h, and removed 0.3 m of till from the bluff face and edge (Figure 3.5). Another example occurred on March 16, 1999 when average daily winds of 34 km/h following precipitation of 42.8 mm on March 15 resulted in complex slumping along 30 m of bluff edge and local losses of approximately 0.5 m of till from the bluff face. Deep water wave heights on March 16 reached a maximum of 6.4 m.

In contrast to M14, M15A and B are southwest facing, high and have gentle bluff top slopes with no tension cracks. Retreat rates are lower at M15A and B. A prominent cobble and boulder lag-covered shore platform extends southwest of all three lines but is best aligned for dissipation of wave energy at M15A. Following the breaching and washover of an extensive single-crested barrier protecting the southwest face and flank of the drumlin in 1945 (see also Figures 4.2k-n), Big Thrumcap evolved from a small needle-like promontory to a rounded headland (Chapter 5). The position of the shore platform marks the former location of the promontory and also where Thrumcap Hook was anchored to the flank of the drumlin at M15A. Boulders are common near these lines. The beach fronting M15A and B is drift-aligned with a boulder frame that reaches the bluff toe. The frame has more interstitial gravel and cobbles than at M14 but exposed till is common below boulders. Armoured mud balls (*cf.* Pringle, 1985), rounded balls of

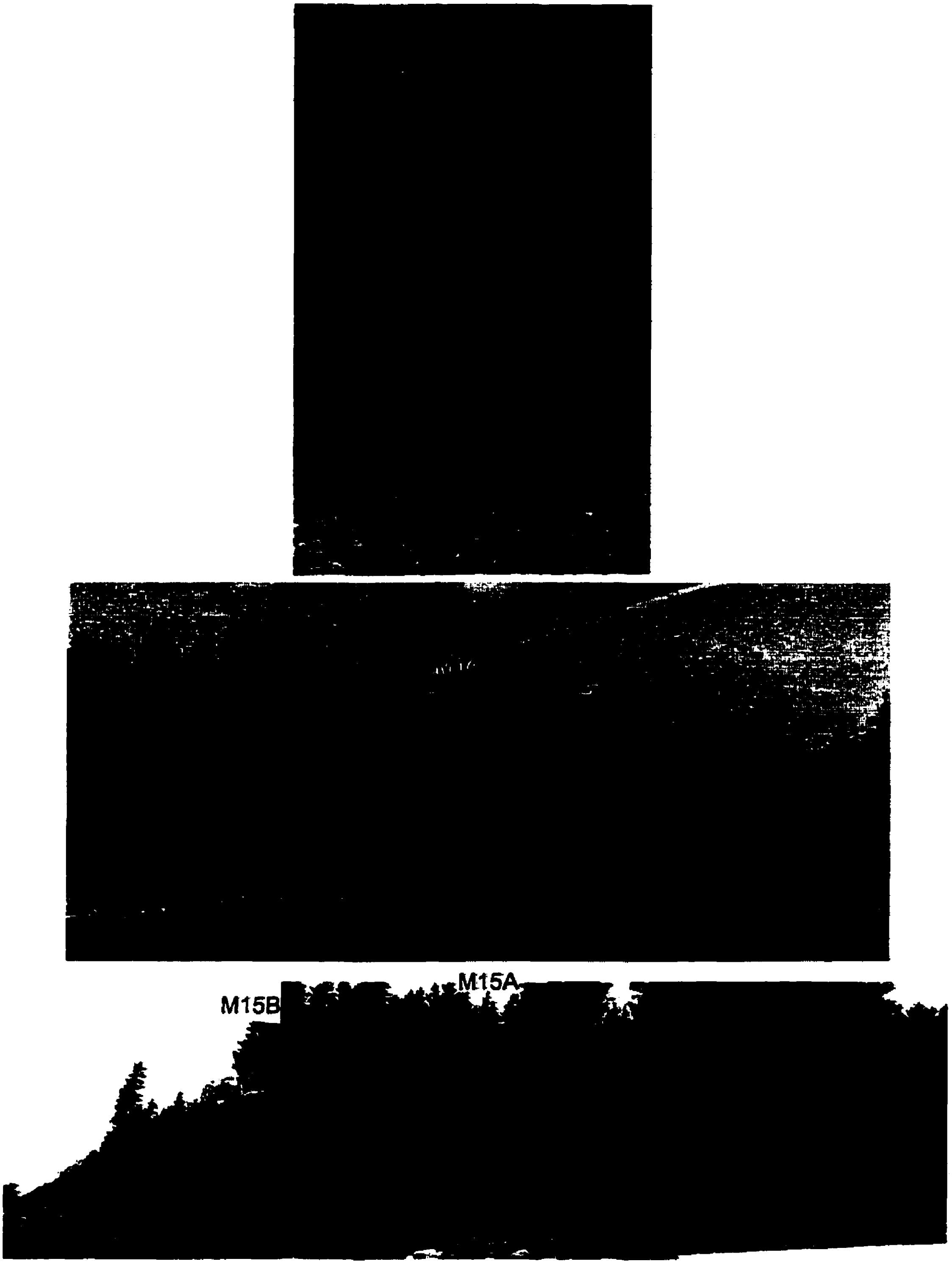


Figure 3.5 Typical failures in drumlin bluffs. (Top) Failure in the sandy facies near L4+40. The hammer handle on the colluvium (circled) is 0.25 m long. (Middle) The October 11, 1998 slump at M14. The width of the colluvium is approximately 8 m. (Bottom) The February 3, 1999 slump near M15B (dashed outline). The bluff is approximately 10 m high. Note seepage above slump block at M15A.

till with a covering of pebbles, are often present on the foreshore of this section following storms and are interpreted as rip-up clasts from the foreshore.

Retreat at M15A and B occurs through small topples of cobble- and boulder-rich material which may land on the three slump blocks present and be subsequently incorporated into flows down the sides and wave-cut scarp of the slump blocks. Blocks are in various stages of erosion; one northwest of M15B and one southeast of M15A have relatively high terraces, while the one directly below M15A is low and narrow, and appears to be in an erosional stage.

One large failure that occurred was a slump originating over a 1 m length below the bluff edge below M15B on February 3 or 4, 1999 following precipitation of 21.6 mm, mean daily wind speed of 29 km/h, and maximum daily wave height of 5.1 m. This failure also occurred after warming to 5 °C after 9 days of below zero mean daily temperatures.

Erosion and till water content were monitored at two stations on Big Thrumcap: at M14+1 and near the drift-divide at M15A-25. Till water contents are higher at M14 and shear strength therefore lower; erosion is greater at M14+1 and peaks at different times than M15A-25.

To summarize, Big Thrumcap is an actively eroding drumlin composed of clay facies connected to McNab's Island by Dunn's Beach. The section comprises lines M14, M15A and M15B. The bluff at M14 is steep, low, has a steep bluff top slope with tension cracks and is rapidly retreating. Little beach sediment is present and exposed till is common in the foreshore. An oblique foreshore scarp migrated downdrift during the winter of 1998/99 and caused approximately 0.5 m of foreshore lowering. Small failures from the bluff edge are common and occasional large slumps may also occur, for example during storms on October 11, 1998 and March 16, 1999. The bluff at M15A and B is, in contrast to M14, steep and high with a gentle bluff top slope and is slowly retreating. The boulder frame is well-developed over the till foreshore at M15A and B. Several slump blocks in various stages of erosion are present at the bluff toe. Large slumps can occur at M15B, for example, during a thaw coincident with a moderate storm and precipitation in February, 1999. A drift divide occurs between M14 and M15A; both sites are drift-aligned.

3.2.8 Fort McNab's and Strawberry Hill Sections

RTK-GPS surveying was unsuccessful in collecting beach and bluff elevations at the Fort McNab's section (M17) and the Strawberry Hill section (M18 and M19). Both of these sections are relatively stable, have high steep bluffs in clay facies overlain by 0.6 to 1.3 m of sandy facies, except M18 which periodically has a 2 m section of Hartlen Till exposed in the bluff toe. The presence of Hartlen Till is assumed at M17 but is thought to be buried by slump and flow deposits of the overlying Lawrencetown Till clay facies. Where it is exposed, bluffs have complex slopes with a steep toe and more gently sloping upper bluff with the slope break occurring near the Lawrencetown-Hartlen contact. The Hartlen Till may lend stability to bluffs because its higher shear strength at natural water contents (Table 2.4) renders it less susceptible to flow and toe erosion may be slowed. The presence of Hartlen Till may also reduce the depth of propagation of rotational failure planes.

3.2.9 Gravel Barrier Beaches

Drumlins in the study area trend almost parallel to the dominant wind, wave and drift directions which produces strong morphodynamic structure in the study area. This structure occurs in the form of morphodynamic process cells approximately identified as lengths of shoreline between maxima in angles of wave breaking (Figure 3.1). Cells can be drift- or swash-aligned and tend to form embayments between eroding bluffs. Wave breaking angle is the angle between an incident wave ray and a perpendicular to the shore as measured from vertical airphotos, so that a wave breaking angle of 90^{o} corresponds to shore-normal breaking and swash-alignment. Angles greater or less than 90^{o} indicate drift-alignment and longshore sediment transport potential as waves approach from an observer's right or left respectively.

Wave breaking angle shows asymmetry in some cells where shore-normal wave approach is usually at the down-drift end of a drift-aligned cell, but this pattern is not well shown at the strongly drift-aligned West Gut and Green Hill sections where wave angle increases downdrift (Figure 3.1). The pattern of wave breaking angle is dependant upon the deep water wave direction which affects refraction and reflection of shoaling waves by submarine topography. Under different wave conditions wave breaking angle varies resulting in only moderate agreement between wave breaking angle and beach height. Doyle Point consists of a series of small cells controlled primarily by the presence of shore platforms which refract waves. Shore-normal approach, where single-crested gravel barriers are well-developed, tends to coincide with maximum beach heights and loose, open framework overtop deposits. Minimum beach heights occur at low points on the shoreline where the bluff toe and maximum beach elevation are coincident (*i.e.* there is no intervening beach terrace or crest).

Two single-crested high gravel barrier beaches are identified on Figure 3.1, Green Hill Cove Beach and Dunn's Beach. Green Hill Cove Beach is a drift-aligned sandy gravel barrier spit that formed between 1966 and 1982 enclosing a lagoon. A second landward barrier that formed prior to 1867 (Rowe, 1867) encloses a second inner boggy lagoon. The outer barrier is subject to overwash at a breach that formed during the February 25, 1998 storm, exposing turf in the channel floor. A sandy washover lobe prograded into the back-barrier lagoon during overwash, and the breach was completely infilled with sandy gravel by November 1998 and did not overwash in the winter of 1998/99. A flat cobble frame with infilled sand and gravel is observed seaward of the washover breach. Dunn's Beach is swash-aligned, high, cobble-boulder barrier subject to overtopping which deposits loosely packed cobbles at the beach crest. The beach has connected Big Thrumcap to McNab's Island since before 1759, although it has gradually migrated landward keeping pace with retreat of Big Thrumcap. Cobbles are most angular updrift to the southwest toward Big Thrumcap. The beachface is steep and beach cusps up to 2 m in wavelength commonly develop. An imbricate well-sorted boulder frame is present high on the beachface.

In summary, gravel beaches are divided into shore-parallel zones consisting of a seaward outer boulder frame and a landward gravel-sorting zone. Clasts in the gravel-sorting zone are mobile and subject to longshore movement in drift-aligned areas and onshore movement in swash-aligned areas. During storms, in particular those with elevated water levels such as occurred on February 25, 1998, barriers may breach and overwash (*e.g.* Green Hill Beach). Onshore movement of sediment through the breach may form washover lobes in back-barrier lagoons. During fairweather conditions, onshore movement results in the formation of overtop deposits (*e.g.* Dunn's Beach).

3.3 Sub-Annual Forcing of Bluff Erosion

While the preceding section focused on the geographic and morphodynamic variability of annual retreat, this section is concerned with sub-annual temporal variability of several different parameters at a limited number of sites. Results of monitoring erosion, shear strength, water content, precipitation, wind speed, wave height, and water level are presented.

Figure 3.6 shows internal and external water contents of the four monitoring stations and precipitation measured over the monitoring period. Correlation is generally good between the external water contents of the four monitoring stations and these relate reasonably well to precipitation events. Correlation of internal water contents is, however, less apparent. A general trend towards increasing internal water content during the winter follows the annual precipitation trend suggesting that while individual precipitation events may not be important in increasing water content and decreasing shear strength, the frequency of prior precipitation events may be important in pre-conditioning the clay facies to wave attack and erosion.

Figure 3.7 shows precipitation, wind speed, wave height, and water level measured adjacent to the study area, and erosion rate and shear strength measured at each monitoring station during the monitoring period. Whereas wind speed and wave height correlate well, not all wind events produce wave events and not all wave events require

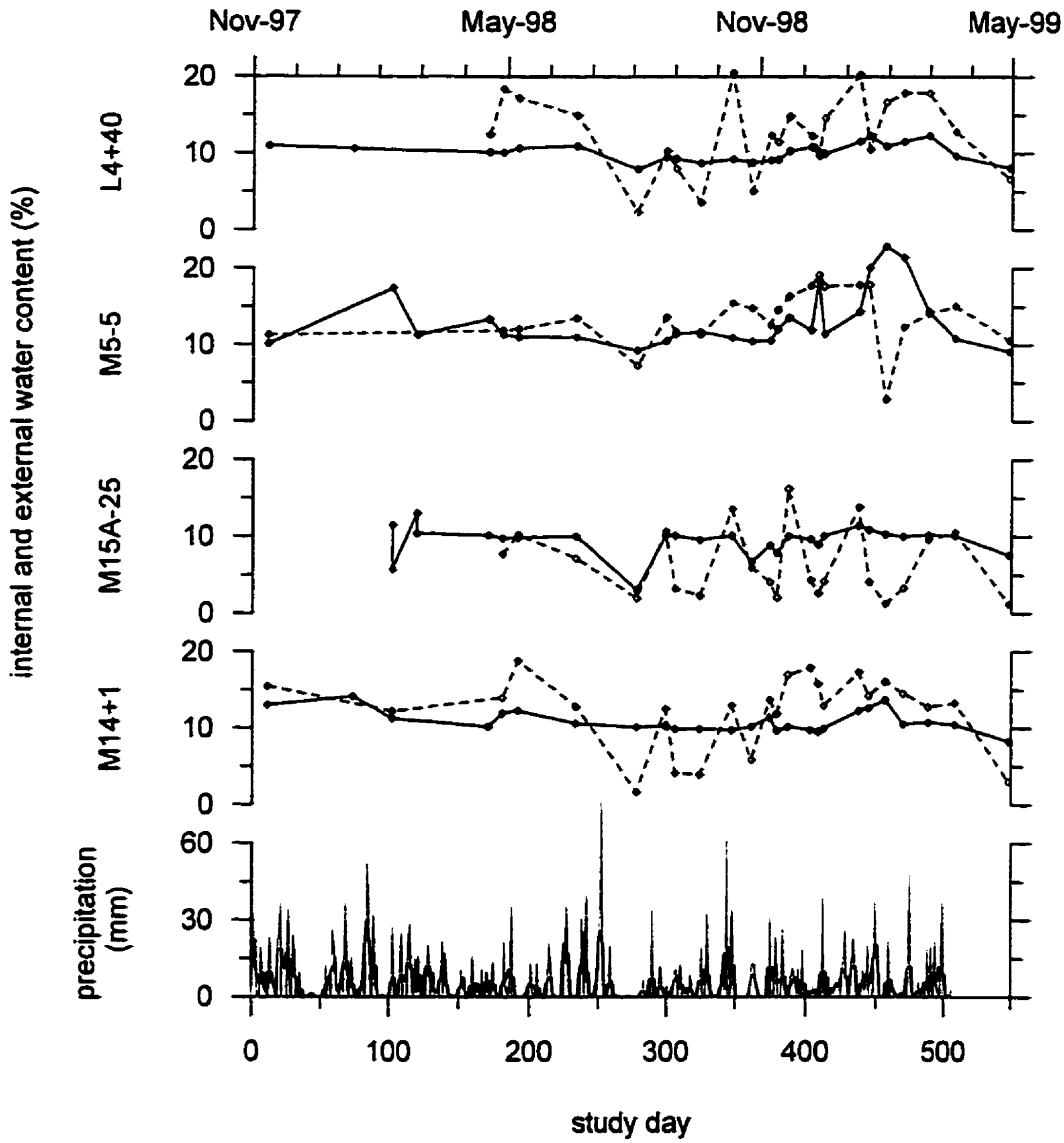


Figure 3.6 Comparisons of precipitation and external (dashed) and internal (solid) water contents measured at each monitoring station from November 1997 to May 1999. The dark line on the precipitation graph indicates the 5 day running mean.

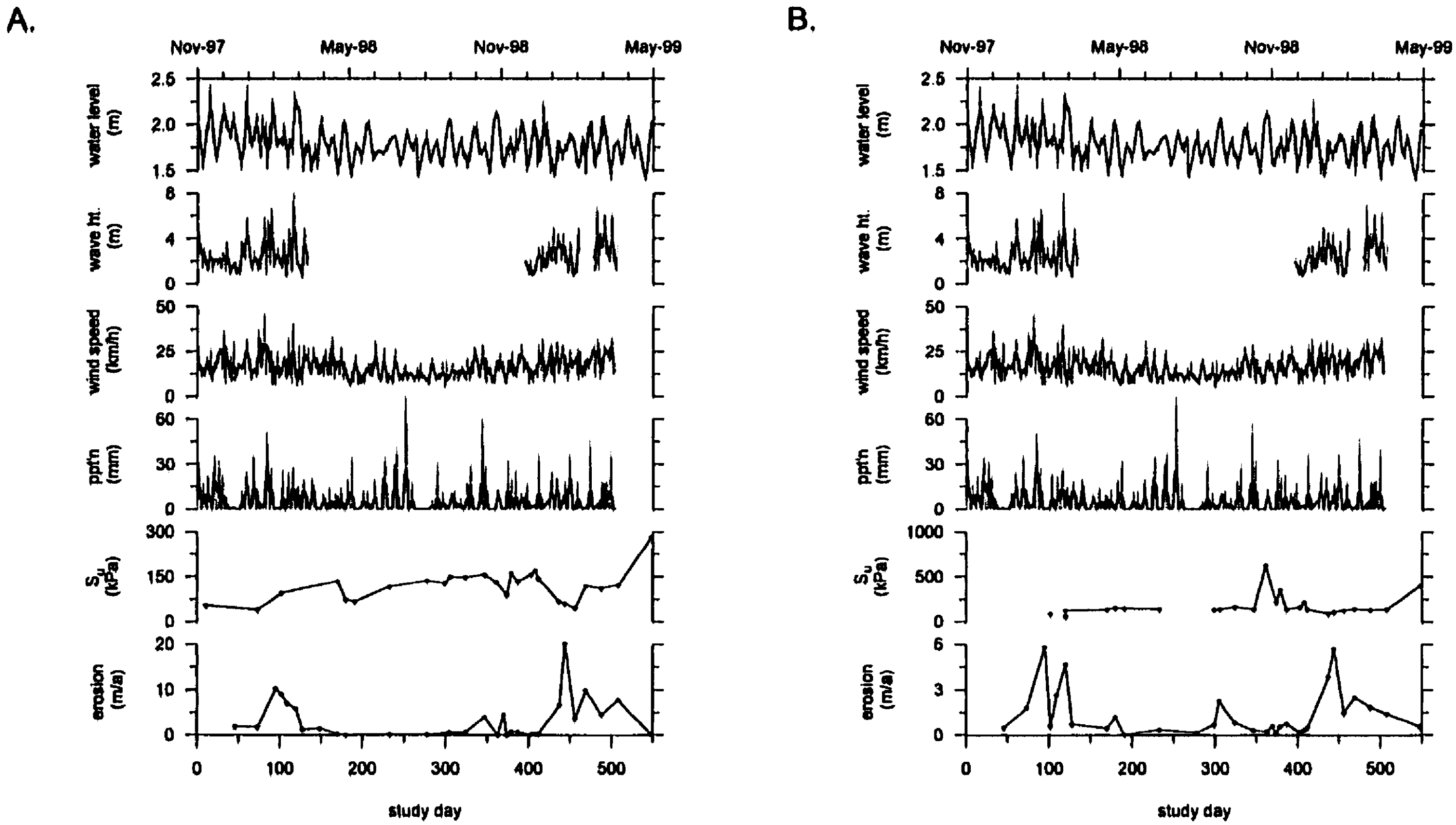


Figure 3.7. A. Comparisons of bluff face erosion rate, till shear strength, precipitation, mean daily wind speed, maximum daily significant wave height, and maximum daily water level for monitoring station M14+1 from November 1997 to May 1999. Dark lines on precipitation, wind speed, wave height, and water level plots indicate 5 day running means. B. As in A but for monitoring station M15A-25.

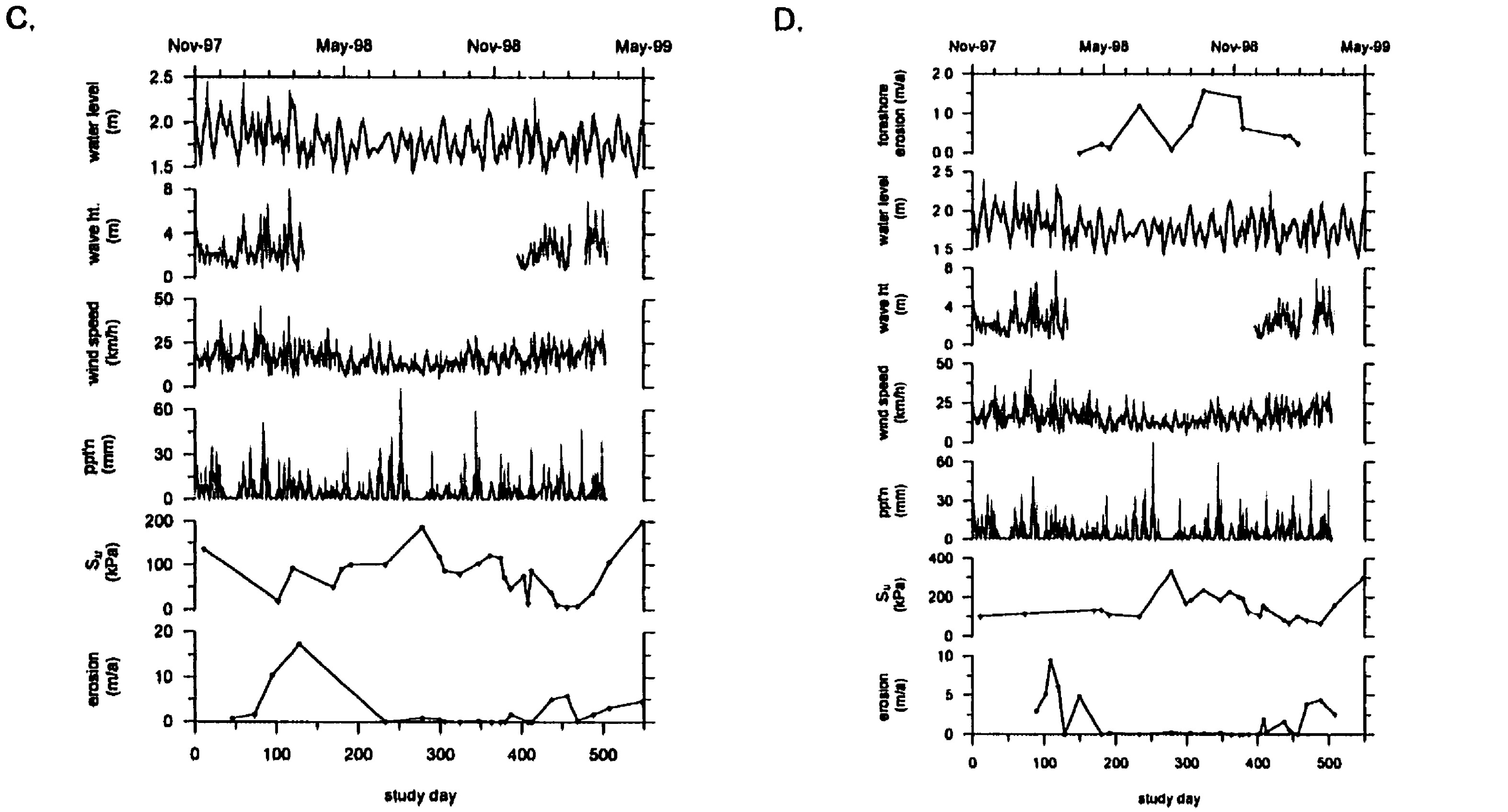


Figure 3.7 C. As in A but for monitoring station M5+5. D. As in A but for monitoring station L4+40 and includes average foreshore erosion measurements.

locally high winds. Local large wave events are produced most effectively by southwesterly to southeasterly winds but swell may also be produced by distant storms that do not coincide with local wind events. When wind and wave events coincide high measured water levels (*i.e.* storm surges) also tend to occur. These appear to be more related to wave events rather than local winds suggesting a possible influence of wave setup due to distant storms. Precipitation may or may not coincide with wind events and magnitudes rarely correlate. In the following treatment surge events are considered to occur when maximum daily water levels are greater than the 5 day running mean which at times of low winds appears to resemble the predicted tide level, or when the 5 day running mean appears exceptionally high. Erosion and shear strength measurements in Figure 3.5 are shown on the date of measurement at the end of the measurement period.

In the winter of 1997/98 erosion peaked at M14+1 and M15A-25 following 3 closely spaced wave events in mid to late January. One of these (January 21) was accompanied by wind and precipitation, and one (January 29) was accompanied by high water levels. Prior to the erosion maximum, shear strength had been at a minimum. M15A-25 also showed a secondary peak in erosion rate following a single event on February 25, 1998 when a local wind event coinciding with moderate precipitation produced significant wave and surge events. Station M5-5 experienced maximum 1997/98 retreat rate following this storm. Shear strength at M15A-25 was relatively low for this station prior to this storm and at M5-5 was very low. Shear strength at M14+1 was at a relatively high value and erosion rate did not peak during this storm. Erosion at L4+40 peaked prior to this event in apparent response to a minor wind, wave and precipitation event on February 19. This storm also breached the outer barrier at Green

Hill Cove, causing overwash that damaged trees on the inner barrier and formed a sandy washover lobe that prograded into the outer lagoon.

Foreshore erosion measurements at L4+40 recorded no erosion caused by winter storms due to infilling of stations by mobile sediment, and wave height data are not available for the measurement period. Some correlation is shown however; wind events between May 1998 and November 1998 appear to correspond to peaks in the foreshore erosion rate while seasonal minimum water level coincides with the minimum measured erosion rate.

In the winter of 1998/99 erosion rate peaked at M5+5, M14+1 and M15A-25 following 3 closely occurring wave events in early to mid-January which correlate with moderate wind events and low shear strength measurements but neither high water levels nor precipitation. These were however the largest wind events since June 1998. Erosion at L4+40 showed a minor peak during these events but had a seasonal peak coinciding with two wave events in mid-February to early-March and with low shear strength at this site. M15A-25 and M14+1 showed subdued peaks in erosion rate which coincide with this period of wave activity and M5-5 showed increasing erosion rate after these events and an increase in shear strength. The previously described failure near M14 also occurred during this time.

3.4 Discussion

Table 3.1 and Figure 3.1 do not show any one morphologic or morphodynamic characteristic that explains differences in measured retreat rates or observed failure styles. Nevertheless, certain characteristics are common between rapidly retreating bluffs. While there are exceptions (e.g. M2), bluffs with high retreat rates tend to be low with steep eroding faces and bluff top slopes, and are generally associated with beaches less than 2 m in elevation. These tend to be formed predominantly of cobbles and boulders with sparse interstitial pebbles and sand in a thin layer over intermittently exposed till. Cavities in exposed till at the bluff toe and foreshore are formed when thin (<5 cm) layers of sandy gravel are present which abrades exposed till. Incident wave energy is dissipated by lag-covered shore platforms which protect bluffs (*e.g.* Lawlor Point section), yet, though not shown by microerosion measurements, erosion of the foreshore and ramp presumably strongly contribute to retreat. All rapidly retreating sites had permanent or intermittent exposures of till in the nearshore.

Foreshore erosion has often been considered to occur because an equilibrium shoreface profile is maintained by vertical erosion of the foreshore accompanying horizontal bluff retreat (*e.g.* Davidson-Arnott and Ollerhead, 1995). Over time the shape of the profile does not change but is translated landward and under rising sea-level, upward (Bruun, 1988). The assumptions of the equilibrium profile hypothesis for sandy beaches include that underlying geology does not play a role in the profile shape, and sediment movement is not unidirectional along or offshore (Pilkey *et al.*, 1993). Clearly, in drift-aligned cells or where shore platforms are present because of antecedent drumlin morphology, the equilibrium hypothesis does not apply. This is especially true over decadal time scales when morphodynamic feedback between beaches, bluffs, and retreat forcing mechanisms can cause rapid shoreline changes not predicted by the equilibrium profile hypothesis. Vertical lowering of the foreshore does not occur to maintain an equilibrium profile but, rather, is simply a consequence of the assailing force produced by wave activity. Wave activity removes debris from the bluff toe and lowers protective cohesive foreshores, both of which, in a positive feedback loop, allow increased attack of the bluff toe by following incident waves.

Foreshore erosion occurs despite the presence of boulder frames and shore platforms which dissipate wave energy. Shore-parallel gaps in the boulder frame (*e.g.* L4+40, M5+5, M14+1) indicate separation of the gravel-sorting zone from the less mobile boulder frame (see Figure 1.2). Separation may occur as thin, low, stranded beaches migrate landward in contact with the eroding bluff toe or are destroyed and dispersed downdrift. The less mobile frame is left behind and the shore parallel gap forms between the upper part of the frame and the toe of the remaining beach. In an extreme example of foreshore exposure promoting bluff retreat, airphotos indicate that a beach prism fronting the bluff toe at the Green Hill section that was completely destroyed between 1992 and 1997 and resulted in reactivation of the previously vegetated bluff. Hurricane Hortense, in September 1996, is a possible candidate for destroying the beach at this site and exposing the cohesive foreshore to direct wave attack but it is unclear whether several storms are required for the destruction of stranded drift-aligned gravel beaches. As evidenced by all rapidly retreating bluffs having exposed till foreshores, development of till exposures is conducive to foreshore erosion and results in increased rates of lowering that may affect retreat over longer than annual and sub-annual time scales.

Comparisons of cumulative bluff-face erosion and cumulative bluff-edge retreat at stations and adjacent lines over the monitoring period show that they are not equal, indicating a change in the bluff profile (Table 3.1). Although monitoring stations are not located exactly at lines and bluff face erosion is underestimated due to loss of rods during storm events (section 2.2), profiles confirm that M5, M14, and L4 have become less steep (Figure 2.8). Bluff profiles may show small-scale cyclic instability between steep and gentle slopes (*e.g.* Hutchinson, 1973) or large-scale, long-term cyclicity (Quigley *et al.*, 1977). As the bluff edge retreats, colluvium is deposited at the bluff toe and is subsequently removed by wave activity exposing the toe to wave attack and promoting oversteepening and subsequent failure at the bluff edge. In the study area, because of high wave energy and the low shear strength of remolded Lawrencetown Till with increasing water content, colluvium deposited at the toe of rapidly eroding bluffs rarely survives all winter storms and likely does not contribute significantly to toe protection. If, however, boulders are present in the colluvium, or if the colluvium is deposited high on a beach terrace, suitably-sized sediment may be incorporated into the gravel sorting zone or boulder frame. Given the generally low percentage of beach-forming sediment in the clay facies (average 17% w/w >2 mm) and the strong long-shore currents that develop in morphodynamic cells, sediment delivered by bluff retreat does not usually remain protecting the bluff toe over longer than sub-annual time scales. The colluvium at more slowly eroding bluffs is not rapidly removed and may persist, providing longer term toe protection.

Environmental parameters that appear important in contributing to sub-annual bluff face erosion rates in the study area are those that coincide with storms: high winds, waves, and surges. Seasonal erosion maxima (Figure 3.7) coincide most often with wave events and coincident elevated water levels. When local high winds generate high waves and a storm surge develops (*e.g.* February 25, 1998) severe erosion can occur regardless of bluff shear strength. When events are lesser, showing no coincidence of high water levels and high local winds (*e.g.* three wave events in January 1999) low bluff shear strength may contribute to seasonal erosion maxima. Storm surges also contribute to changes in beach morphology. On February 25, 1998 the barrier at Green Hill Cove breached and overwashed. The combination of high waves and setup and elevated back-barrier lagoon water levels due to storm surges may increase pore pressures within the beach and render it unstable.

Cohesive bluffs initially erode quickly as the outer weathered skin is removed at the beginning of a storm (Amin and Davidson-Arnott, 1995) and then more slowly as the unweathered internal material is attacked. Long intervals between storms may pre-condition bluffs to erosion by allowing deeper penetration of weathering, reduction of the resisting force, and erosion by relatively small storms.

Conditioning of bluffs to retreat on annual or longer scales is evidenced at the Green Hill section and at M14, where bluffs have been vegetated and inactive between 1982 and 1997. Vegetation visible on airphotos indicates gently sloping bluff faces not subject to significant translational failure and wave attack. It is thought that hiatuses in wave attack allow bluffs to become stable but prone to sub-aerial processes. Precipitation and accumulation of groundwater result in increases in water content and the development of small-scale slumps and tension cracks, as observed on the steep bluff top slopes at M14 and M5. Upon re-initiation of wave attack, the bluff is of high water content, has bluff face parallel zones of weakness at tension cracks, and therefore initially is prone to rapid retreat. Retreat rate may decrease as unweathered material is attacked, although little is known about rates of till softening and water content and shear strength gradients with depth in the Lawrencetown Till. Tension cracks and failure planes allow penetration of water likely deep into the unweathered and relatively impermeable till and may be of great importance in the development of deep-seated rotational failures.

The presence of vegetation may contribute to either bluff stability or instability. Vegetation contributes to stability through the development of root systems, and interception of precipitation and reduction of water content due to evapotranspiration. Conversely, vegetation increases the mass of a slope and is subject to wind shear stress, both of which promote failure (Greenway, 1987). Root systems also increase the depth of weathering and may assist in transporting water deep into the till. In the McNab's Island area slowly retreating bluffs are at least partially vegetated, usually by grasses or small trees, suggesting that the dominant effect of vegetation is stabilization, but these slopes may be vegetated because they are slowly retreating for other reasons and vegetation can be supported.

Failures originating at the bluff edge appear to be caused by elevated water contents resulting from precipitation (*e.g.* M14, M11) and are influenced by temperature and stratigraphy (*e.g.* M2, L4). Groundwater accumulates in permeable strata during intervals of below-freezing temperatures and may contribute to short-term stability. Upon melting, however, water content greatly increases, shear strength decreases and, under the influence of gravity, failure occurs. Wave activity plays an important role in removing support and promoting gravitational failure, but, at the bluff edge, this is an indirect effect. The indirect impacts of wave attack were observed at lines M9 and M10, where wave activity during strong storm events cuts a low (0.3-0.5 m) scarp and the shallow sloping but very low shear strength sandy colluvium flowed in response to loss of toe support. Loss of toe support also contributed to the failure at M15B in February, 1999.

At the bluff toe erosion occurs directly due to wave activity. The amount of erosion that occurs is determined by both the wave energy (assailing force) and till shear strength (resisting force). As previously discussed, till shear strength is determined by water content. During storms both precipitation and sea spray increase water content while at the same time wave energy increases; the assailing force and the resisting force therefore share an inverse relationship promoting erosion during storms.

The shear strength of till in the foreshore is, at natural water contents, lower than that of bluffs (Table 2.2). Erosion occurs due to shear stress under unbroken waves and the much stronger compressive force of breaking waves in the intertidal zone (Sunamura, 1992). Abrasion due to sand and fine gravel may greatly increase the effectiveness of the assailing force; small amounts of sand and fine gravel are present in cavities in the ramp and foreshore at M14. Foreshores in Lawrencetown Till have a mean shear strength of approximately 60 kPa, orders of magnitude higher than values of critical shear stress (the incident shear stress above which erosion occurs) which include the abrasive effect of sediment reported for Lake Erie tills (9 Pa) (Skafel and Bishop, 1994) and estuarine muds (1.5 Pa) (DeVries, 1992). Abrasion by mobile sediment may be a critical process in controlling foreshore erosion. Abrasion was not well measured on McNab's and Lawlor Islands where, in an attempt to limit burial of stations, micro-erosion meter stations were placed in lower energy areas where sediment mobility was thought to be low.

The effect of tidal cycles on water content and shear strength of foreshore till exposures is unclear. Duration of submergence likely plays an important role in determining the shear strength of till foreshores, and intervals between storms may also be important in controlling the erosion that occurs. Further information is required on the rate of water content increase with submergence of the Lawrencetown Till clay facies, and the variability of water content across till foreshores. External shear strength of till exposed in foreshores in the study area is of low temporal variability, suggesting foreshore erosion likely varies due to variability of the assailing force.

The relative importance of the assailing and resisting force changes over the bluff profile. Bluffs experience bluff edge retreat mainly in response to decreasing resisting force. Slowly eroding bluffs have beaches at the bluff toe which reduce the assailing force over the foreshore and at the bluff toe. Retreat of slowly retreating bluffs is therefore mainly due to decreases in the resisting force with lesser indirect contribution from the assailing force during particularly strong storm events accompanied by waves, suggesting that under stable sea-level and invariant storm climate, a shallow, stable slope would result. The situation becomes more complex at the bluff toe, where storms push the dynamic equilibrium between the resisting and assailing forces towards erosion by both decreasing the resisting force and increasing the assailing force. Till foreshores may experience erosion mainly in response to increasing assailing force. Due to submergence, the resisting force is low and of possibly low variability. The assailing force under broken waves in the presence of sand and gravel is high, and may be of greater relative importance in controlling the rate of foreshore erosion.

3.5 Conclusions

1) Environmental parameters contributing significantly to retreat and erosion of bluffs are high waves, water levels, winds, and precipitation which occur during storms. While waves or precipitation can alone cause local retreat, widespread retreat is caused by coincidence of all of the previously mentioned parameters and is of especially high magnitude when accompanied by warming from below freezing temperatures.

2) Foreshore lowering is an important process in bluff retreat caused by wave activity and abrasion by sediment with a lesser influence from variable water content, and results in increased wave energy at the bluff toe. Foreshore erosion can occur where the equilibrium shoreface hypothesis does not apply.

3) Bluffs retreat mainly through episodic rotational failure and flow processes, commonly during winter storms in February or March. Erosion of the bluff face, toe and till foreshore are important at rapidly retreating sites and bluff erosion correlates well with storms. Bluffs with high retreat rates tend to be low with steep bluff face and bluff top slopes and have thin beaches with periodic or permanent exposures of till in the nearshore zone. Bluffs with low retreat rates tend to be fronted by well-developed beaches.

4) Bluff face erosion occurs in response to both increasing assailing force and decreasing resisting forces during storms. The assailing and resisting forces are not independent, due to the dependence of shear strength on water content and the co-occurrence of precipitation and storms. The relative importance of these forces differs over the bluff face and foreshore and also between rapidly and slowly retreating bluffs. Slowly retreating bluffs experience lower assailing force.

Chapter 4

Decadal-Scale Coastal Change: Towards A Sediment Budget

4.1 Introduction

The long-term evolution of the Eastern Shore has been considered to be controlled by a balance between sediment supply to barrier beaches and the rate of sea-level rise whereby, if sediment supply decreases or the rate of sea-level rise increases, barrier overwash and destruction can occur. A new barrier then forms at a more landward location (Boyd *et al.*, 1987; Carter and Orford, 1988). Although the dominant sediment source for the formation of barrier beaches is thought to be eroding drumlin headlands, previous budget calculations on the Atlantic Coast of Nova Scotia have indicated an abundance of beach sediment in excess of that supplied by drumlins (Piper, 1980; Sonnichsen, 1984) suggesting that sediment is transported landward from an offshore source during transgression. Shoreface sands on the Atlantic coast of Nova Scotia are disconnected and concentrated in the vicinity of barrier beaches and rarely extend below the 20 m isobath (Wang and Piper, 1982; Hall, 1985; Piper *et al.*, 1986; Carter *et al.* 1995), suggesting that any present offshore source is local. In the McNab's Island area, possible sediment sources include eroding drumlins, overwashed barrier beaches, remnant eroded drumlin shoals, and estuarine facies outcropping seaward of existing barrier beaches. The tide gauge at Halifax records stepwise relative sea-level rise since 1896 at rates between 3 and 40 cm/century (Figure 2.20).

Sand and gravel removal from Nova Scotia beaches has been shown by Bowen *et al.* (1975) to result in increased susceptibility to erosion and overwash. Significant beach mining in the study area started before 1849, resulting in several instances of anthropogenically-induced overwash and barrier beach destruction.

The purpose of this chapter is to investigate decadal-scale coastal changes in the study area, and to examine the relationship between coastal change under rising sea level and the dispersal of sediment eroded from drumlin bluffs. The various elements of the sediment budget will be examined and interpretations and measurements of historic coastal evolution presented. The roles of sediment delivered from drumlin bluffs and offshore sources in contributing to coastal stability will be discussed.

4.2 Elements of the Sediment Budget

A simple sediment budget for the study area is presented in Figure 4.1. Sediment of mixed grain sizes is produced from several sources. Gravel and coarse material are delivered to beaches. Mud bypasses the temporary beach sink to be deposited directly in deep basins, sand is transported to the shoreface sand sheet, and cobbles and boulders may ultimately reside in lag deposits. This section further describes the various sources and processes of the sediment budget.

Bluffs in the study area are described in detail in Section 3.2. The formation of bluffs in drumlins by rising sea level has been considered to proceed initially quickly as the drumlin is first attacked and provides little protective sediment. Retreat may then slow as the bluff grows in height and length and supplies more sediment, and then accelerates as bluff height and length diminish to the low stoss end of the drumlin (Boyd et al., 1987). Chapter 3 has shown that, mainly due to conditioning by sub-aerial processes, low bluffs do retreat quickly as they are first subject to wave attack, yet

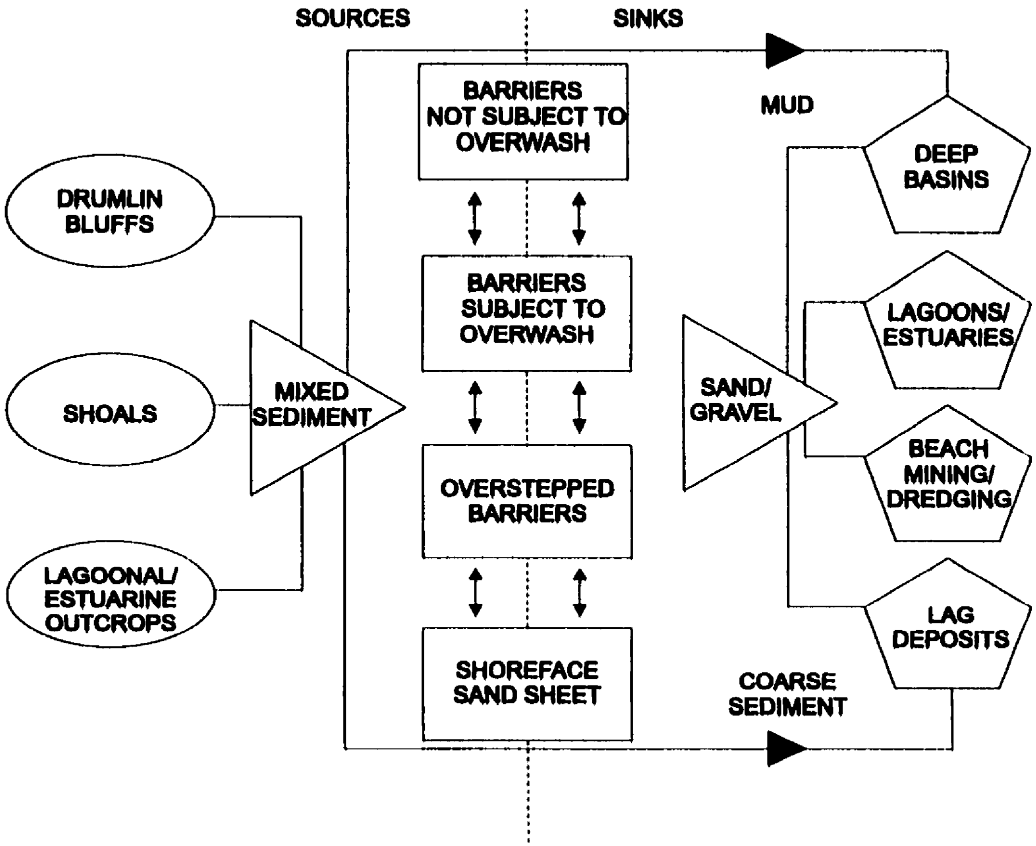


Figure 4.1 A simple sediment budget model for the McNab's Island area. Sediment is delivered to different types of beaches from eroding drumlin bluffs, offshore shoals, and estuarine or lagoonal deposits outcropping seaward of existing barriers. Beaches can act as both sediment sinks and sources, and temporarily store sediment prior to it being deposited in more permanent sinks. Mud and coarse material may bypass beaches and be deposited directly in deep basins or lag deposits, respectively. Beach mining and dredging has been conducted in the study area since at least 1850 and represents a significant loss from the sediment budget.

remnant drumlins, can, perhaps under special circumstances, be stable (*e.g.* Story Head at the eastern entrance to Chezzetcook Inlet). The spatially and temporally discrete nature of sediment supply from drumlin sources may control decadal-scale coastal evolution of drumlin shorelines by providing sediment in local, relatively short-lived pulses.

Three types of beaches are identified in Figure 4.1: submerged overstepped beach forms, emergent beaches subject to overwash (type S2; Forbes et al., 1995a), and emergent beaches not subject to overwash (types S1 and S2; Forbes et al., 1995a). All of these may behave as either sources or sinks for sand and gravel. Most beaches in the study area lie on drumlin flanks down-drift of eroding headlands. These tend not to be subject to overwash, are stranded with low accommodation space, drift-aligned, and generally thin (type D3 of Forbes et al., 1995a). Drift-aligned beaches may terminate in spits that prograde across embayments, possibly enclosing lagoons. Where spits prograde into deep water significant volumes of sediment may accumulate.

In contrast, a small number of beaches are, or have been in historical times, well-developed high gravel or sandy gravel barriers. Examples include Barrie Beach, Noonan's Beach, McCormick's Beach, Thrumcap Hook, Doyle Beach, Hangman's Beach, and Maugher's Beach (Figure 1.1). Gravel barriers usually have both drift- and swash-aligned sections, a high seaward crest, and can be divided into 3 shore-parallel zones: an outer cobble or boulder frame, an active zone where clasts are traded between the frame and beach face, and a gravel-sorting zone in which resides the beach crest. Barriers of type S1 (Forbes et al., 1995a) are not subject to overwash and are prograding (*e.g.* McCormick's Beach, Maugher's Beach), while barriers of type S2 (*e.g.* Dunn's Beach, Hangman's Beach), contain more gravel, have high open framework crests and may be slowly migrating. Type S3 barriers (*e.g.* Barrie Beach, Thrumcap Hook) are subject to overwash and undergo rapid migration. These are low and wide and cut by washover channels. Barriers subject to overwash tend to lose sediment to landward lagoons or prograding beaches. Sediment may also be removed from type S3 gravel barriers subject to overwash during overstepping (Forbes et al., 1991a) although the mechanism of overstepping and subsequent evolution of the overstepped remnant are unclear.

Shoreface sands, which in the study area extend seaward from the outer cobble-boulder frame in approximately 2 m water to depths greater than 10 m, are morphodynamically closely related to beaches in the study area. Sand and gravel are transferred across coarse-clastic beaches by swash-backwash motions controlled by oblique swash bars (*cf.* Carter et al., 1990) present on drift-aligned sections (*e.g.* the West Gut section). Storms may cause overwash and the deposition of washover landward of the beach crest or may mobilise sediment offshore to the boulder frame and shoreface sand sheet and move sand, gravel, and coarse material in the direction of longshore drift. During less stormy conditions the sediment is returned to the beach and the crest builds in height through overtopping (Carter *et al.*, 1990). Beaches, both subaerial and submerged, and the shoreface sand sheet act as both sediment sources and sinks and may together form the largest reservoir of active sediment. The distribution and seaward limit of the shoreface sand sheet in the study area has not been defined.

Relict submerged beach forms preserved seaward of existing barriers during transgression have been observed on the Atlantic Coast of Nova Scotia by Forbes *et al.* (1995a) and Barnes and Piper (1978) and may represent an additional source of sand and gravel. Conditions promoting preservation of these structures are not well understood but may relate to changes in the rate of sea-level rise or sediment supply (Rampino and Sanders, 1980; Forbes *et al.*, 1995a; Forbes *et al.*, 1995b). The narrow width (less than 100 m) of these features has meant that they were not well sampled by traditional sounding techniques and therefore no measurements are available to determine rates of erosion and their importance as an alternate offshore source.

Most large shoals in the study area are the submerged remnants of eroded drumlins (*e.g.* Thrumcap Shoal). They are generally capped by coarse lag deposits and may have bedrock outcrops; Cox Comb, for example, is an outcrop of the Halifax Formation. Other smaller rounded shoals usually found in more protected areas are composed of sand, gravel, and coarse sediment and appear to be related to the formation, migration, and destruction of drift-aligned spits. Large shoals frequently act as anchor points for barrier beaches and appear to lend stability to these features. Transverse ridges are prominent drift-aligned sediment accumulations that form nearly perpendicular to the shoreline down-drift of shoals as submerged trailing spit-like features and may act as conduits for mobile sediment (Orford et al., 1991)

Estuarine or lagoonal deposits outcropping on the shoreface and inner shelf have been observed by Forbes *et al.* (1995b) and Forbes and Boyd (1989), and also in this study and represent an additional source of sandy mud. During transgression, barrier beaches may migrate landward over muddy back-barrier lagoonal or estuarine sediments and continued erosion of the shoreface can expose these sediments seaward of the existing barrier. Estuarine deposits are commonly exposed in submarine valleys on the inner Scotian Shelf from depths of 50 m to the present shoreline (Forbes *et al.*, 1991b), however their extent in the study area remains unknown.

Glacially over-deepened basins and shallow estuaries are more permanent sinks for sediment. Sand delivered from the erosion of the various sources is thought to reside in beaches and the shoreface sand sheet, possibly for long time periods, before being transported to these sinks. Sandy laminae in muddy basin sediments west of McNab's Island have been correlated to storm events indicating offshore movement of fine sand and silt to basin sinks during stormy intervals and mud deposition during fair weather intervals (Delure, 1983). Mud may also be moved well offshore to deep basins on the Scotian Shelf (Piper, 1980; Piper *et al.*, 1986). Elsewhere on the Eastern Shore shallow estuaries and prograding marsh environments are significant sinks for sand and muddy sediment (Scott, 1980; Boyd and Honig, 1992). These environments are rare in Halifax Harbour, although washover sediment may be deposited in relatively small back-barrier lagoons or sheltered embayments. Coarse material is eventually deposited in lag deposits where cobbles and boulders with low mobility accumulate in a thin layer on shoals and shore platforms. Even in the intertidal zone lag deposits appear stable, except perhaps in severe storms.

4.3 Historical Coastal Change in the Study Area

4.3.1 1711

The first chart of the study area is from 1711 and records French plans for the defense of then Baye de Chibouquetou (Delabat, 1711) (Figure 4.2a) (see also Figures 1.1, 3.3 and 4.3 for place names). McNab's Island (Isle de Chibouquetou) and especially Lawlor Island are unfortunately not well depicted and the chart is of little

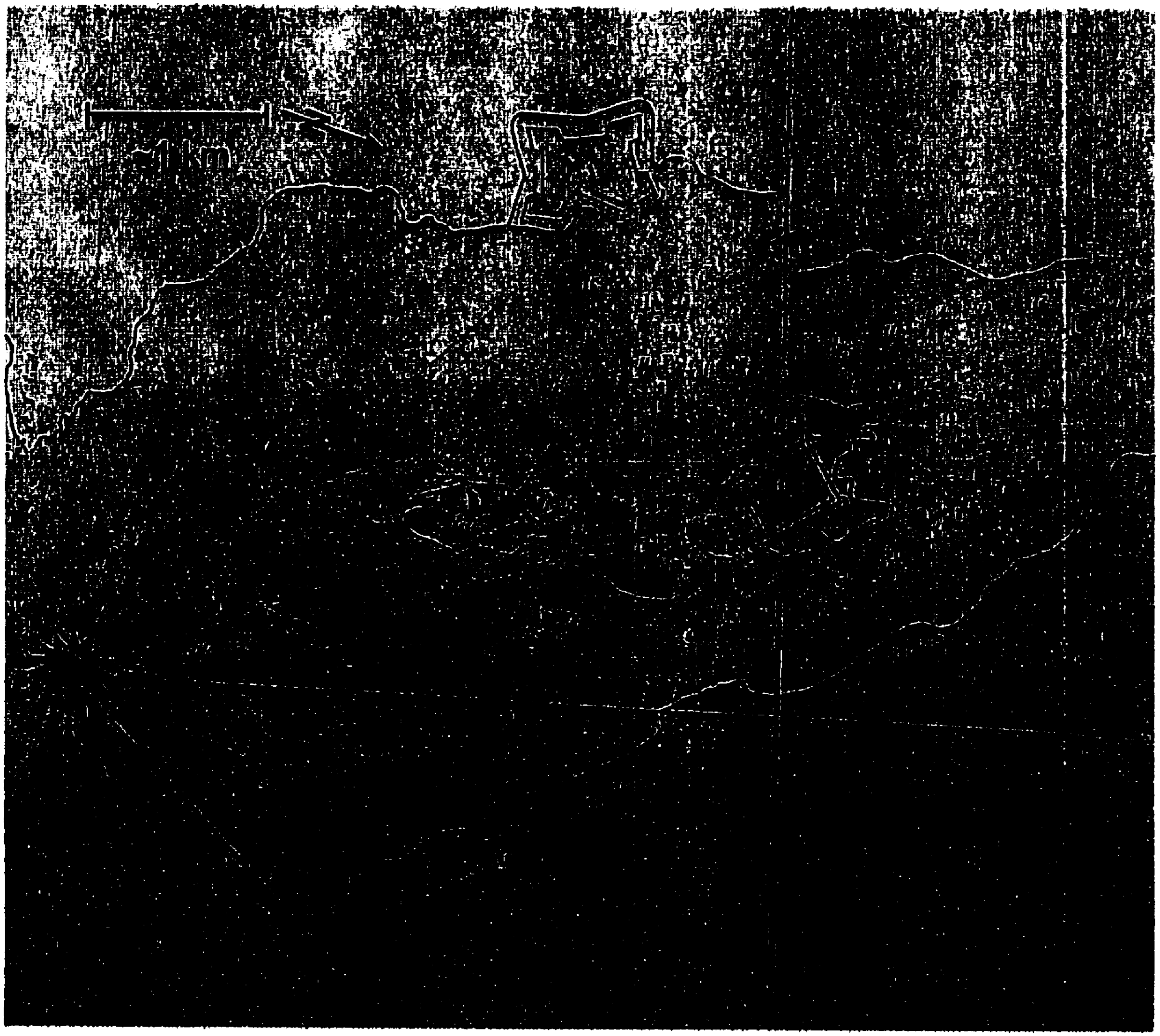


Figure 4.2a A portion of the first chart of Halifax Harbour (la Baye de Chibouquetou) by Delabat (1711).

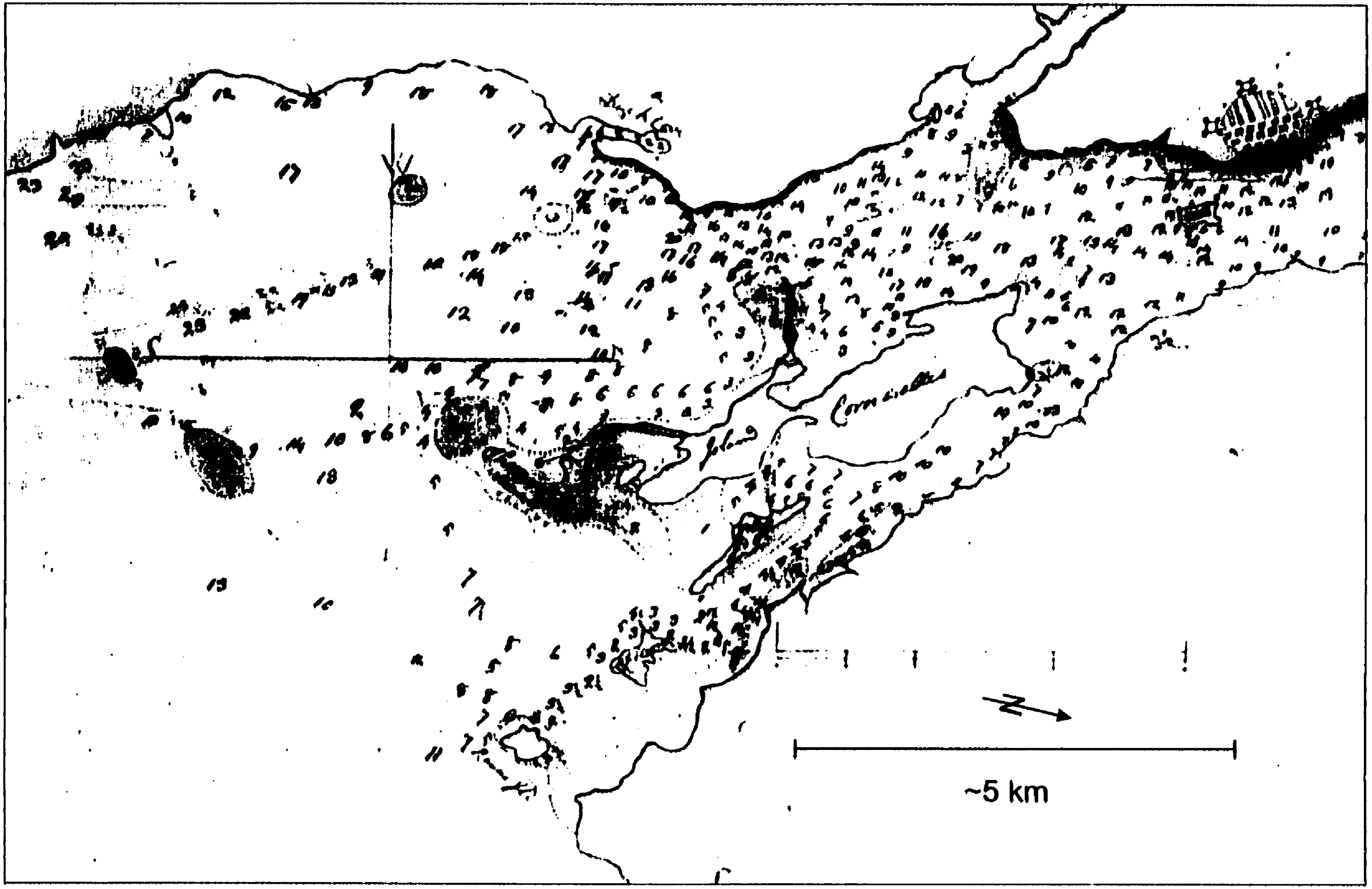


Figure 4.2b A portion of a chart by James Cook (1758).

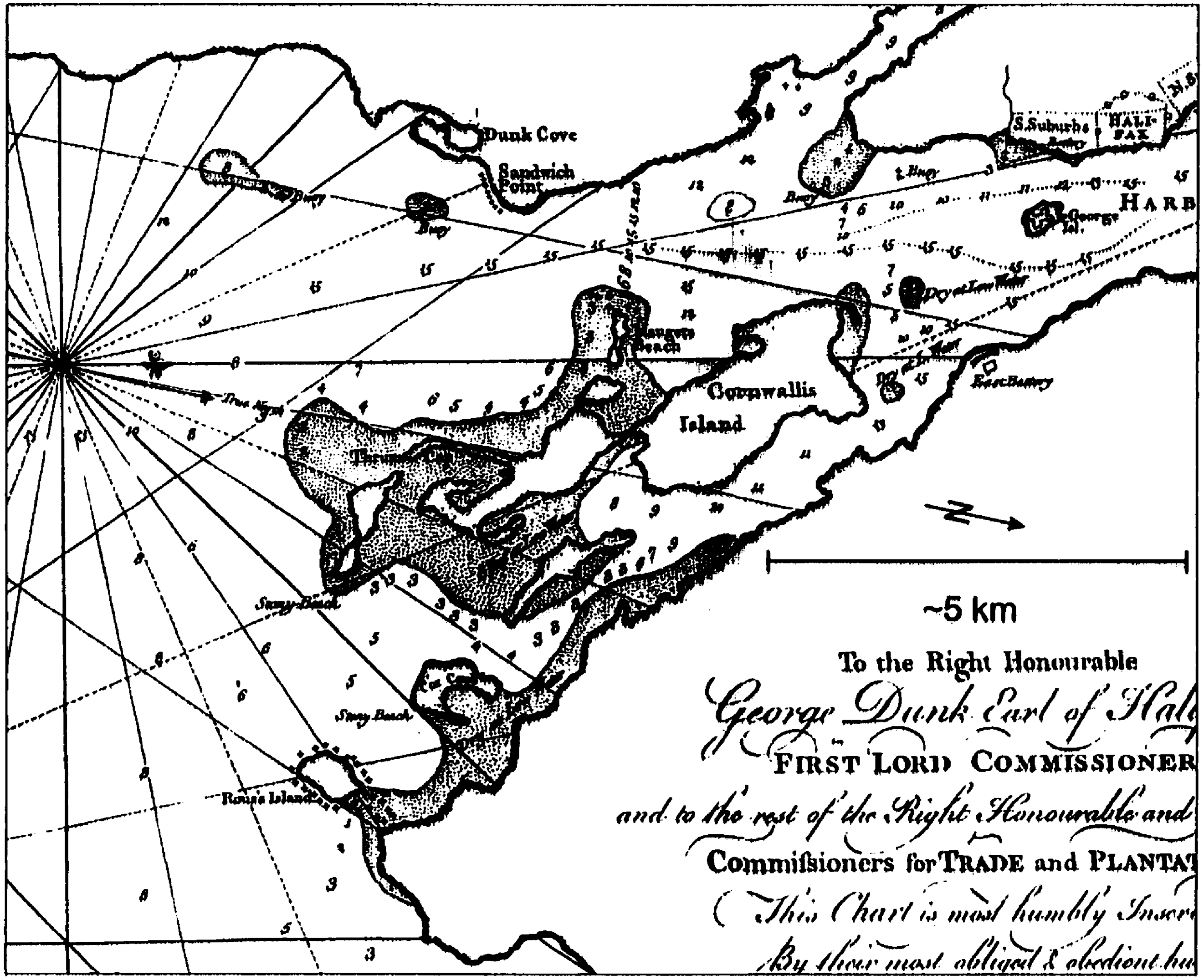


Figure 4.2c A portion of the 1759 chart by Morris and Jeffries (1759).

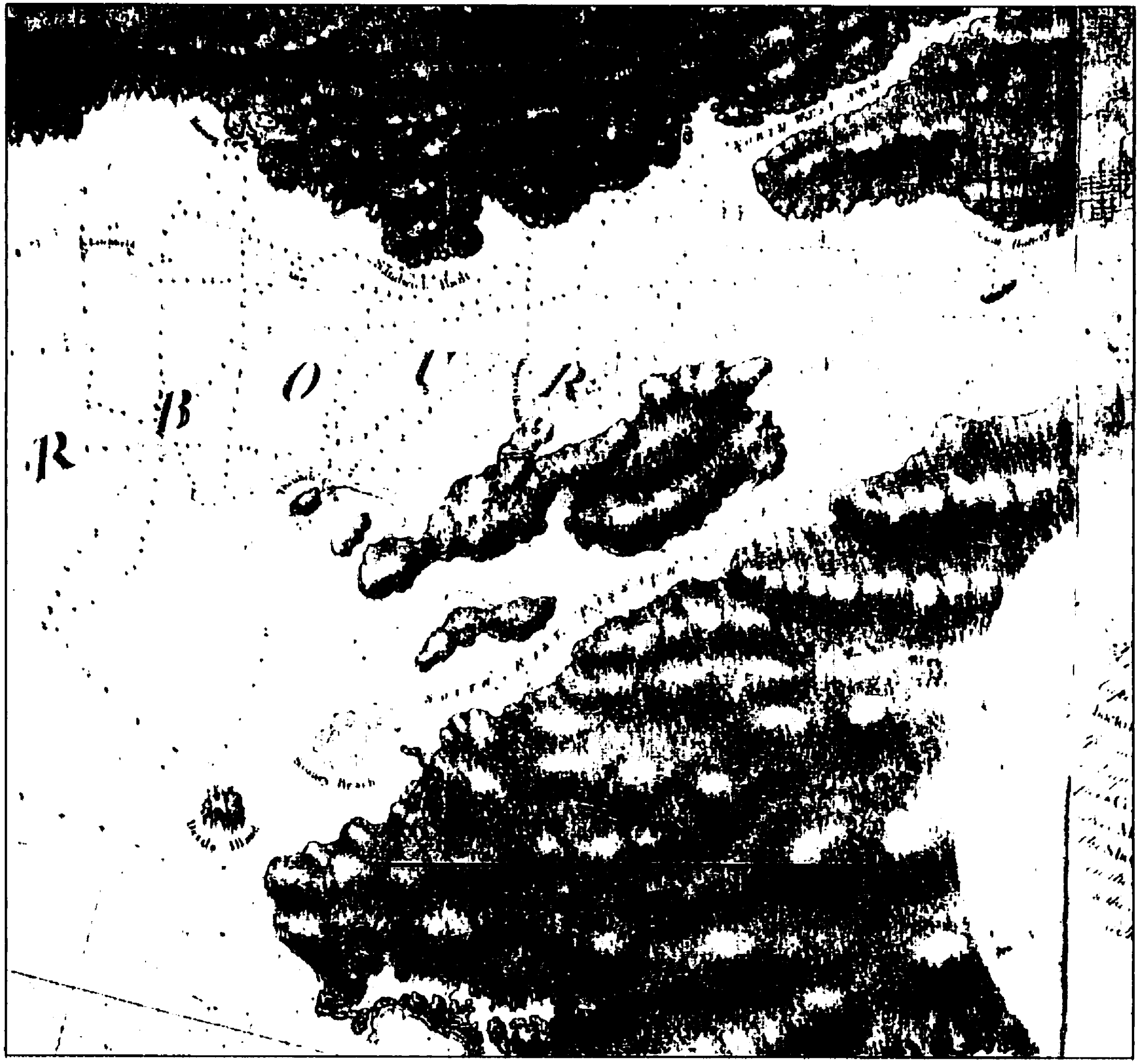


Figure 4.2d A portion of the chart by Des Barres (1776).

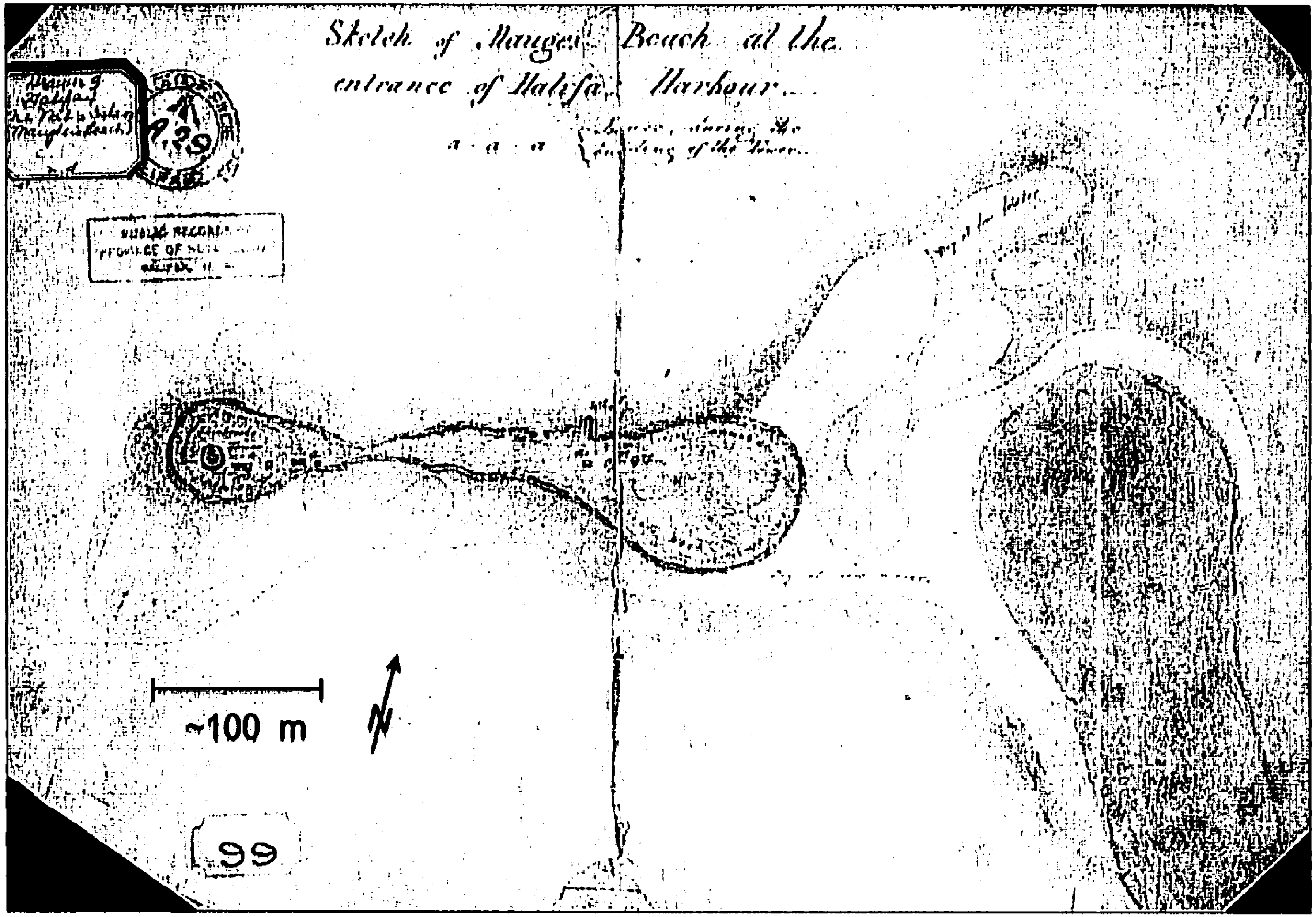


Figure 4.2e An 1826 sketch of Hangman's Beach showing tidal channel and spits dry at low water (Toler, 1826). The spit extending to the northeast continued to prograde and eventually formed Maugher's Beach as it appears today.

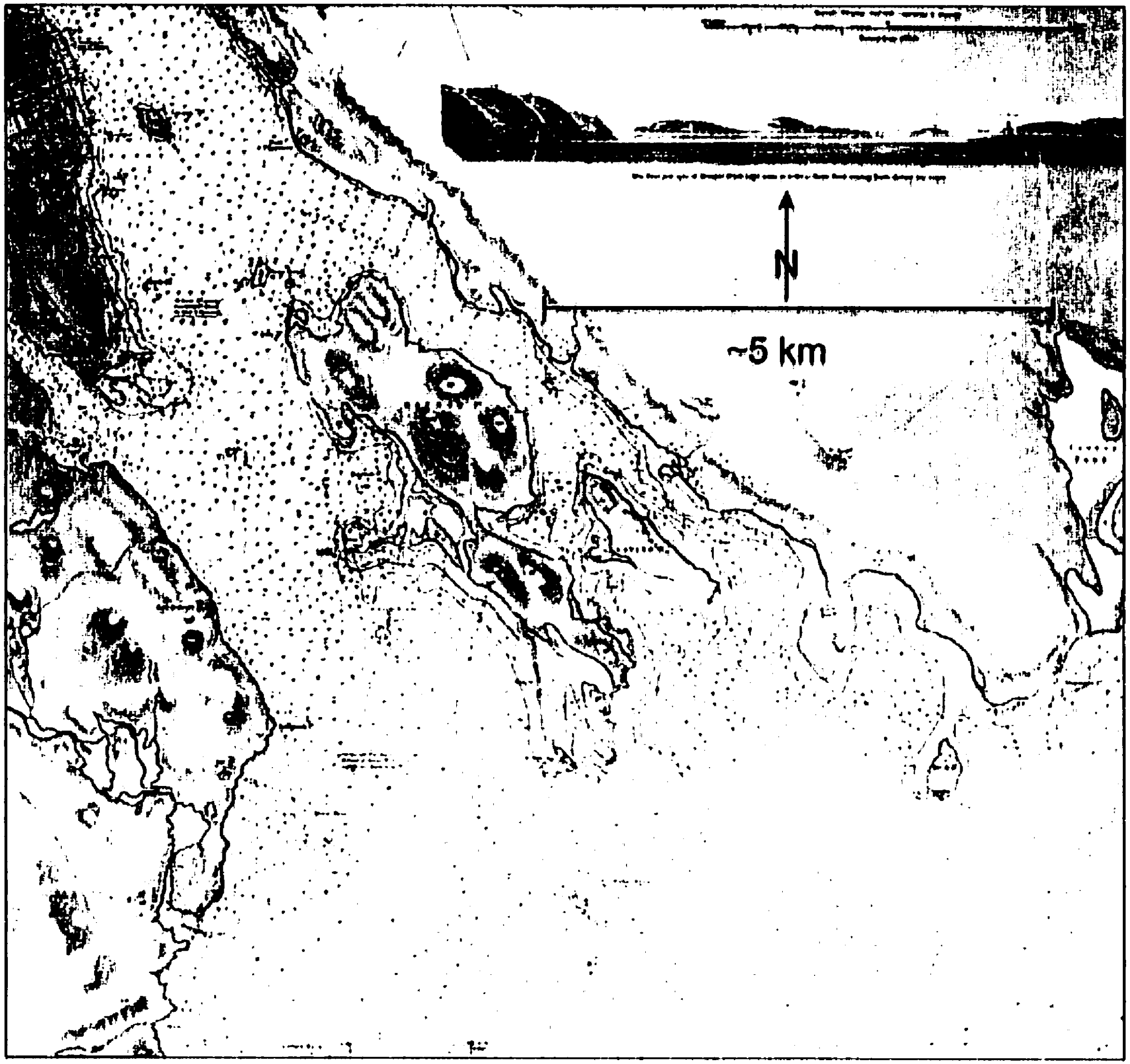


Figure 4.2f A portion of a chart by Bayfield (1853).

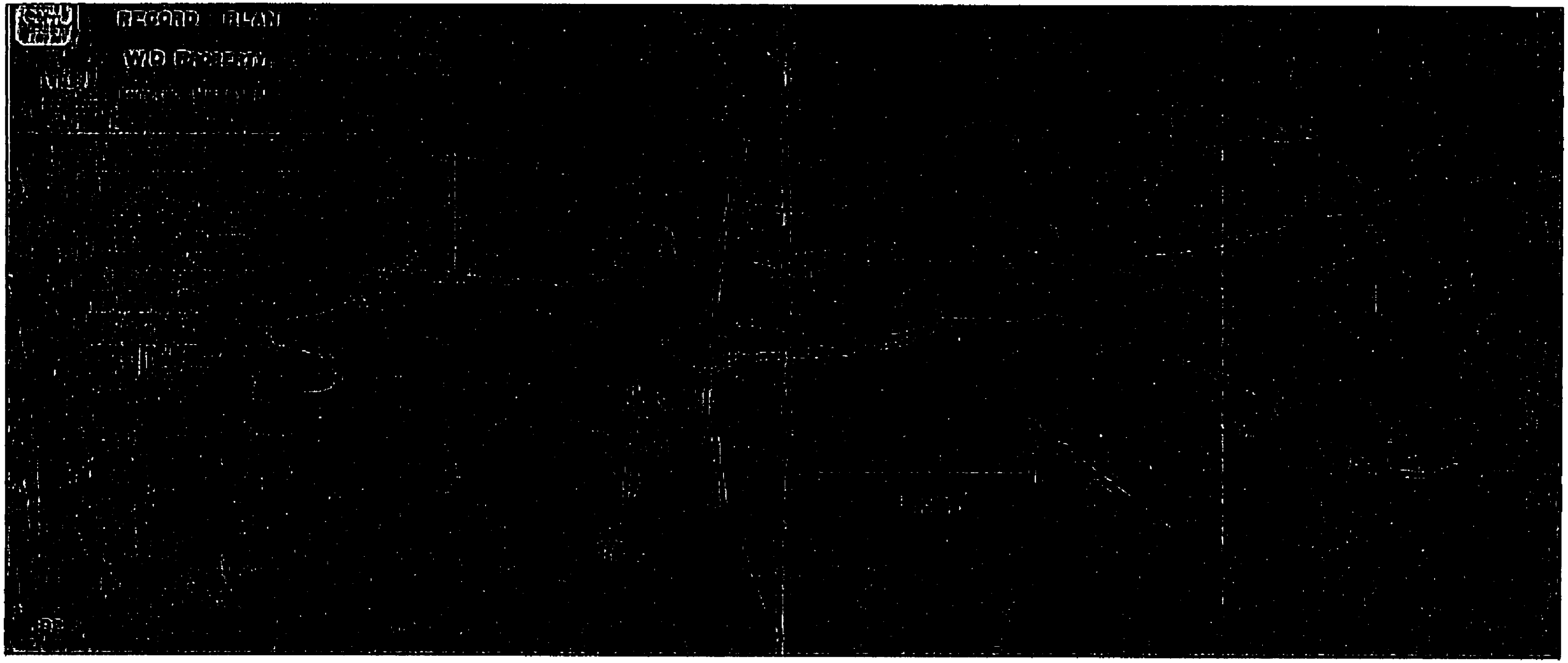


Figure 4.2g A map of the south end of McNab's Island from 1867 (Rowe, 1867).

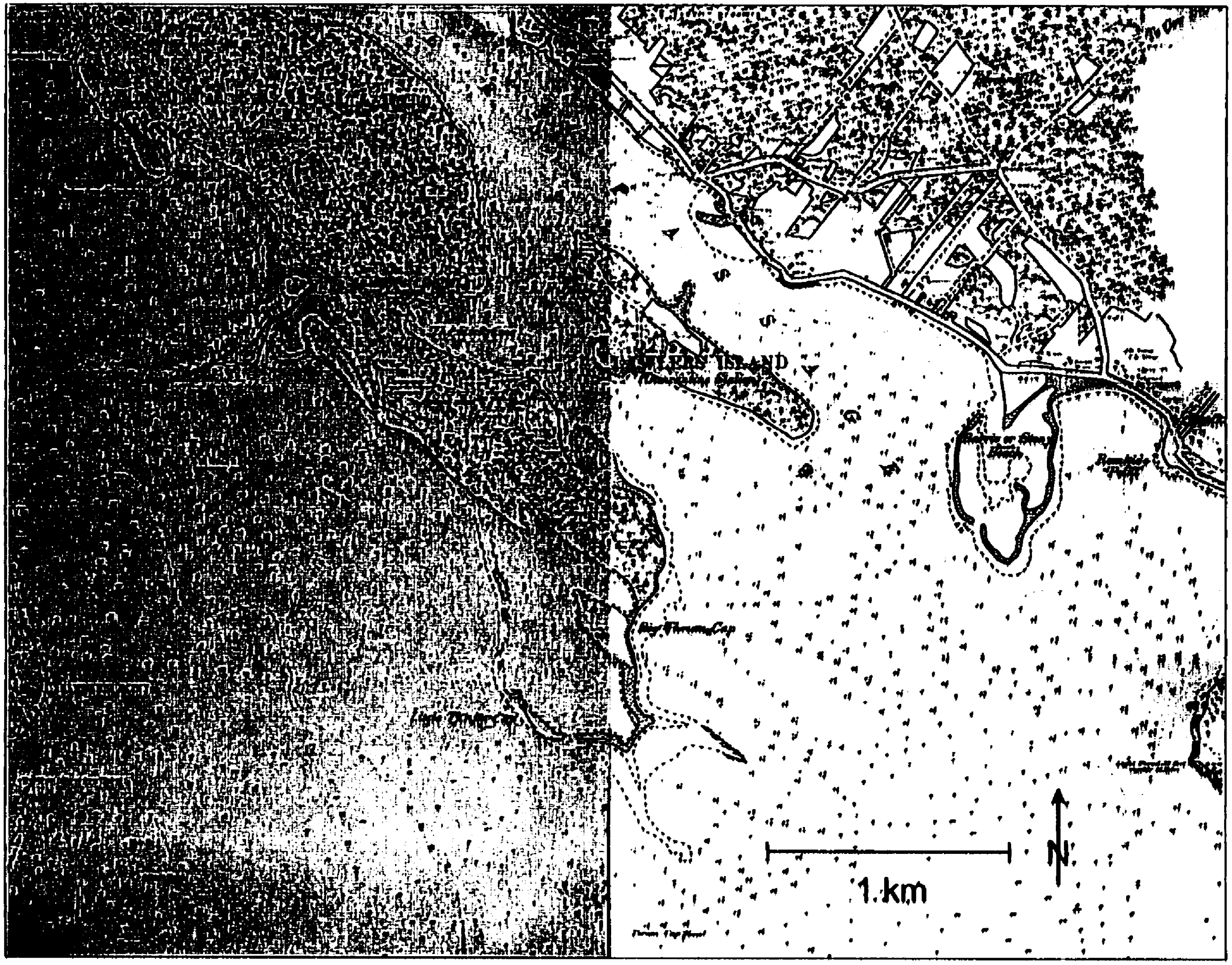


Figure 4.2h A portion of a mosaic of charts from 1886 (Akers, 1886).

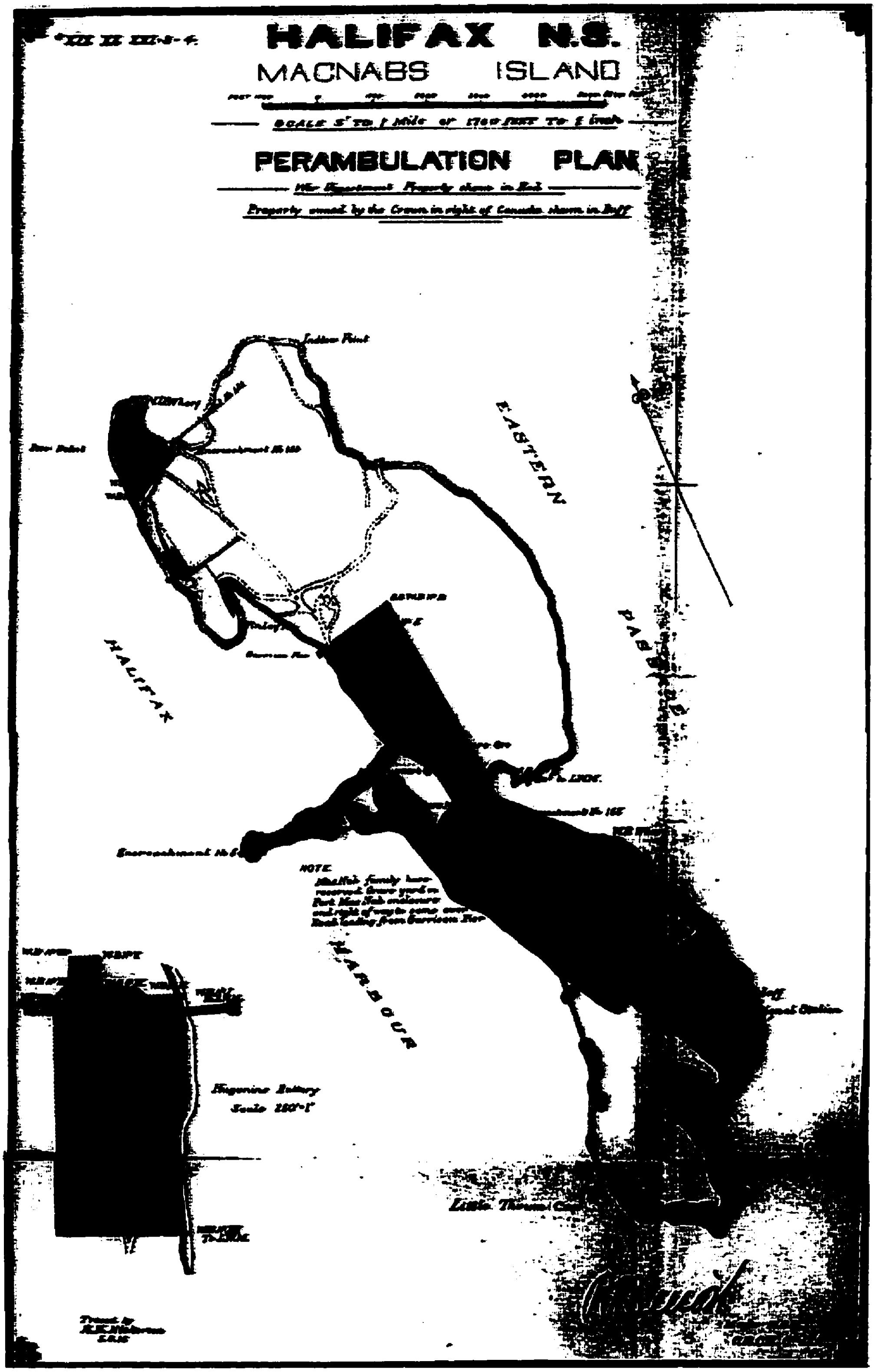


Figure 4.2i Perambulation Plan for McNab's Island (War Department, 1915).

Figure 4.2j Airphoto mosaic from 1934.

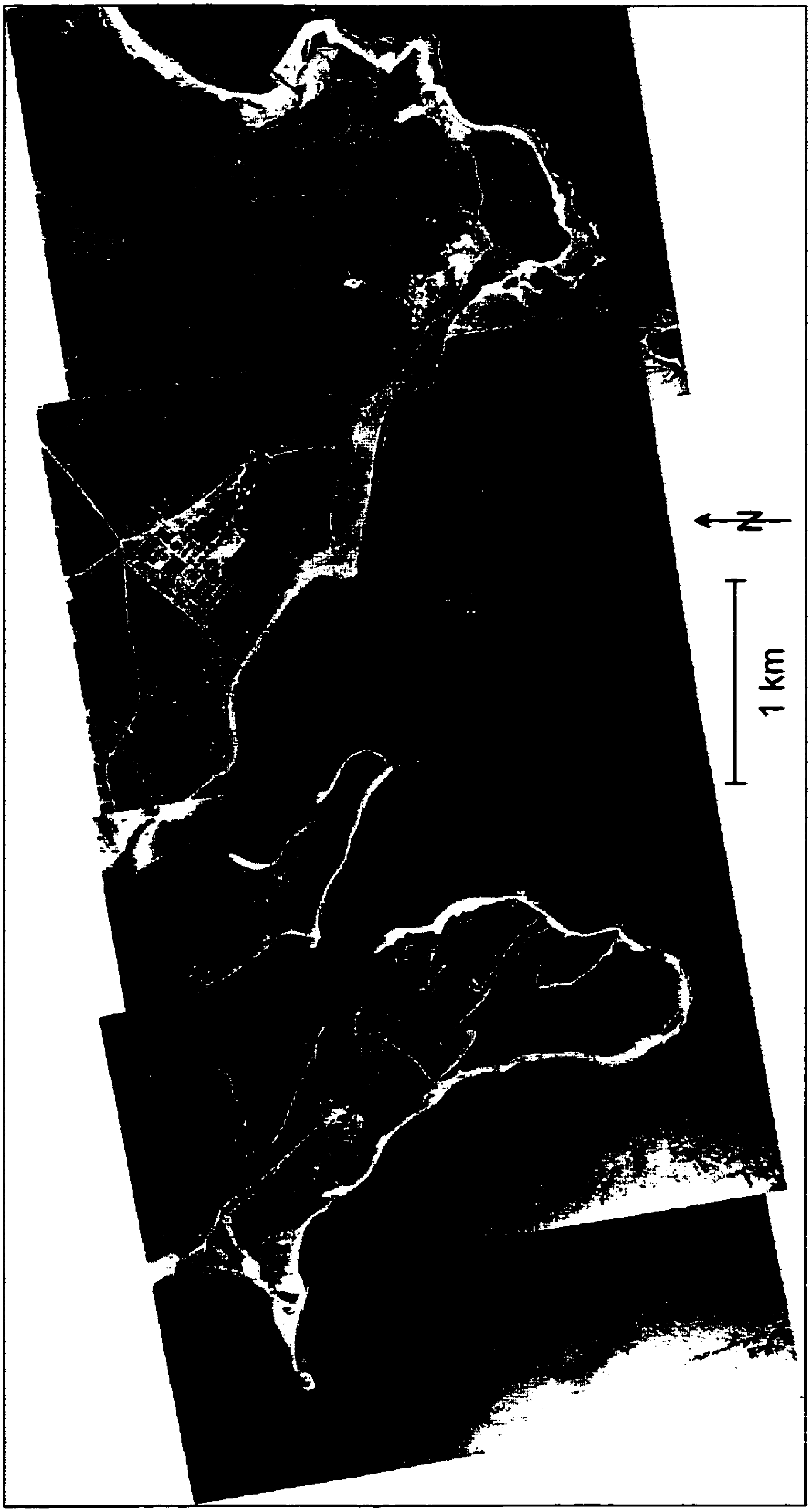


Figure 4.2k Airphoto mosaic from 1945.

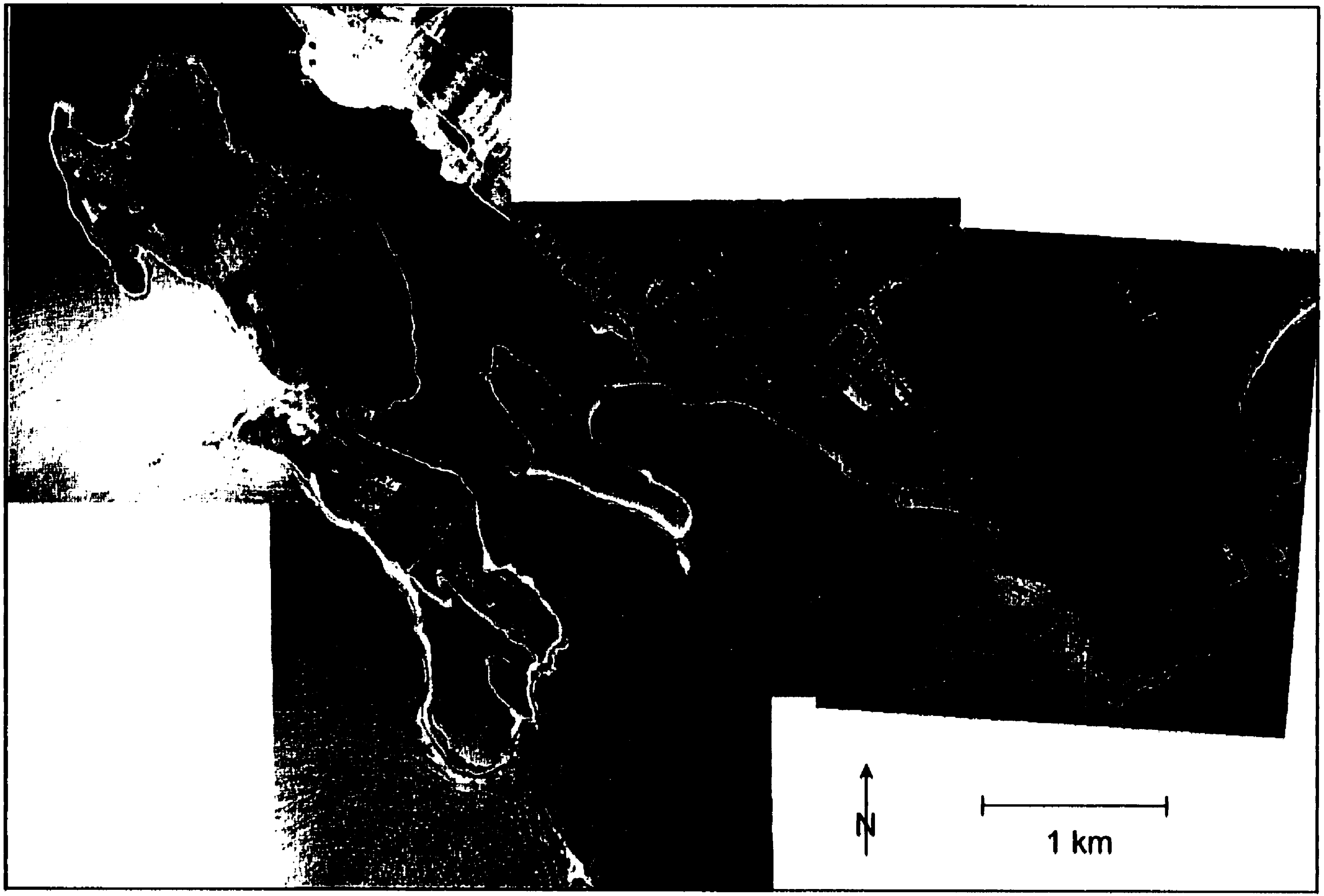


Figure 4.21 Airphoto mosaic from 1954.

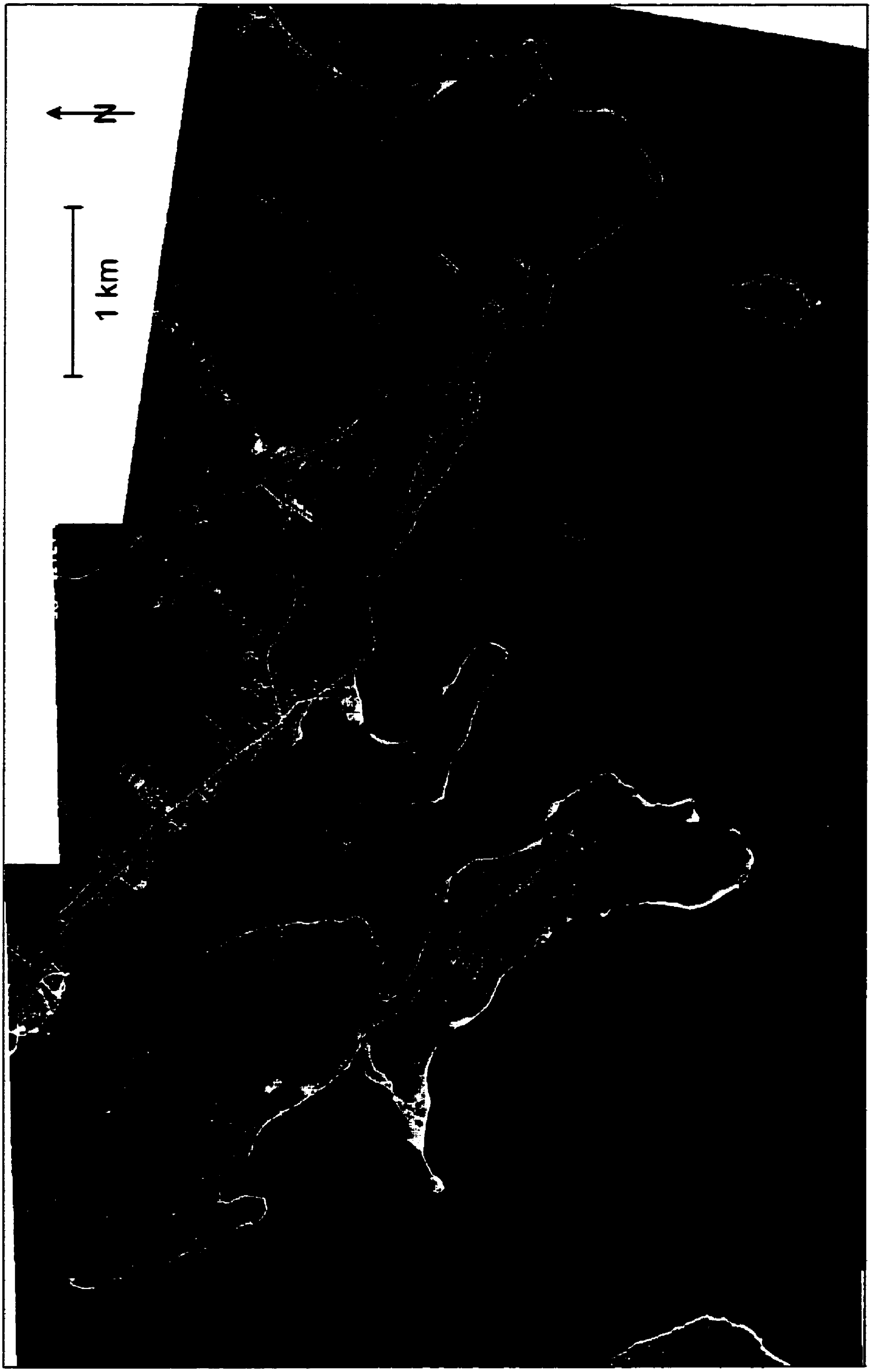


Figure 4.2m Airphoto mosaic from 1960.

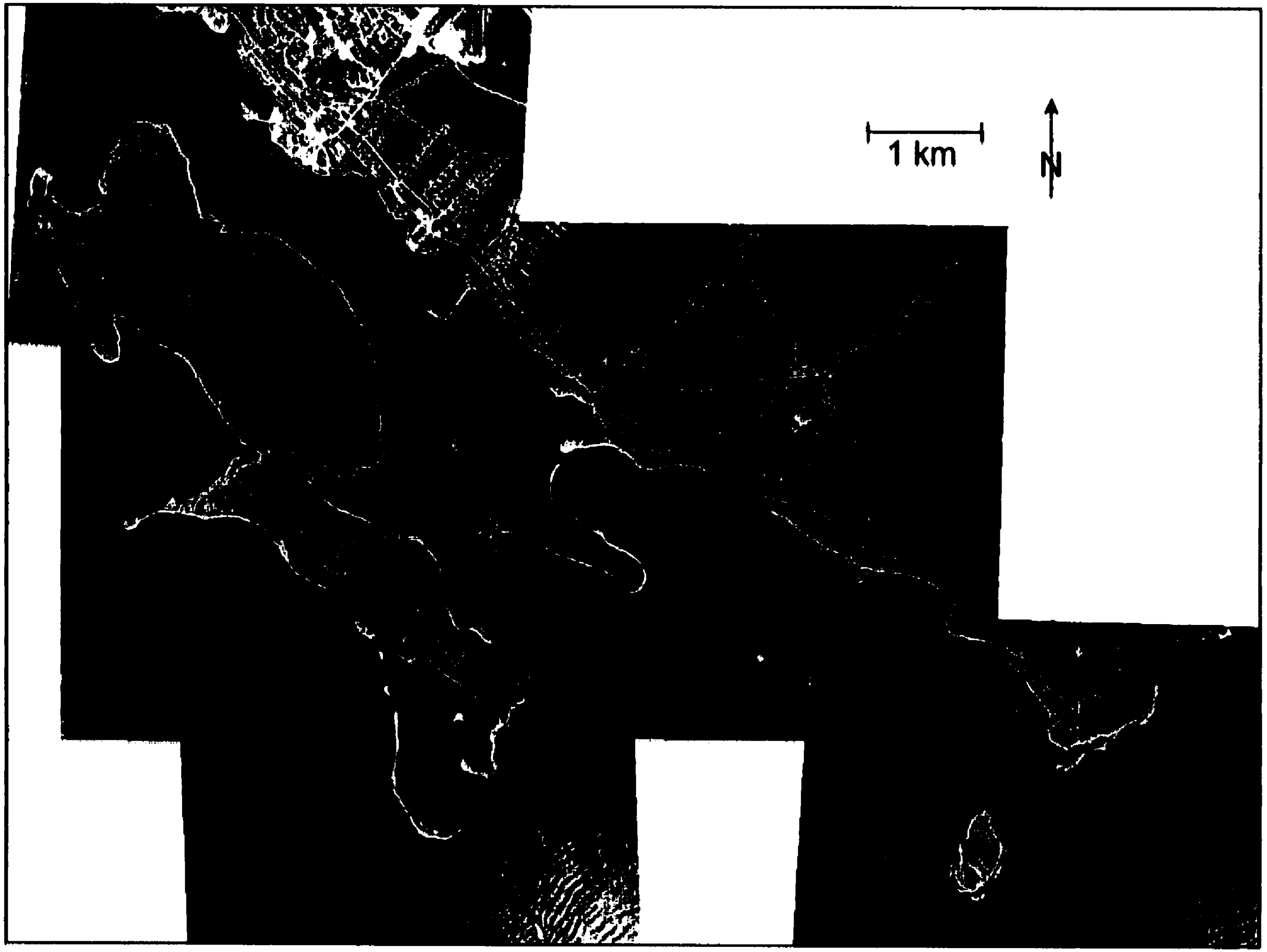


Figure 4.2n Airphoto mosaic from 1966.

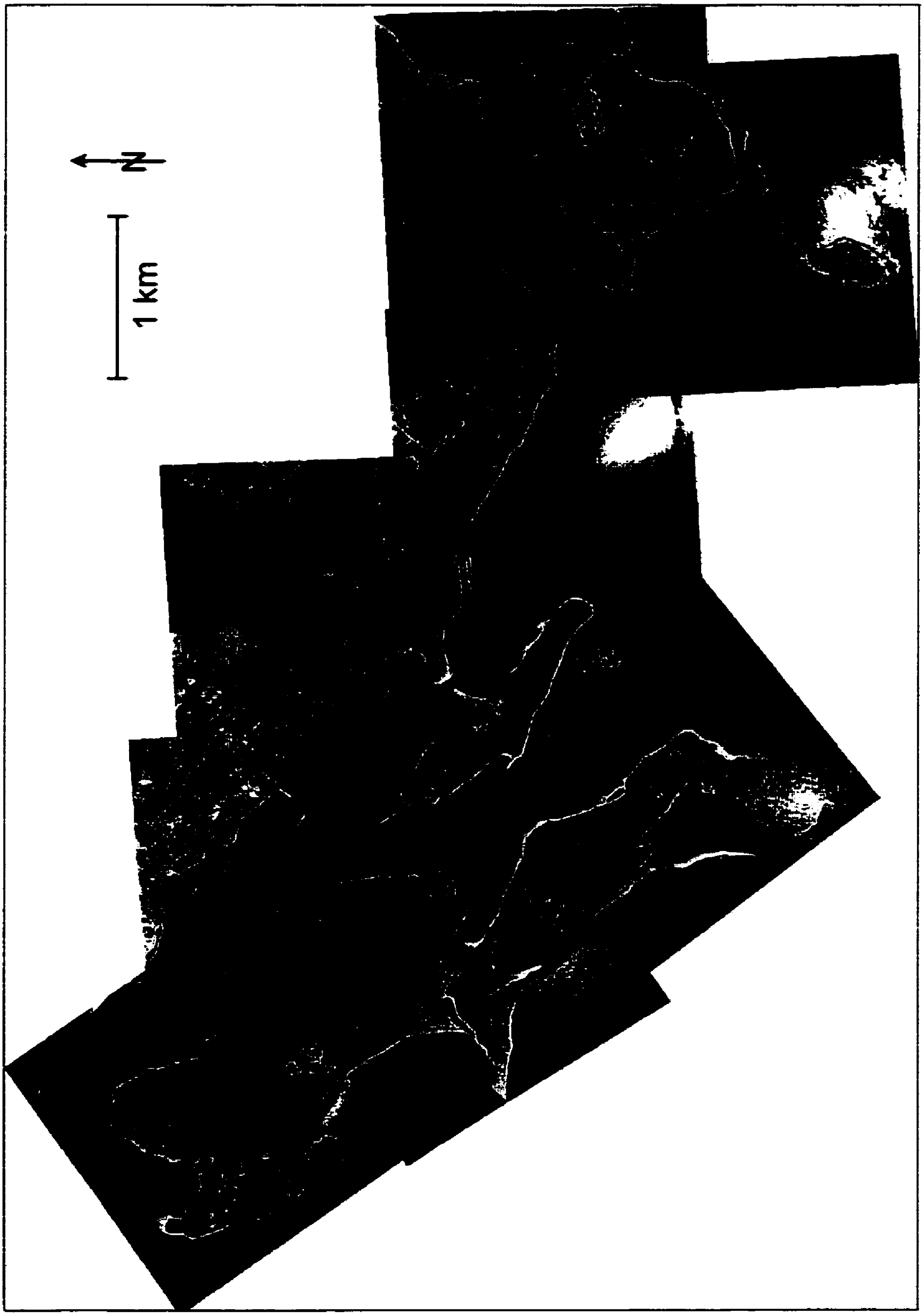


Figure 4.2o Airphoto mosaic from 1982.

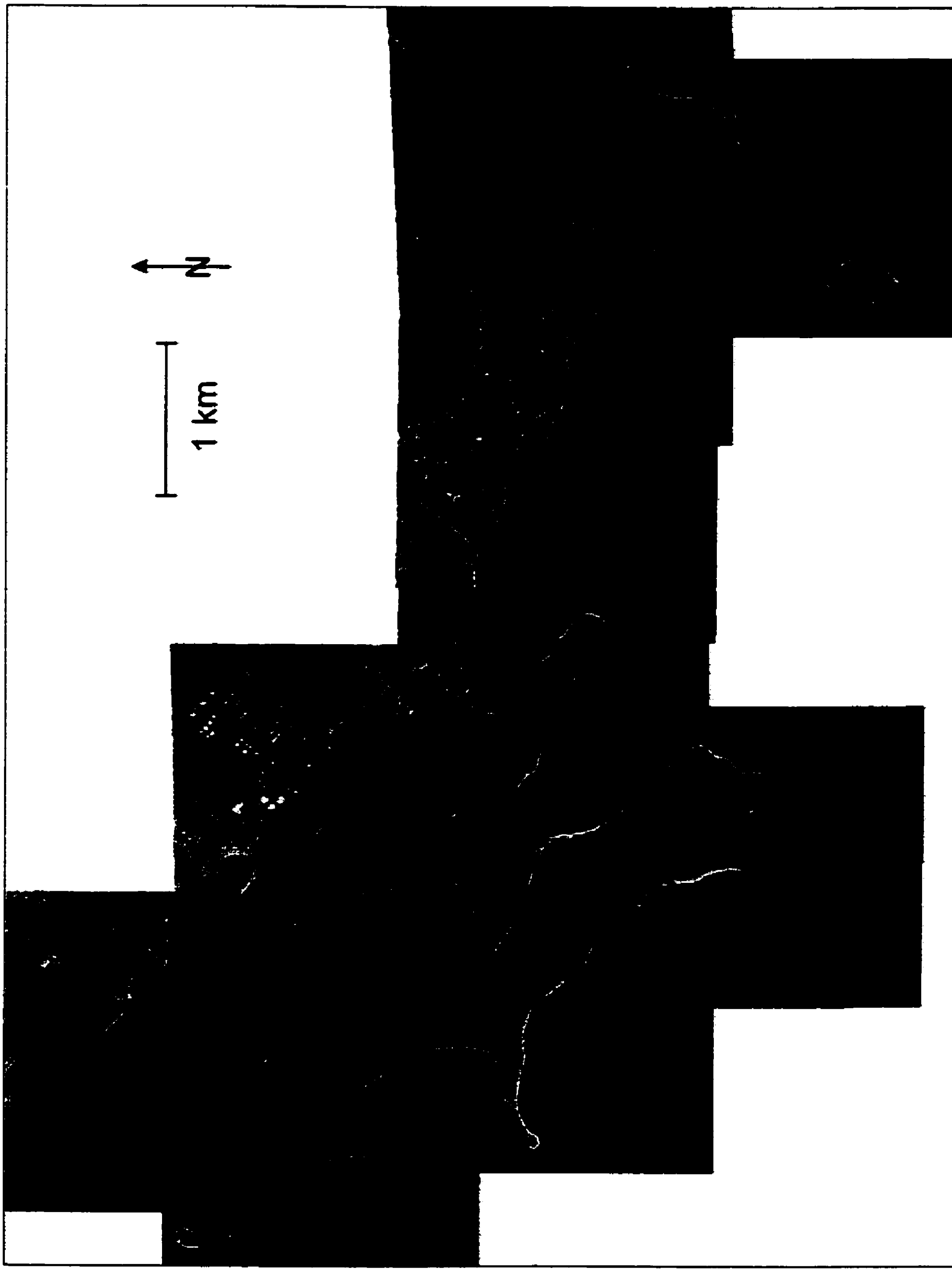


Figure 4.2p Airphoto mosaic from 1992.

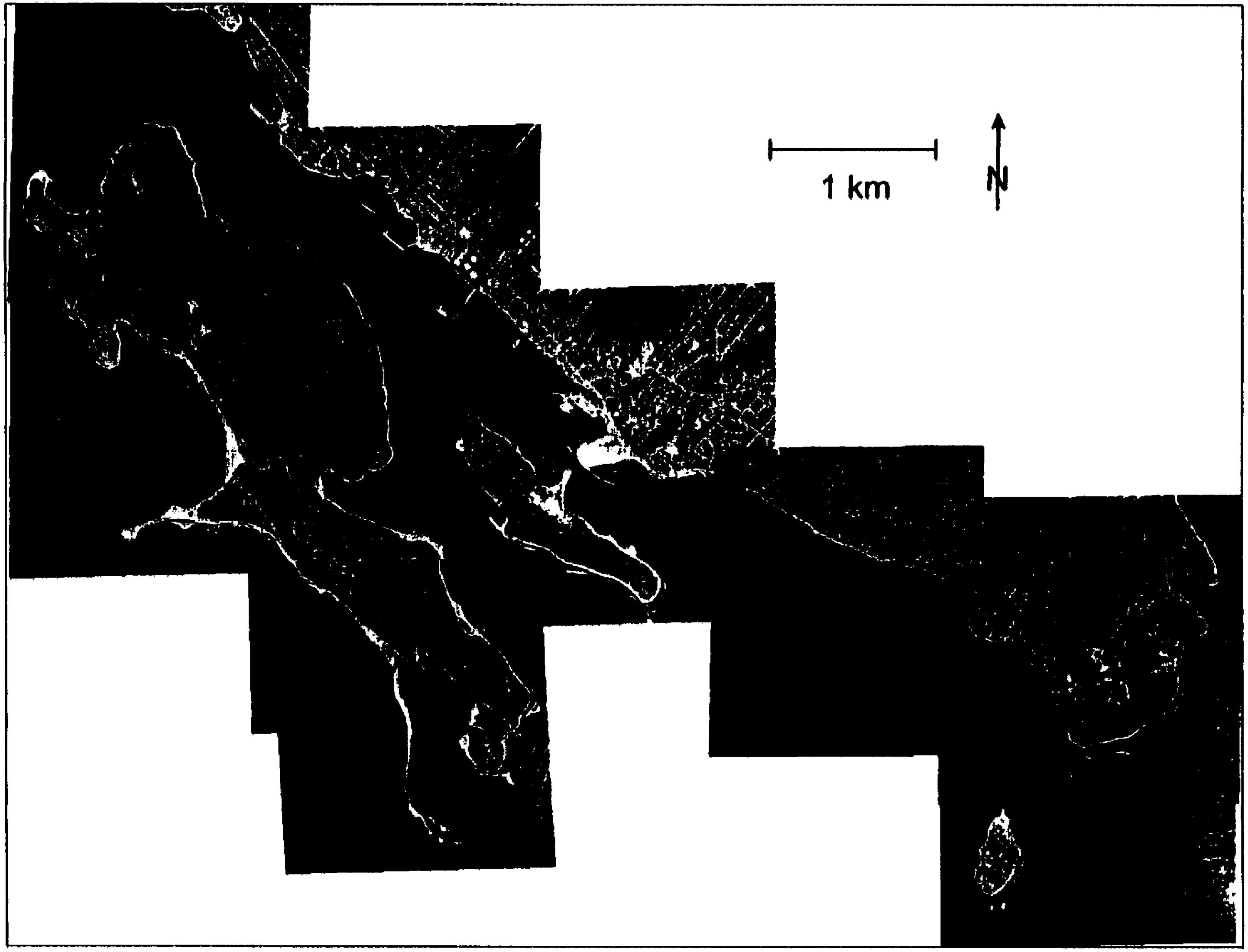


Figure 4.2q Airphoto mosaic from 1997.

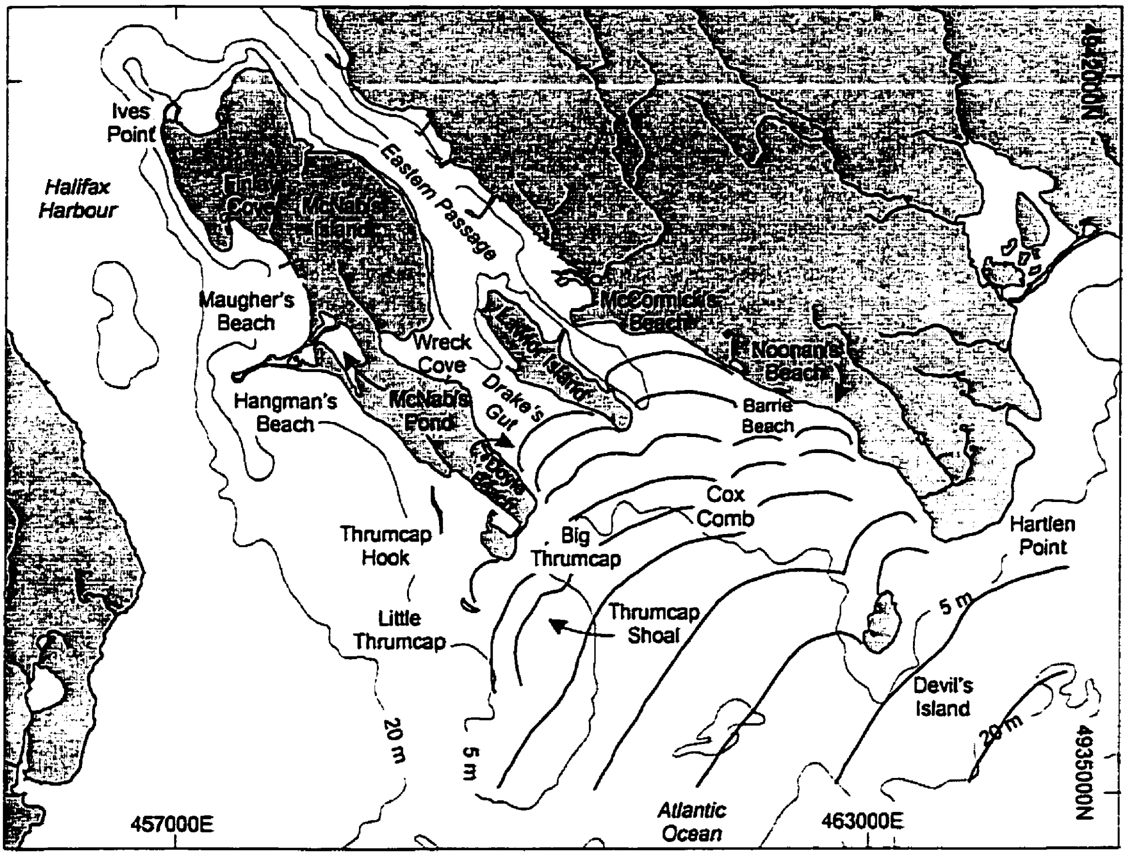


Figure 4.3 Crests of selected waves digitized from 1960 airphotos. The wave period is uncertain but is approximately 10 s from the southeast. Significant diffraction and refraction occur around Devil's Island and in the Barrie Beach area. The 5 m and 20 m bathymetric contours are also shown.

geomorphologic use. Soundings in Eastern Passage indicate depths of 3 fathoms (5.4 m).

4.3.2 1711 to 1758/59

Better quality charts are available from 1758 and 1759 (Cook, 1758; Morris and Jeffries, 1759) (Figures 4.2b and c) which are in good agreement with each other although some collaboration between surveyors or engravers is likely. These charts show an island over Thrumcap Shoal connected to Little Thrumcap, and Big Thrumcap as a much larger feature than present (Figure 4.3). Thrumcap Hook extended south from McNab's Island and was separated from Little Thrumcap by a tidal channel. Hangman's Beach was also bisected by a tidal channel. McNab's Cove was open to the harbour as Maugher's Beach, in its current form, was not present. Local stony beaches were present at Thrumcap Shoal and Cox Comb, and Doyle Beach stretched northwest from Doyle Point. Depths are shown as 6 feet (1.8 m) in Drakes Gut and 3 fathoms (5.4 m) in Eastern Passage. The Gap between Devil's Island and Hartlen Point was partially blocked by a curved bar with depths less than 1.8 m (1 fathom). Two shoals north of McNab's Island are shown to have been dry at low water. Lawlor Island shows protrusions, likely beaches, on the east and west sides. Cox Comb was surrounded by a stony beach (Barrie Beach) and connected to the mainland by a sand flat that was dry at low water. A prominent embayment immediately south of Cox Comb was also dry at low water.

4.3.3 1758/59 to 1776

While the most elaborate of the early charts, a 1776 chart (Des Barres, 1776) (Figure 4.2d), is of somewhat doubtful quality. Large changes are shown at Thrumcap Shoal where the land mass appears to have been eroded and Thrumcap Hook became connected to Little Thrumcap. Bluffs are shown at Doyle Point (then a rounded headland), at Little Thrumcap and at Big Thrumcap. Barrie Beach became an irregular form with two drift-aligned spits extending east towards a small tombolo on the mainland.

4.3.4 1776 to 1853

Maps of the Hangman's Beach area from ca. 1830 show submerged spits to the north and south of the beach marking a healed washover breach (Toler, 1826; Anon., ca. 1830) (Figure 4.2e) but do not depict the rest of McNab's Island. A chart from 1853 (Bayfield, 1853) (Figure 4.2f) shows the whole of Halifax Harbour and is considered the first reliable chart of the area. It shows two transverse ridges connected to a sizable barrier joining Little and Big Thrumcap: one transverse ridge was anchored to Thrumcap Shoal and the other to a shoal southeast of Big Thrumcap. Thrumcap Hook was cut near Little Thrumcap by a tidal channel and enclosed a large lagoon. Little Thrumcap had eroded considerably since 1776 and Big Thrumcap had evolved to an asymmetric needle-like promontory. In Drakes Gut a curved bar is shown between the northern end of Doyle Beach and a prominent triangular pad (*cf.* Carter et al., 1990) with a small beach separated from Lawlor Island near the present location of the spit at Sandy Cove. A round shoal, known locally as The Stone Pony, is shown east of Doyle Point. A second narrow barrier in Drake's Gut encloses a long, narrow lagoon in Green Hill Cove. Hangman's Beach appears to have grown somewhat since 1776 resulting in the narrowing of a tidal channel, and significant sand deposition had occurred partially enclosing the entrance to McNab's Cove (now McNab's Pond). A third spit extended toward the entrance to McNab's Cove. At Ives Point, a drift-aligned spit extended from the shore and recurved to the east. The north and northeast shorelines of McNab's and Lawlor Islands were stable and continue to show no major changes at any time up to 1999. The first record of beach mining is from this period as 'large quantities of ballast stone were sold annually' from McNab's Island (*Novascotian*, 1849) although it is not known from which beach these were removed.

Barrie Beach had evolved by 1853 to a well-developed double trailing spit with both drift- and swash-aligned sections almost in contact with the mainland and a single tombolo. The prominent embayment to the southeast continued to have few beach deposits. Some beach development occurred at Eastern Passage between 1776 and 1853 at the current location of Fisherman's Wharf. The Gap between Devil's Island and Hartlen Point was shallow with a shoal and three triangular pads present on the Hartlen Point side.

4.3.5 1853 to 1867

A detailed survey of the southern end of McNab's Island conducted in 1867 (Rowe, 1867) (Figure 4.2g) shows Doyle Beach as an irregular complex barrier cut by a wide tidal channel. The barrier partially enclosed a large lagoon and an inner half-ovoid ness (*cf.* Orford et al., 1991) enclosing a small lagoon. The rapid transition from a long contiguous barrier to an irregular dissected beach of odd appearance occurred over less than 14 years and may represent expansion of the previously mentioned ballast mining operation to supply 'a splendid brickworks' built at Eastern Passage in 1855 (*British North American*, 1855). Additionally, significant construction of roads and buildings was also occurring on McNab's Island at this time.

Small lagoons were enclosed by barriers at Green Hill Cove and also to the northwest at the mouth of Wreck Cove. The barrier connecting Big Thrumcap and Little Thrumcap was cut by tidal channels at either end of Little Thrumcap and tidal channels exposed at low tide were also present at the north end of Thrumcap Hook. Little Thrumcap is shown as 11.0 m (36') high at the bluff edge, ~60 m wide, and the bluff face was ~250 m long. Hangman's Beach was cut by two tidal channels: a large one at the central beach, and a smaller one exposed at low tide at the western end of the beach. A small spit is also shown extending into Finlay Cove, northwest of McNab's Cove.

4.3.6 1867 to 1914/15

Barrie Beach, shown on a chart from 1886 (Akers, 1886) (Figure 4.2h), was very similar in form to 1853. Changes since 1853 to the tombolo connected to the mainland may indicate mining activity. A building is indicated on the tombolo. Negligible beach deposits are shown in the adjacent embayment.

The Perambulation Plan for McNab's Island (War Department, 1915) (Figure 4.2i) does not show many changes from 1867 but is useful in conjunction with photos taken in 1914 by J. W. Goldthwait of the Geological Survey of Canada. The northwestern portion of Doyle Beach extended into a spit almost enclosing a large lagoon and the tidal channel separating the two portions of Doyle Beach had narrowed. A gentle promontory near the present location of M13 appears to have been eroded since 1867 and a photo by Goldthwait (1914a) (Figure 4.4a) shows the low eroding tail of a bluff. Big Thrumcap had not changed appreciably since 1867 and the same photo shows a vegetated inactive bluff on the east side of the drumlin well protected by a fringing gravel barrier. Dunn's Beach is also shown to have been very similar in appearance to its present form. Little

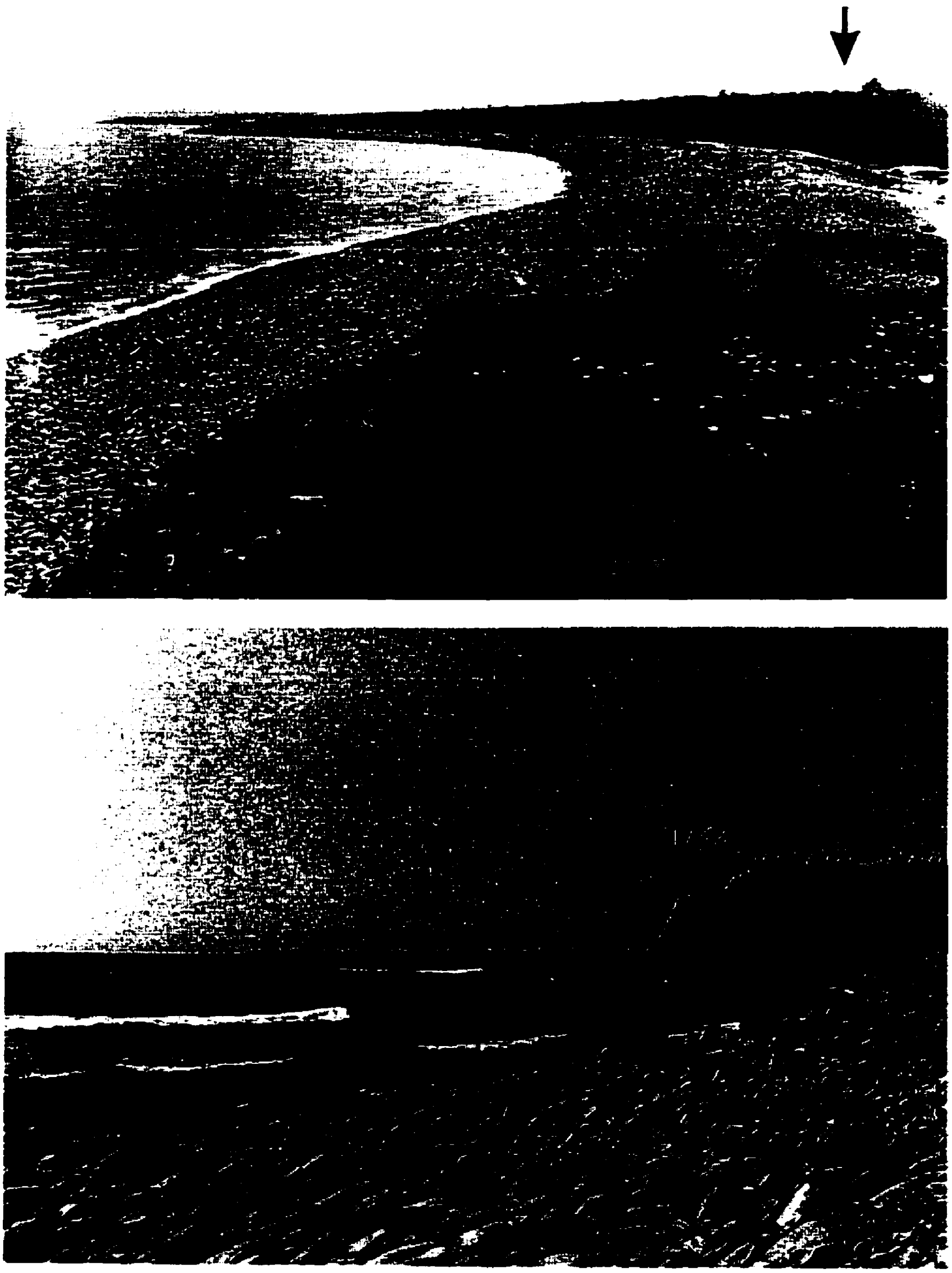


Figure 4.4a (Top) 1914 photo of Dunn's Beach taken from near M13 (Goldthwait, 1914a) with Big Thrumcap in background. Note the large beach fronting Big Thrumcap and the absence of active bluffs. Arrow indicates approximate current bluff edge. (Bottom) A 1998 photo of Big Thrumcap showing bluff and steep, cusped face of Dunn's Beach. Line M14 is shown. Note surf breaking on the shore platform seaward of Big Thrumcap.

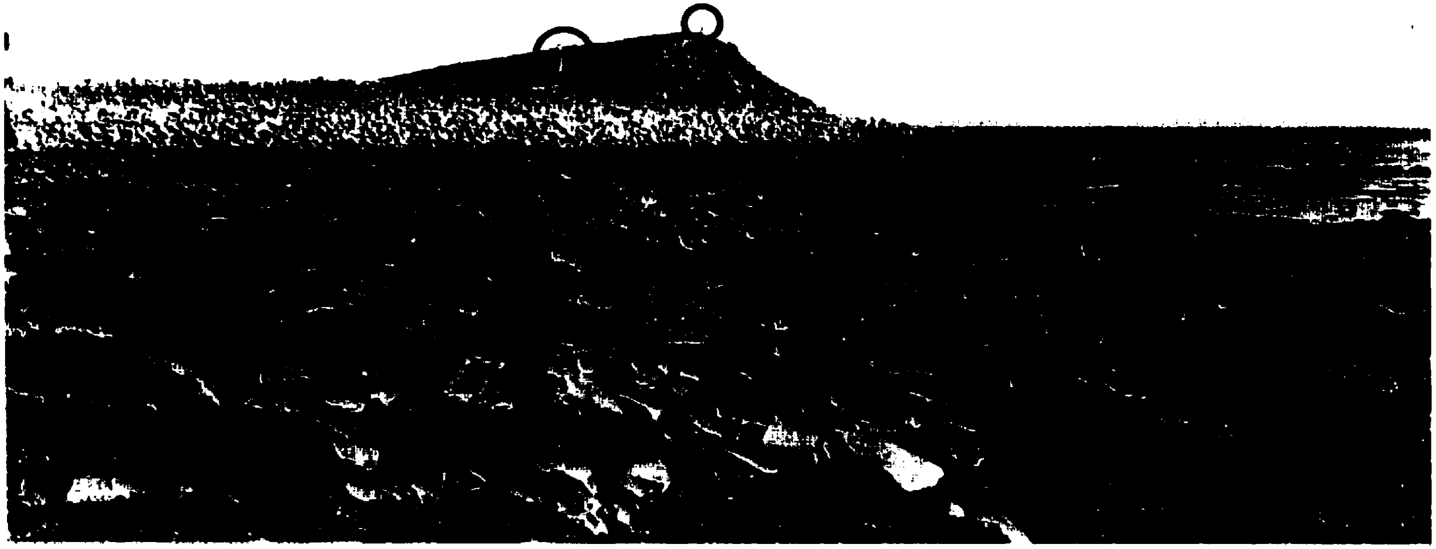


Figure 4.4b A 1914 photo of Little Thrumcap. Approximate scale is indicated by what appears to be a ~1.5 m broom set upright and a perched bird (circles).

Thrumcap was approximately 3 m high and 25 m wide (Goldthwait, 1914b) (Figure 4.4b) indicating 35 m of retreat (a rate of 0.75 m/a) since 1867. The bluff length in 1914 was unknown as the photographic and map evidence do not match well (the 1915 map overestimates the size of Little Thrumcap and shows no retreat since 1867). If constant length and height since 1867 are assumed, by 1914 retreat of Little Thrumcap delivered $96*10^3$ m^3 of total sediment and, assuming an average grain size for the Lawrencetown Till clay facies (Section 2.3), $16*10^3$ m^3 of gravel and coarser sediment. These are overestimates as the photographic evidence clearly indicates lowering and shortening of the bluff face.

Hangman's Beach was shown by Goldthwait (1914c) (Figure 4.3c) to be a wide gently sloping cobble beach with sandy sections. The smaller channel at Hangman's Beach and the entrance to McNab's Cove in the present location of Maugher's Beach were at least partially closed by a causeway serving a lighthouse and Martello Tower at the western end of the beach. Likewise a causeway was constructed between 1867 and 1915 from Ives Point to the end of the drift-aligned spit and fully enclosed a small lagoon.

4.3.7 1914/15 to 1934

The first partial airphoto coverage of McNab's and Lawlor Islands from 1934 shows Doyle Beach not cut by tidal channels enclosing a lagoon (Figure 4.2j). The spit previously extending to the northwest appears to have submerged since 1915 and a wide, short spit developed in its place. A washover lobe had extended since 1867 into Green Hill Cove from the enclosing barrier. A spit extending west into Drake's Gut from Lawlor Island had grown since 1853. Big Thrumcap does not appear to have changed shape since 1915 but Thrumcap Hook and Little Thrumcap are not visible due to photo

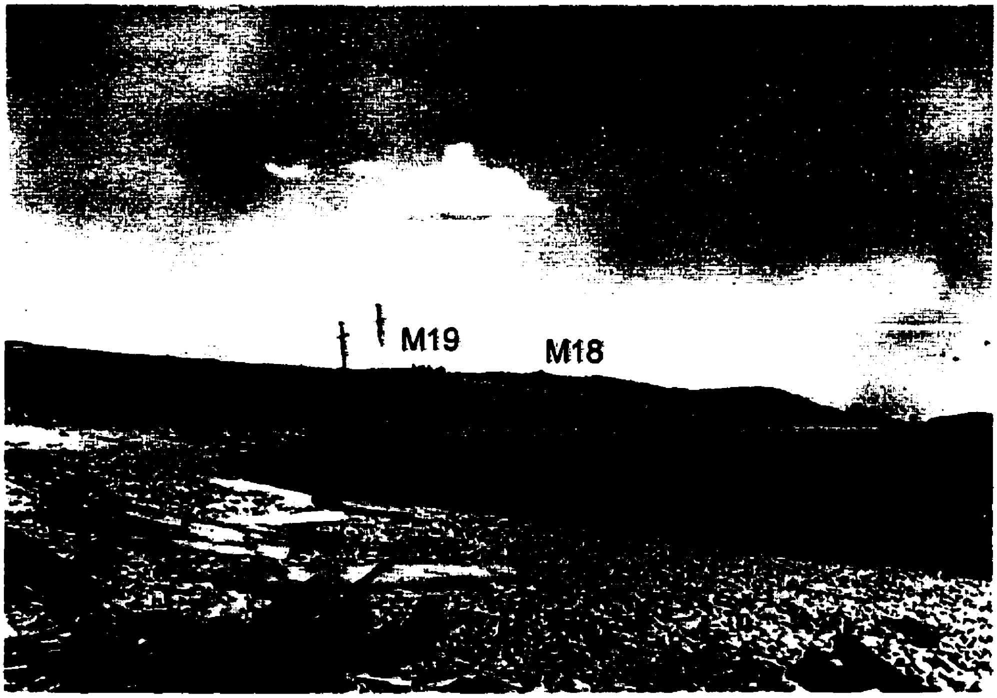


Figure 4.4c (Top) 1914 photo of Hangman's Beach and the Strawberry Battery Section. The approximate locations of lines M18 and M19 are shown. Note the gently sloping sandy cobble beach (Goldthwait, 1914c). (Bottom) The Strawberry Battery Section in 1998. Note the steeper beachface and protruding ships timbers and planks. The bluffs have decreased in elevation but are otherwise of similar morphology to 1914. Hartlen Till is exposed to the left of M19 at the bluff toe.

saturation. Overwash lobes infilled the main tidal channel through Hangman's Beach and sand bars developed in McNab's Cove at the eastern end of Maugher's Beach causeway. The small spit in Finlay Cove had grown to enclose a small lagoon.

4.3.8 1934 to 1945

Air photographs from 1945 (Figure 4.2k) show that, since 1886 (the previous chart showing Eastern Passage), sand flats accumulated at the position of present McCormick's Beach, narrowing the channel in Eastern Passage. Sand accumulation was likely assisted by a line of piles (shown as a dark line on Figure 4.2k) which 'blocked' Eastern Passage (*Morning Chronicle*, 1914) between McCormick's Beach and Lawlor Island as part of the wartime defences of Halifax Harbour. The line of piles at Eastern Passage remained after World War 1. Barrie Beach was submerged due to removal of sediment to construct the Hydrostone Properties and other parts of Halifax following the Halifax Explosion in 1917 (Clarke, 1994; Ross, 1920). A hydrostone plant was built on site in Eastern Passage in early 1918 and produced 3500 to 4000 partially hollow hydrostone blocks per day each weighing approximately 35 kg and of dimensions 23 cm by 23 cm by 60 cm (Ross, 1920). Noonan's Beach, a prograded pocket beach approximately 1.1 km long, formed in the embayment to the southeast of Barrie Beach and was actively being mined in 1945 for materials to, among other purposes, extend the airfield at CFB Shearwater. The sand flats at McCormick's Beach had accumulated sediment since 1934 and McCormick's Beach began to form at the eastern end of the line of piles. The beach at Fisherman's Wharf was eroded and may also have been mined for construction materials.

Doyle Beach had again extended into a drift-aligned barrier partially enclosing a lagoon and was very similar in morphology to 1759. Small rounded shoals behind the barrier mark the distal termini of former spits. Retreat and sediment delivery from the Wreck section stopped as a slump block at M1 became inactive. The small barrier enclosing Green Hill Cove breached, significantly infilling the cove. Between 1934 and 1945, $14.3*10^3$ m^3 of sediment was released by eroding bluffs from Doyle Point and $6.8*10^3$ m^3 from the West Gut section, of which $3.0*10^3$ m^3 and $1.2*10^3$ m^3 respectively was gravel-size and coarser. The amount of sediment delivered by retreat on Lawlor Island is unknown as the 1934 airphotos do not extend far enough east; the spit at Sandy Cove extended northwest and a ness was formed on the east side of the island. A line of piles between this spit and Doyle Beach, placed to prevent submarines from entering the harbour, is visible on the 1945 airphotos. It is not likely that a line of piles was placed in Drake's Gut during World War 1; no piles are shown on the Perambulation Plan (War Department, 1915) or the 1934 airphotos.

Retreat of Big Thrumcap delivered $0.6*10^3$ m^3 of gravel and coarser sediment from Line M14 and a breach was formed at the southern end of Thrumcap Hook. Tidal channels on either side of Little Thrumcap infilled. McNab's Cove continued to infill and sediment began to accumulate at Maugher's Beach as an eastward migrating ness-like feature.

4.3.9 1945 to 1954

Between 1945 and 1954 Doyle Beach was again mined for unknown purposes resulting in complete submergence of the barrier (Figure 4.21). A vegetated ness present since 1867 began to migrate downdrift to the northwest and another formed in front of

M9. The breach in the barrier enclosing Green Hill Cove infilled. Following submergence of Doyle Beach, retreat rates and volume of sediment delivered from the Green Hill section initially increased while retreat and volumes from the West Gut section did not change significantly. Retreat and volume supplied from the Doyle Point section peaked immediately following beach mining; a total of $42.1*10^3$ m^3 of sediment was delivered of which $8.9*10^3$ m^3 was gravel or coarser. Barrie Beach continued to erode after 1945 and Noonan's Beach, with continuing mining, developed several 70 m long washover lobes. McCormick's Beach prograded over the adjacent sand flats rapidly during this time, assisted by trapping of sand by the line of piles. A total of $14.1*10^3$ m^3 of sediment was delivered from retreat of the Lawlor Point section, of which $2.5*10^3$ m^3 was gravel and coarser and $0.8*10^3$ m^3 was sand. The spit at Sandy Cove appears to have been eroded during this period when the East Gut section delivered no significant sediment. No significant volume was delivered from Big Thrumcap either, and little change occurred at Thrumcap Hook; the breach at the southern end may have widened and Little Thrumcap eroded moderately. A spit at Maugher's Beach prograded east towards the entrance to McNab's Cove and a beach formed across Finlay Cove enclosing a second lagoon.

4.3.10 1954 to 1966

An airphoto mosaic is given from 1960 (Figure 4.2m) but due to the small scale of the airphotos, the unusually high tide at the time of imaging, and the short time interval since the 1954 airphotos, there is little discernible change. Continuing erosion where Barrie Beach formerly connected to the mainland necessitated moving a shore-parallel road landward. The tidal channel at the south end of Thrumcap Hook grew and an additional washover channel formed.

By 1966 mining at Noonan's Beach was discontinued, leaving a narrow beach fronting till bluffs (Figure 4.2n). McCormick's Beach extended northwest and west, further narrowing the channel at Eastern Passage, and was eroded at its eastern end adjacent to the mainland, apparently developing a high seaward crest. Sediment delivered at the Lawlor Point section increased to total $46.5*10^3$ m^3 of which $8.3*10^3$ m^3 was gravel or coarser; no significant change occurred on the east side of Lawlor Island but the spit at Sandy Cove continued to erode despite a total sediment supply of $35.4*10^3$ m^3, of which $9.5*10^3$ m^3 was gravel or coarser, delivered as retreat of the East Gut section peaked.

Sediment delivered from Doyle Point totaled $6.6*10^3$ m^3, of which $1.4*10^3$ m^3 was gravel or coarser, whereas that from the West Gut section totaled $17.3*10^3$ m^3, of which $3.0*10^3$ m^3 was gravel or coarser. Retreat increased at the West Gut section in response to the northwest migration of nesses that previously protected the bluff. The two nesses merged in front of the Green Hill section, stopping significant retreat and sediment delivery. Big Thrumcap changed dramatically between 1954 and 1966, most of which occurred after 1960, resulting in rounding of the former promontory. Retreat at M14 and M15A delivered $14.2*10^3$ m^3 of sediment of which $3.6*10^3$ m^3 was gravel or coarser. A ness formed fronting M15B and a spit trailing Big Thrumcap began to prograde across the entrance to the inner cove behind Dunn's Beach. After 1960, the tidal channel and washover channel at the south end of Thrumcap Hook merged and widened and Little Thrumcap eroded considerably. A prominent washover breach formed between the north end of Thrumcap Hook and Little Thrumcap. Little change occurred at Maugher's Beach except the causeway across the tidal inlet to McNab's Cove was widened and blocked the tidal channel, preventing circulation into McNab's Cove.

4.3.11 1966 to 1982

Small scale airphotos exist from 1973 but, for the same reasons as the 1960 airphotos, they will not be discussed except that by 1973 sand accreted seaward of the causeway across the entrance to former McNab's Cove, which at this time became McNab's Pond. As shown by an airphoto mosaic from 1982, change at former Barrie Beach and Noonan's Beach decelerated after 1966 in part due to the placing of rip-rap boulders along sections of the shoreline prior to 1982 (Figure 4.2o), however bluff retreat appears on airphotos to have increased downdrift to the northwest of protected areas. Seaward progradation of McCormick's Beach occurred between 1966 and 1982, significantly widening the beach. Retreat at the Lawlor Point section peaked between 1966 and 1982 and delivered $54.7*10^3$ m^3 of total sediment, of which $9.8*10^3$ m^3 was gravel or coarser, and $17.9*10^3$ m^3 was sand. A second ness developed on the east side of Lawlor Island adjacent to Lawlor Point. The East Gut section delivered a total of $3.8*10^3$ m^3, of which $2.7*10^3$ m^3 was gravel or coarser, and the spit at Sandy Cove extended northwest. The ness fronting the Green Hill section extended into an outer barrier seaward of the existing beach ridge at Green Hill Cove and enclosed a second lagoon. Retreat at the Green Hill section delivered no significant sediment during this time but $20.6*10^3$ m^3 was delivered by the West Gut section and $14.8*10^3$ m^3 by the Doyle section, of which $3.5*10^3$ m^3 and $3.1*10^3$ m^3 respectively was gravel or coarser.

Sediment delivery from the Wreck section peaked as retreat accelerated between 1966 and 1982 and delivered a total of $21.1*10^3$ m^3 of which $2.8*10^3$ m^3 was gravel or coarser. A second small ness formed near the entrance to Wreck Cove while the one already present grew. Big Thrumcap continued to become more rounded and a ness migrated northward contributing sediment to the prograding trailing spit. Sediment volume delivered by bluff retreat at M15A and M15B reached a maximum during this period of $28.7*10^3$ m^3, of which $6.5*10^3$ m^3 was gravel or coarser. Little Thrumcap was completely eroded by 1973 and, using bluff measurements from Goldthwait (1914b) (Figure 4.3b) and average clay facies grain sizes, it contributed approximately $7*10^3$ m^3 of sediment of which approximately $1*10^3$ m^3 was gravel or coarser. Retreat has occurred at a rate of approximately 0.4 m/a since 1914. A crescentic boulder lag shoal remains in 1999. Erosion continued at the south end of Thrumcap Hook, submerging the remaining beach south of Little Thrumcap. Some landward migration of sediment occurred toward the drift-aligned northern section of Thrumcap Hook before 1973 and by 1982 had partially infilled the previously long-lived tidal channels. The beach crest appears to have increased in elevation.

Historic echosounding profiles over Thrumcap Shoal, which is capped by a cobble-boulder lag deposit, show that little erosion occurred between 1950 and 1979 except at the shallowest portion where likely beach deposits were eroded. Maugher's Beach continued to accrete sand between 1973 and 1982.

4.3.12 1982 to 1992

The period between 1982 and 1992 (Figure 4.2p) was characterised by general decreases in retreat, sediment delivery, and coastal change. Bluff retreat continued northwest of former Barrie Beach, necessitating the placement of more rip-rap boulders in unprotected areas, however no significant sediment was delivered by the East Gut, Lawlor Point, and West Gut sections. The spit at Sandy Cove extended further northwest. The Green Hill section showed a minor increase in sediment delivery but the bluff was inactive and revegetated by 1992. Big Thrumcap continued to retreat at a decelerating rate and delivered $17.5*10^3$ m^3, of which $3.8*10^3$ m^3 was gravel and coarser. Only minor changes occurred to the ness and the spit did not appear to prograde significantly. Except for slow continuing retreat at its seaward end, little change occurred at Thrumcap Hook after 1982.

4.3.13 1992 to 1997

The period from 1992 to 1997 (Figure 4.2q) likewise was characterised by little coastal change; all sections show sediment delivery measured from airphotos not significantly different from zero and retreat underwent a general decline with the exception of M1 and M14 and lines at the Fort McNab's/Strawberry Hill section.

4.3.14 1997 to 1999

Coastal changes between 1997 and 1999 are discussed in detail in Chapter 3 and are characterised by an acceleration in coastal change in contrast to the period 1982 to 1997. Due to the large error associated with measurements from airphotos between 1992 and 1997, volume increase is not statistically significant at any survey lines and increasing retreat rate is only significant at lines M2, M5, M6, M11, all lines at Big Thrumcap, and L4. M19 shows a significant decrease in retreat rate.

Echosounding conducted in 1998 and 1999 shows significant vertical erosion when compared with a 1964 CHS fieldsheet (CHS, 1964). Since 1964 at Barrie Beach

(Figure 2.12), up to 2 m vertical erosion between the two beach crests accompanied by up to 50 m downdrift (NW) movement and 1.5 m lowering of the northwestern crest is apparent while, at the southeastern crest, up to 1 m of vertical erosion with little migration occurred. Erosion over a bedrock outcrop charted on the 1964 field sheet is negligible and some deposition appears to have occurred in the lee of this obstruction. At Thrumcap Shoal, erosion greatly increased between 1979 and 1999 (Figure 2.13). Two profiles from the shallowest part of the shoal show up to 3 m of vertical erosion but less at shallow depths. Narrowing of the shoal or trailing transverse ridge occurred at Line 2.

Figure 4.5 is a 1998 Knudsen echosounder trace showing a submerged prism-shaped feature with a steep seaward face and more gently sloping landward face in 7.8-9.5 m water depth seaward of Dunn's Beach and Big Thrumcap. This structure is interpreted as an overstepped beach form but this has not been confirmed in the field. At the extreme northwest end of the trace, hummocky, eroded, estuarine or lagoonal muds have been observed in 6 m water depth. This unit was investigated by SCUBA and is sandy mud containing rare sub-angular cobbles interpreted to be ice-rafted from an adjacent beach and wood and shell debris. Penetration of the 28 kHz signal can be observed in muddy units and also adjacent to the beach structure, possibly indicating additional lagoonal or estuarine facies associated with this submerged beach form.

4.3.15 Summary

The evolution of the study area prior to approximately 1853 is characterised by little apparent erosion but slow beach development (*e.g.* Barrie Beach, Thrumcap Hook). After 1853, mainly due to mining of beach material, coastal change accelerated and was characterised by rapid changes in beaches (*e.g.* Doyle Beach, Barrie Beach, and Noonan's

Beach), often resulting in complete beach submergence and accelerated bluff retreat in adjacent areas, in particular at the West Gut and Green Hill sections and at Barrie Beach. Pronounced maximum rates of bluff retreat and sediment delivery were reached between 1954 and 1966 at a number of locations (*e.g.* the Green Hill, West Gut, Lawlor Point, and East Gut sections). This corresponds both to a period of intensive mining of a number of beaches in the study area and, as will be discussed in Chapter 5, a marked period of increased storminess (Figure 2.18) and rapid sea-level rise (Figure 2.20). Reorganization of beaches followed mining, resulting in submergence and subsequent formation of new beaches at a more landward location. The main beaches to form during this period were large sandy gravel beaches (*e.g.* Maugher's Beach, McCormick's Beach) and a number of short-lived nesses that extended into spits (*e.g.* the spits at Sandy Cove and Green Hill Cove).

4.4 Discussion

Although historical changes in the study area are partly related to beach mining and are not therefore natural, the movement of sediment after mining occurs rapidly and results in obvious morphologic changes easily observable on airphotos. Investigation of these movements and changes may help elucidate the role of overwashed beaches in supplying sediment to prograding beaches and the morphosedimentary links between bluffs and beaches. The formation of several morphologic features of drumlin shorelines may also be explained.

The relationship of bluff retreat and beach formation is apparent in certain locations. Notable examples are nesses that form in response to accelerated bluff retreat following destruction of protective beaches at Drake's Gut, Lawlor Point, Big Thrumcap, and the Wreck section. These each correspond to local releases of more than 3000 m^3 of gravel and coarser sediment between successive airphotos. Due to interactions of the newly delivered sediment with the incident wave field (Figure 3.3, Figure 4.3) and the pre-existing morphodynamic cell structure, nesses may migrate rapidly downdrift. Between 1954 and 1966 a ness in Drake's Gut migrated downdrift at rates up to 20 m/a. When a migrating ness encounters a low-energy embayment the ness may stretch across the embayment as a spit and enclose a lagoon (*e.g.* Green Hill Cove). Drift-aligned spits initially prograde rapidly over shallows, but slow when they prograde into deep water (Ruz *et al.*, 1992). Doyle Beach and the spit at Sandy Cove have been through several cycles of progradation and destruction. Each progradation contributes sediment which may be spread over a flat cobble lag area as the spit is destroyed; the next cycle of progradation initially occurs quickly and then slows as the spit extends off the flat area into deeper water. The spit at Sandy Cove initially extended quickly over a cobble-boulder pad from 1966 to 1992 but has since slowed. Although reduced supply of sediment as bluff retreat decelerated after 1982 may contribute to decelerating progradation, the distal end of the spit also slopes steeply into water depths up to 9 m.

Curved bars in inter-drumlin channels between islands represent the overwashed remains of barrier beaches (Carter and Orford, 1988). If the channel is shallow relative to its width and sediment supply plentiful, spits extending from adjacent headlands may join forming a swash-aligned barrier. Curved bars are morphologically associated with triangular pads and both occur at the shallowest point in Drake's Gut and in The Gap between Devil's Island and Hartlen Point. Pads appear to represent the former point of connection of a barrier to a drumlin flank and may indicate an area of past, and perhaps repeated, spit and beach formation and destruction.

In the same manner that beach growth over annual and sub-annual scales protects bluffs and slows retreat and erosion rates (Chapter 3), ness formation and migration results in the variability in decadal retreat rates at bluffs, as shown by examples from Drakes Gut between 1954 and 1966 (Manson, 1999). Nesses cause the opposite effect of ords, sediment deficiencies in the nearshore promoting bluff erosion (Pringle, 1985). Ords can vary in length from 250 to 2000 m and are much larger than the 5 to 50 m long exposures of till foreshores in the McNab's Island area, perhaps best referred to as micro-ords, but appear to play a similar morphodynamic role.

Whether bluff retreat accelerates due to the removal of protected beaches or the migration of ords or similar features, sediment delivery from bluffs presents a mechanism for negative feedback and self-regulation of the bluff-beach system. Episodes of retreat produce sediment and build protective beaches, which then slow retreat and result in less sediment delivered. As discussed in Chapter 3, with diminishing retreat, subaerial processes dominate and condition the bluff towards future retreat, resulting in an initial pulse of sediment upon wave attack. On drumlin shorelines where longshore currents readily develop in morphodynamic cells, the locus of sedimentation and feedback migrates, and may contribute to decadal scale cyclicity in retreat rates (*e.g.* the Green Hill section and M14).

Whereas ness formation corresponds to short-lived episodes of accelerated sediment supply, the slower development of major sandy gravel beaches (*e.g.* Maugher's Beach and McCormick's Beach) occurs due to sustained sediment supply. The extent of sand flats formed in the study area in historic time, although volumes are not known, appear too large to have come from bluff retreat, and their development is not correlated with accelerated bluff retreat. The development of McCormick's Beach appears to be accompanied by accelerated retreat of Lawlor Island only from 1966 to 1982, but this occurred after the beach was already well-formed. As no accelerated change is apparent at Hartlen Point either in measured rates (R. Taylor, pers. comm., 1997) or on airphotos, this is also not a significant source.

Barrie Beach and Noonan's Beach show pronounced anthropogenically-induced erosion. Barrie Beach is seen on historical charts from 1759 (Morris and Jeffries, 1759) to 1886 (Rowe, 1886) as a stable feature, but following mining it submerged. Updrift from Barrie Beach, McCormick's Beach began to accrete after 1853, accelerated after 1914 assisted by trapping of sand around a line of piles, and was well established by 1954. Noonan's Beach, directly landward of Barrie Beach, was not present in 1886, but, following mining of Barrie Beach, grew to approximately 1100 m long and 150 m wide and was being mined in 1945. With continued mining, by 1954 washover lobes were deposited and bluff retreat was occurring downdrift to the northwest, forcing (prior to 1960) the relocation of a major shore-parallel road.

Forbes *et al.* (1995a) considered natural susceptibility of a beach to overwash to increase as it grows in height and an open framework ridge develops. Overwash occurs as coincident high wave and tide conditions result in catastrophic destruction of the ridge or crest over a period of hours to days (*e.g.* Green Hill Cove, February 25/1998). Sand removal from Nova Scotia beaches has been shown by Bowen *et al.* (1975) to result in increased susceptibility to erosion and overwash. Following mining, rather than a single and rare event causing catastrophic overwash, more frequently occurring moderate wave and tide conditions may result in breaching of the crest. Rapid lowering of the beach results in submergence and delivery of sediment landward to a location of lower incident wave energy. The formation of Noonan's Beach, McCormick's Beach and the buildup of sand in Eastern Passage are directly related to erosion of Barrie Beach following artificial lowering of the crest and submergence, and subsequent bluff retreat on the mainland side of Eastern Passage southeast of McCormick's Beach. Although charts prior to 1853 show depths of 3 to fathoms (5.5 m) (*e.g.* Delabat, 1711; Morris and Jeffries, 1759), depths of 4.5 fathoms (8.2 m) are shown in Eastern Passage on an 1853 chart (Bayfield, 1853). More recent charts show depths of 7.5 m (CHS, 1929) and 5.5 m (J. P. Porter Co., 1969). Conservative estimates suggest sea level rose approximately 0.3 m between 1853 and 1969, indicating approximately 2.4 m of deposition during this period. Dredging of this newly deposited sediment was conducted from 1969 to 1972 for materials to build the Halifax Container Terminal (D. Buckley, pers. comm., 1998).

The origin of Maugher's Beach is less easily explained. It is clear that causeway construction changed the hydrodynamic regime at McNab's Cove and sand infilled the entrance, however, the source of sand is not identified. Similar to the McCormick's Beach area, the development of Maugher's Beach was accompanied by no accelerated updrift retreat, in this case at the Fort McNab's/Strawberry Battery section or at Big Thrumcap. Bluffs updrift thus cannot be the only sediment source, yet Thrumcap Hook, the other alternative subaerial source, appears stable through the early development of Maugher's Beach. Orford *et al.* (1991) speculate that the presence of dissipative shoreface sands in front of established gravel barriers contributes to their stability, while loss of the sand sheet triggers morphodynamic change. Some evidence is given for this process as sand appears to be the first sediment size to migrate and form beaches downdrift. The sand in McCormick's Beach and Eastern Passage, in a long-term response to artificial crestal lowering and overwash, originates from Barrie Beach and Noonan's Beach. The sand forming Maugher's Beach may have been transported from the shoreface sand sheet adjacent to Thrumcap Hook, contributing to its failure after 1954. Active coarse sand ripples on the shoreface adjacent to Thrumcap Hook (D. Forbes, pers. comm., 1999) indicate sediment transport in this area.

A report on dredging in outer Halifax Harbour (Hunter and Tress, 1970) identifies dredging activity at Thrumcap Hook, but this is based only on airphoto interpretation and mining or dredging is not otherwise known to have occurred. Unlike mined beaches, throughout historical time Thrumcap Hook has had neither roads nor structures. A barge is visible on airphotos from 1966 inside the cove at Thrumcap Hook and may indicate dredging had been initiated, but, as the tidal channel was not navigable shortly before 1966, and shelter from waves of Thrumcap Hook was negligible shortly after 1966, any dredging was likely not significant. Changes at this location may therefore be considered predominantly natural.

The behaviour of Thrumcap Hook changed rapidly after 1954, the reasons for which, as will be discussed in Chapter 5, are complex. This was both a period of increasing storminess and rapidly rising sea-level, but, relevant to this discussion, was also a period of decreasing sediment supply from Thrumcap Shoal. The transverse ridges visible on charts from the mid and late 1800s (Des Barres, 1776; Bayfield, 1853; Rowe, 1876; Akers, 1886), which may have operated as sediment transport corridors (Orford *et* *al.*, 1991) from Thrumcap Shoal, are not apparent on later airphotos. Additionally, little erosion of Thrumcap Shoal occurred between 1950 and 1979 (Figure 2.15). The reduction in supply may have changed the balance between sediment supply and sea-level rise, which was rising rapidly from 1920 to 1970 (Figure 2.20), causing a rapid shift from stability to destruction. An apparent increase in erosion of Thrumcap Shoal after 1979 may have supplied enough sediment to support a smaller beach in equilibrium with less rapidly rising sea-level after 1970, perhaps partially accounting for the stabilization apparent on airphotos after 1982. The decadal scale evolution of the Thrumcaps and its causes are discussed more fully in Chapter 5.

Erosion of till at Thrumcap Shoal likely does not contribute significant sediment due to the presence of an overlying coarse lag deposit. Prior to the erosion of the drumlin shown on charts from the mid-1700s (Cook, 1758; Morris and Jeffries, 1759), fringing beach deposits were likely present. These deposits were reworked landward during sea-level rise, stranded, and subsequently submerged on a bathymetric high; continued reworking of this sediment following submergence formed transverse ridges streaming downdrift and left a coarse lag deposit over the flat-topped shoal. It is thought the lowering seen in Figure 2.15 is erosion of these deposits, however further offshore mapping is necessary to confirm this.

The above discussion has focused mainly on eroding till bluffs and barrier beaches subject to overwash. These are the principal sources of beach sediment because they contain beach-forming sediment, are widespread throughout the study area and are actively eroding. Additional sources that may be significant are overstepped barriers and estuarine or lagoonal deposits outcropping on the shoreface (Figure 4.5), but the

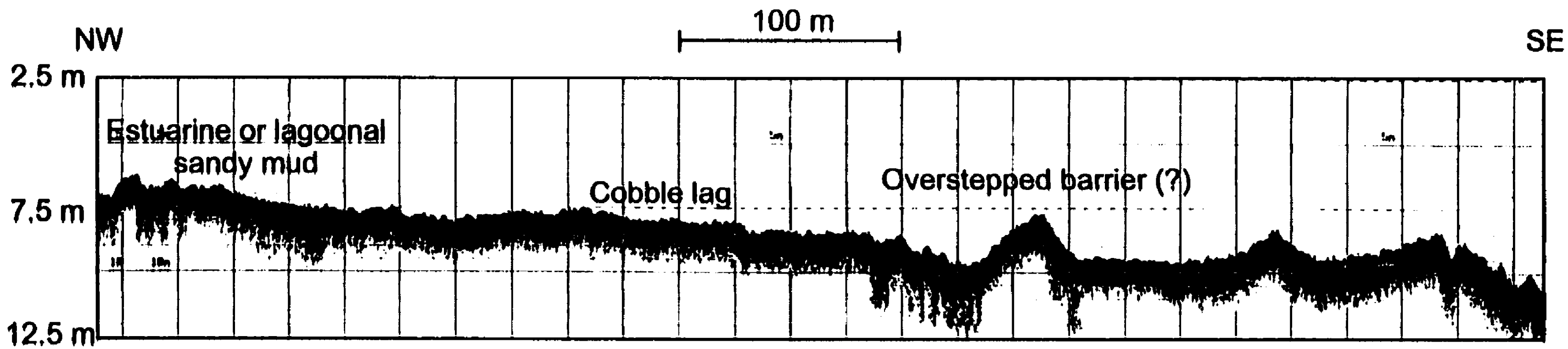


Figure 4.5 A Knudsen echosounder trace showing hummocky estuarine deposits at the extreme northwestern end and an overstepped barrier form at the southeastern end. A cobble lag with interstitial sand and gravel separates the two. Line BT1 (Figure 2.5).

distribution and erosion of these features is not well known. The observed hummocky, scoured, morphology of the cohesive deposit indicates active erosion in at least 6 m water depth (*cf.* Forbes and Boyd, 1989). The pristine profile and sharp crest of the overstepped beach form suggest it is not being significantly eroded, although the structure may be migrating landward intact or may be receiving small amounts of sediment from seaward while losing other sediment landward. The sea-level curve for Halifax Harbour (Shaw *et al.*, 1993) indicates the age of the estuarine or lagoonal deposits at 6.5 m depth is 3.25 ka and, assuming deposition at sea level, the relict barrier at 8 m depth is approximately 3.75 ka.

Erosion of estuarine or lagoonal deposits and overstepped barrier beaches, as landforms composed of sediment delivered from bluff retreat, ultimately provides no new sediment to the system. In the absence of fluvial inputs, any sediment in beaches not delivered directly by the erosion of till or bedrock is reworked sediment delivered by previously eroded drumlins that has been moved landward with the transgressing shoreline. At approximately 11 ka, sea level was 65 m lower than present (Stea *et al.*, 1994) and the coastline was located approximately 12 km southeast of McNab's Island (G. Fader, pers. comm., 1999). Remnant eroded drumlins that supplied sediment to the coastal zone are seen on multibeam bathymetry between McNab's Island and the previous lowstand shoreline. On the inner Scotian Shelf off the Eastern Shore, this sediment has been reworked to extensive lag deposits (Forbes and Boyd, 1987; Amos, 1989; Forbes and Boyd, 1989). In places it continues to be moved onshore in rare ribbons of gravel ripples that migrate over the lag deposit (Forbes and Boyd, 1987) to depths of at least 30 m during storms (Forbes and Drapeau, 1989). Gravel ripples are seen on sidescan sonar records northwest of Devil's Island and may indicate the slow migration of small amounts of eroded glacial sediment from the inner shelf southeast of Devil's Island. Further mapping of offshore sediment distributions and determination of volumes present in beaches are necessary to further elucidate the sediment budget.

Boyd *et al.* (1987) considered the long-term development of the Eastern Shore to be related to the balance between the rate of sea-level rise and sediment supply to barrier beaches. When supply is limited, barriers experience overwash and landward migration, whereas when supply is plentiful, barriers may prograde, keeping pace with rising sea-level. If anthropogenic removal of sediment can be considered a reduction in supply, supply limitation in the study area is observed to result in overwash. The timing of mining activity, overwash, and updrift sedimentation in the Barrie Beach area, as observed on airphotos and charts, indicates that formerly stable beaches whose crests have been artificially lowered by mining become unstable, rapidly change in form, and increase the rate of supply to the sediment budget. Downdrift sedimentation following overwash indicates that movement of sediment from type S3 beaches to type S2 beaches is an important mechanism of transporting sediment landward during transgression.

4.5 Conclusions

(1) Eroding bluffs are important sources of sediment in the sediment budget in the McNab's Island area. Other sources offshore include remnant drumlin shoals, barrier beaches subject to overwash, submerged beach forms, and lagoonal or estuarine sediments outcropping on the shoreface. Of these, barrier beaches subject to overwash and shallow submerged beach forms that were either overstepped or stranded on

bathymetric highs during transgression appear to be most important. Eroding drumlin bluffs represent the only significant source of new sediment.

(2) Historical retreat rates of drumlin bluffs are variable through time and location and, in the study area, are closely related to the migration of nesses and the destruction of protective barrier beaches by mining. As observed on sub-annual to annual time scales, the presence of beaches promotes bluff stability over decadal time scales. Sediment delivered by bluff retreat can affect the morphodynamics of the bluff-beach system; feedback processes may be important in regulating decadal supply from bluffs.

(3) Repeated mining of beaches in the study area has contributed to rapid coastal change. Removal of sediment and artificial lowering of beach crests increases susceptibility of barriers to overwash, and promotes downdrift movement of sediment. Change not believed to be influenced by mining or dredging also occurs rapidly after long intervals of stability.

(4) The cause and effect relationship between sediment supply and barrier beach behaviour is complicated by coincident increasing storminess and rapid sea-level rise. Natural changes are related to the interaction of sediment dynamics, increased storminess, and variable rates of sea-level rise. These interactions are further discussed in Chapter 5.

Chapter 5

Factors Contributing to the Decadal-Scale Morphodynamic Evolution of the Thrumcaps

5.1 Introduction

The importance of beaches in protecting bluffs over decadal time scales was illustrated in Chapter 4, where the sediment sources of beaches were investigated. An offshore source consisting of stranded and submerged beach deposits was determined to be important in supplying sediment to past and present beaches near Big Thrumcap. Sediment supply variability is not the only variable or factor that controls coastal behavior. It was demonstrated in Chapter 3, that on annual or sub-annual time scales, storms and storm surges are important in causing coastal change; extrapolation of these short-term forcing mechanisms to decadal time scales suggests that storminess and sea-level change may play a role in controlling decadal-scale coastal behaviour. It remains unclear whether, over decadal time scales, storminess, sea-level rise, or sediment supply controls morphodynamic evolution and the shift from barrier beach stability to instability.

The McNab's Island area is not an ideal location to study decadal-scale coastal evolution because of the amount of anthropogenic disturbance that has occurred. One area that has arguably not been subjected to significant mining or dredging is the Thrumcaps. Thrumcap Hook, Thrumcap Shoal, Big Thrumcap and Little Thrumcap will be used as examples to investigate the morphodynamic evolution of a coastal system. An introduction to nonlinear dynamical concepts and terminology will be given and decadal trends in storminess and sea-level rise and their causes discussed. The historical evolution of the Thrumcaps will be reviewed and lastly the factors controlling their morphodynamic evolution will be evaluated.

5.2 Nonlinear Dynamics in the Coastal Zone: An Introduction

The number of publications on nonlinear dynamic systems has been increasing exponentially in recent years (Middleton, 1991), indicating recognition of the applicability of nonlinear dynamical theory to natural systems. The following is a brief introduction to nonlinear dynamical systems and an attempt to place the study of coastal change through time in a dynamical context by describing selected feedback relationships on gravel shorelines.

Dynamical systems arise under conditions of energy dissipation and disequilibria, such as are common on shorelines subject to geological inertia (Forbes *et al.*, 1997). Nonlinear dynamical systems are considered to converge to attractors, mathematical descriptions of their state. Strange attractors are the convergence points or states of apparently chaotic nonlinear dynamical systems and may be expressed as fractals (Goodings, 1991; Nicolis, 1987). Where the state of a system, such as a shoreline, is controlled by more than one parameter, a set of strange attractors results, defining a multifractal basin of attraction (Shaw, 1991) which changes form depending on the dynamical equilibrium between controlling factors or forcing mechanisms.

Nonlinearities result from feedback in the system and give rise to apparently chaotic behaviour or long-term stability. Long periods of stability may terminate in rapid shifts in system state when the dynamical equilibrium between control parameters changes rapidly. Numerous examples of feedback in coastal systems are reported including cusp formation (Sherman *et al.*, 1993), textural sorting and crestal breakdown (Forbes *et al.*, 1995a) and dune scarp erosion (Gaffney, 1993) (see also Section 4.5). Textural sorting, in particular, is an important process on gravel shorelines resulting in distinct shore-parallel sedimentary facies. Sorting occurs through overpassing, the process by which clasts either larger or smaller than the dominant grain size of a facies are rejected from the sediment mass (Carter *et al.*, 1990a; Isla, 1993). An example includes the manner in which gravel is transported over the shoreface sand sheet to be included in a barrier beach. Positive feedback occurs as the sand sheet becomes better sorted and a wider range of clast sizes is overpassed, resulting in even better sorting of the sand sheet.

In coastal systems, morphodynamic self-organisation, the process through which coastal stability results, is controlled by negative feedback. Coastal change occurs mainly through wave energy, but the morphology of a shoreline affects the incident wave energy through refraction and dissipation. For example, as incident energy increases, sandy beaches develop flatter profiles to dissipate more energy offshore, and coarse-clastic shorelines develop steeper and higher profiles and reflect wave energy from the beachface to interfere with approaching waves. Thus, as incident energy increases, it is reduced by negative feedback and coastal stability results. At some critical level of incident energy, and with some critical morphologic condition, negative feedback fails (or positive feedback occurs) and change results. In the context of nonlinear dynamics this represents a bifurcation or sudden shift in the prevailing state, in which, due to a change in the factors upon which the basin of attraction depends, the state of the system changes.

Critical morphologic conditions may include steep open framework crests (Forbes *et al.*, 1995a) and the presence of sand in the nearshore (Orford *et al.*, 1991).

The conceptual resemblance between theoretical nonlinear dynamics and observations of coastal processes through time is striking and bears future consideration. Field studies can assist in elucidating controlling parameters but, due to the number and interactions of controlling parameters in the coastal system, quantitative marriage of theory and observation in the coastal zone is not yet possible. Time-series measurements best show examples of nonlinear behaviour. At present coastal observations lend support to spatially and temporally variable, nonlinear dynamical behaviour in natural systems, and nonlinear dynamical concepts present an approach of use in investigating coastal behaviour over time.

5.3 Storm Climate at Halifax Since 1953

The weather in the Maritime provinces is controlled mainly by eastward flow from a high pressure area over central Canada to a low pressure zone over the Atlantic Ocean. Cold dry air over the continent drifts southeast to meet warm moist air originating in the Caribbean Sea, resulting in extratropical or mid-latitude cyclone formation. These types of cyclones are most intense during winter when the temperature differences between air masses are greatest (Canavan, 1997) and may follow a northeasterly meridional track approximately parallel to the Atlantic coast of the United States (Dolan *et al.*, 1988). Mid-latitude cyclones may also originate over the continent and move east with zonal (*i.e.* latitudinal) flow or, more rarely, may form in the Arctic and move southeast toward the Maritime provinces (Gyakum *et al.*, 1996). Occasional wind storms may be associated with the formation of anticyclones during fair-weather.

A less common type of cyclone originates in the tropical Atlantic Ocean (10^o to 15^o N) where westerly propagating atmospheric waves from west Africa give rise to especially damaging hurricanes from July to October (Goldenberg *et al.*, 1997). These too move northeast roughly parallel to the coast of eastern North America and occasionally cross the coast of Nova Scotia. Distant tropical cyclones and hurricanes are commonly observed at Halifax as long period high waves without local high winds (Figure 5.1).

Historical climate data indicate that from approximately 1954 to 1964 was an anomalous period of decadal scale storminess. Although mean daily winds (Figure 5.2) show no large changes in direction since 1953, maximum monthly winds (*i.e.* storm winds) show a marked change in modal direction (Figure 5.3). In the period 1953 to 1959, modal storm directions were from the southeast but switched to the southwest during the period 1960 to 1969. The number of storm winds from the northeast decreased after 1969 but has again increased in the 1990s. Storm wind directions in the 1990s also show strong westerly and northwesterly components. The mean storm wind direction has migrated continually westward since 1953 but this may not be significant.

Southerly winds have been shown to be important in resuspending mud in Halifax Harbour (Delure, 1983) and the longest wind and wave fetch affecting the McNab's Island area is between 120^o and 240^o. Additionally, Figures 5.2 and 5.3 indicate that modal mean daily and maximum monthly winds are from the southeast to southwest. The following discussions of storminess will therefore focus on southeasterly to

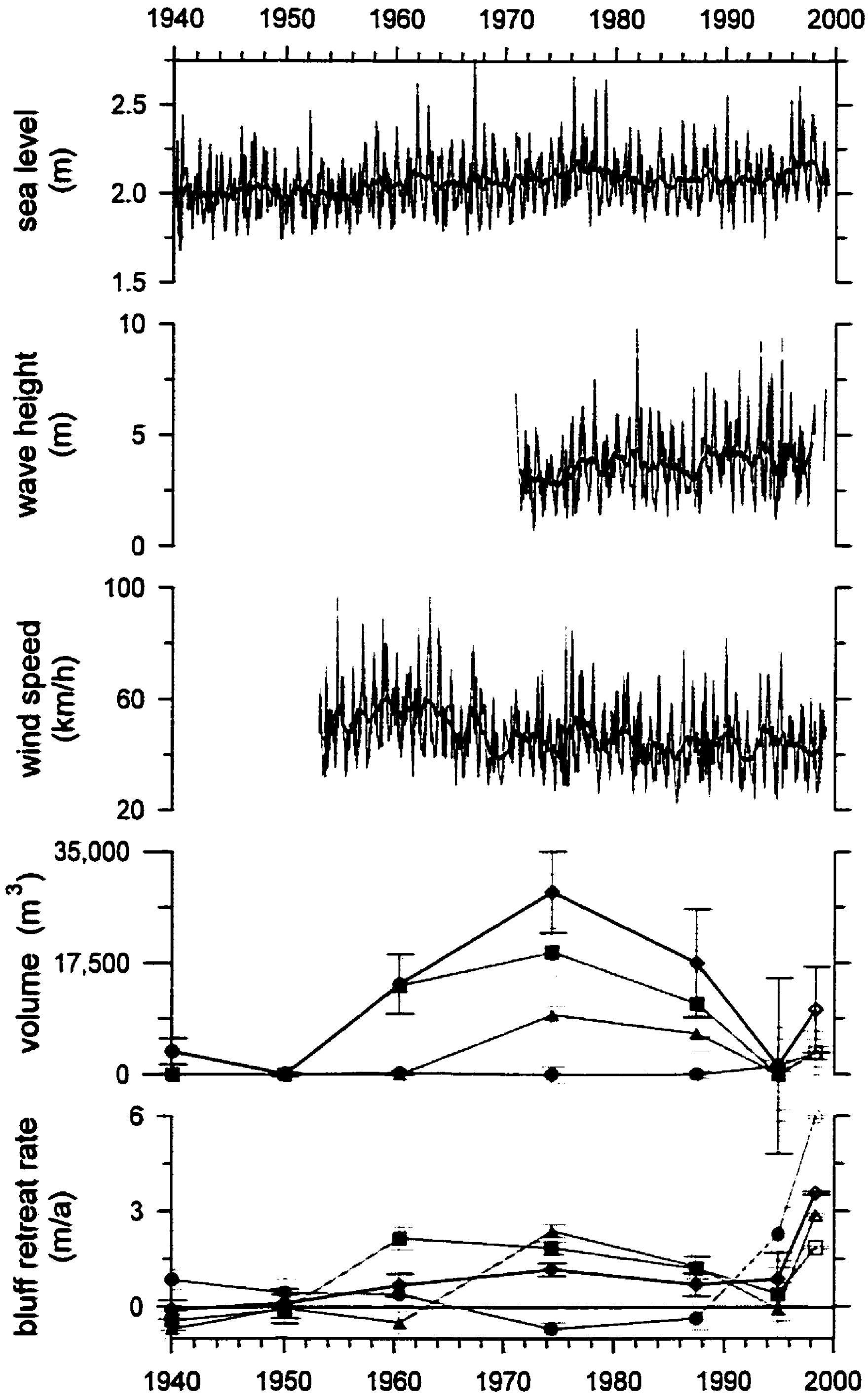


Figure 5.1 Bluff retreat rate, volume delivered by bluff retreat, speed of southeasterly to southwesterly winds, wave height during southeasterly to southwesterly winds, and sea level since 1940 at the Thrumcaps. On the lower two graphs the open symbols indicate field measurements, and the dark lines and diamond symbols represent average retreat rate and total volume delivered. M14 circles, M15A squares, M15B triangles. On the upper three graphs the grey lines represent maximum monthly measurements and the dark lines give 12 month running means.

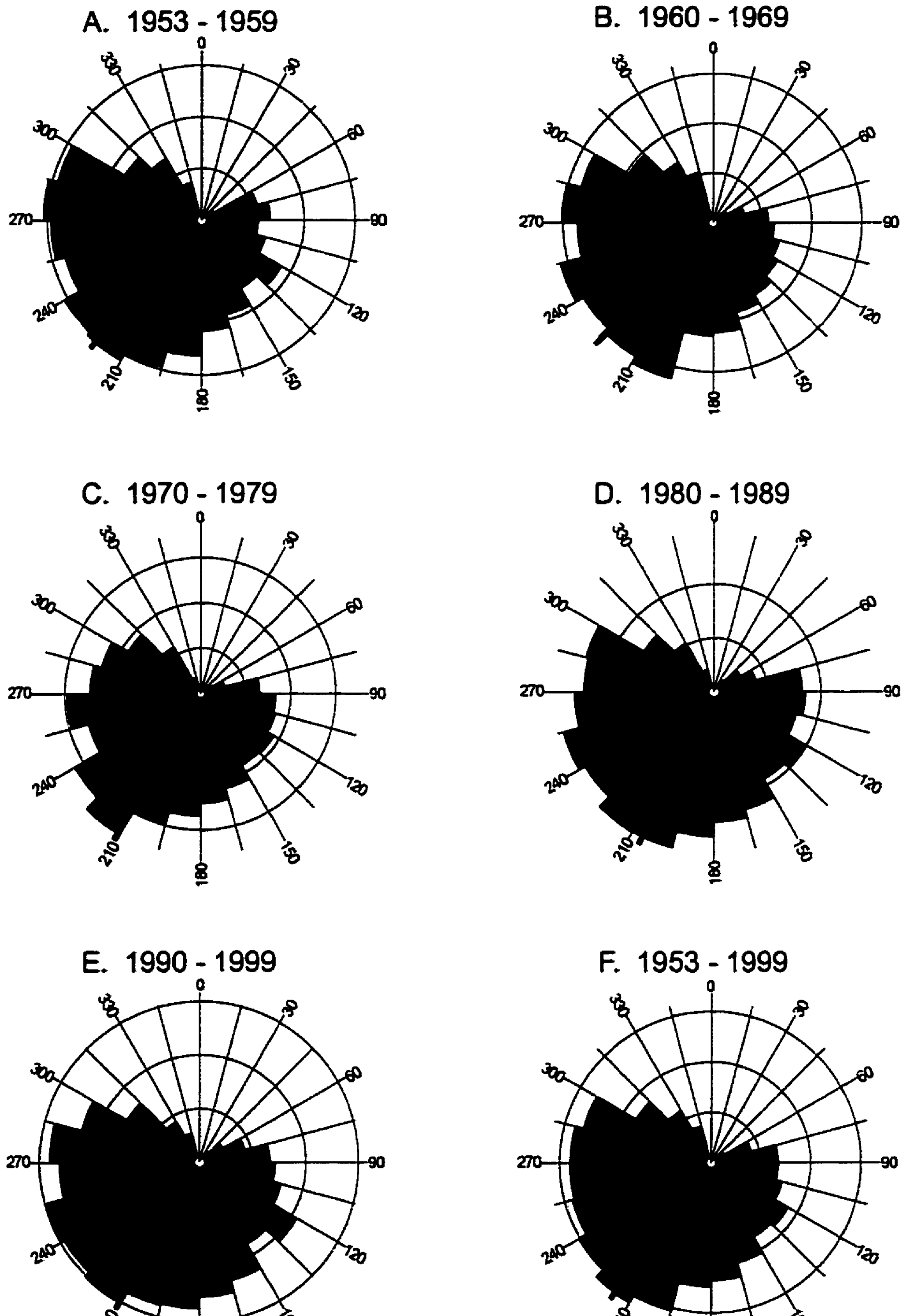


Figure 5.2 Rose diagrams of mean daily wind directions at CFB Shearwater. Circles represent frequency intervals of 0.025. The heavy line indicates the mean daily wind direction for each period. A) 1953 to 1959. B) 1960 to 1969. C) 1970 to 1979. D) 1980 to 1989. E) 1990 to 1999. F) 1953 to 1999.

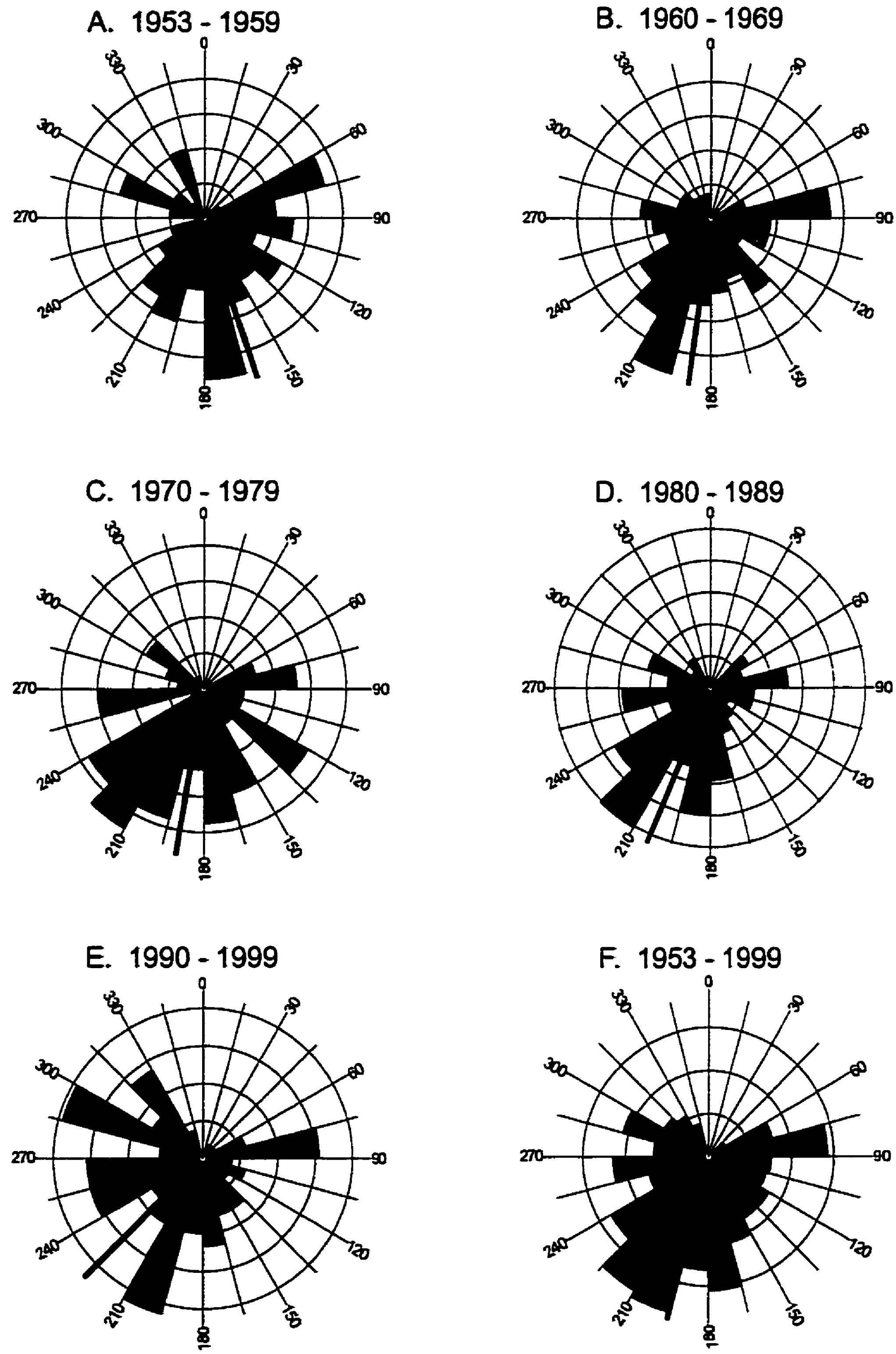


Figure 5.3 Rose diagrams of maximum monthly wind directions at CFB Shearwater. Circles represent frequency intervals of 0.025. The heavy line indicates the mean maximum monthly wind direction for each period. A) 1953 to 1959. B) 1960 to 1969. C) 1970 to 1979. D) 1980 to 1989. E) 1990 to 1999. F) 1953 to 1999.

southwesterly winds from directions between 120° and 240°.

Figure 5.4 shows maximum monthly southeasterly to southwesterly wind speeds and the summer and winter frequencies of mean daily southeasterly to southwesterly winds of speeds greater than 30 km/h. A period of marked elevated storm frequency and strength contributed to by both summer and winter storms occurs between 1954 and 1965 just prior to an historical minimum in the North Atlantic Oscillation Index (Figure 2.18). The wave record starts after 1970 and does not include this stormy period.

These changes in the storm wind field are coincident with a change in the mid-1950s in trend from increasing surface air temperatures in the Maritimes since 1890 to decreasing air temperatures (Lewis, 1997); the trend may have switched again to warming in the 1990s. The coincidence of increasing storm strengths and frequencies and shifting storm directions indicates a brief change in the storm climate of the Eastern Shore between 1954 and 1964 the cause of which may be related to established atmospheric patterns.

Since the 1920s climate research has considered the effects of atmospheric flow patterns indicated by indices of air pressure (*e.g.* Walker and Bliss, 1932). In the equatorial Pacific the Southern Oscillation Index (SOI), the difference of mean monthly normalised sea level air pressures at Tahiti and Darwin, is used (Figure 2.17), whereas in the North Atlantic basin the North Atlantic Oscillation Index (NAOI), the difference between mean normalised December, January, and February sea level air pressures at the Azores and Iceland is commonly used (Figure 2.18).

The SOI is the better known of the two indices and is recognized as indicating El Niño (negative) and La Niña (positive) conditions (*e.g.* Philander, 1990; McFadden,

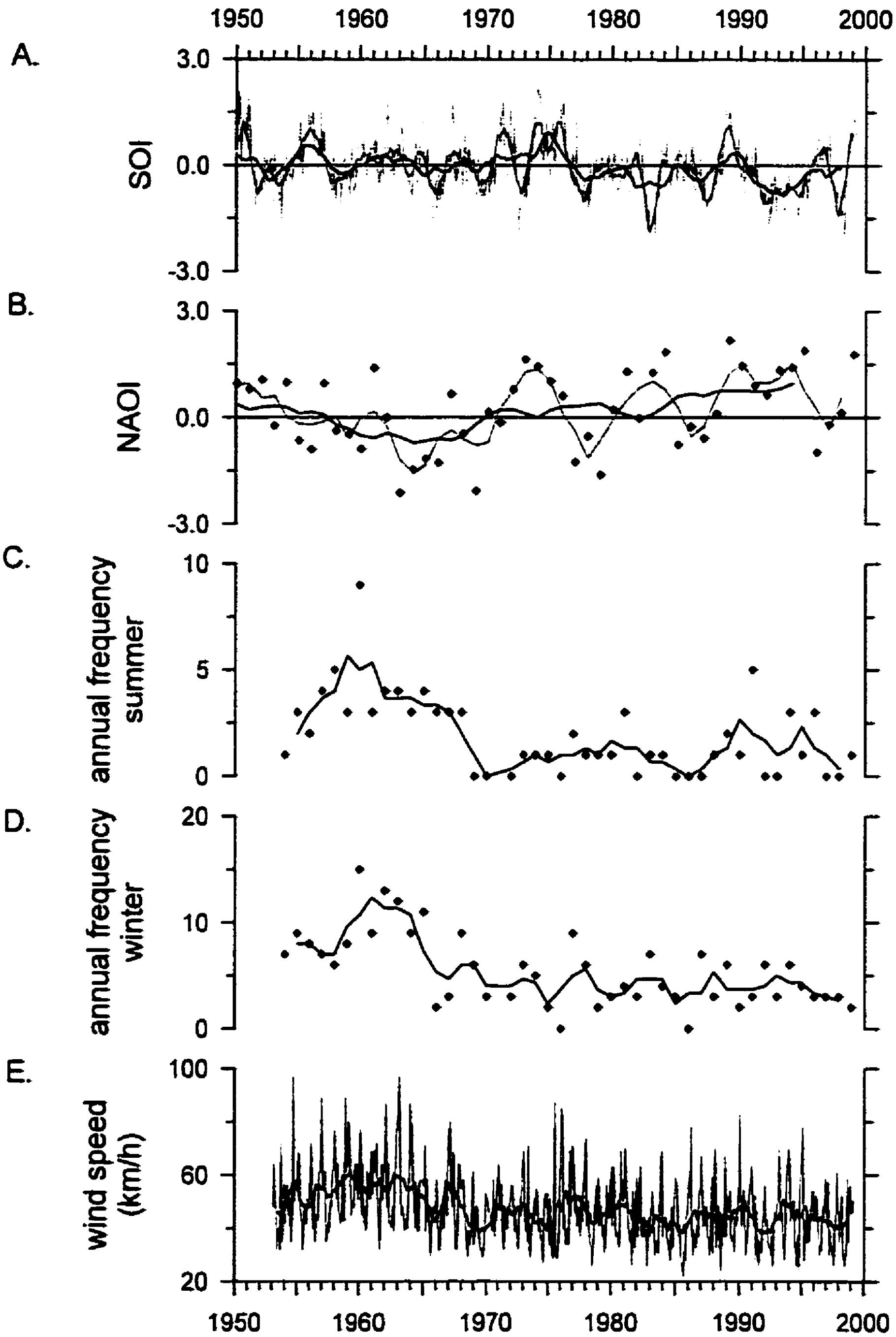


Figure 5.4 Wind climate at Halifax between 1953 and March 1999. A) SOI. Monthly values (light grey line), 12 month running mean (dark grey line) and 3 year running mean (thin black line). B) NAOI. Annual values (points), 3 year running mean (grey line) and 11 year running mean (black line) are shown. C) Annual frequency of mean daily southeasterly to southwesterly winds greater than 30 km/h from June to November of each calendar year. The solid line indicates the three year running mean. D) As in C but from January to May and December of each calendar year. E) Maximum monthly southeasterly to southwesterly wind speed. The dark line indicates the 12 month running mean.

1999). El Niño events are coincident with many remote atmospheric and oceanic responses or impacts, including equatorial Pacific sea surface warming (McFadden, 1999), decreased South Asian monsoon activity (Diaz and Kiladis, 1992), and enhanced precipitation in the mid-latitudes of western North America (Heusser and Sirocko, 1997). La Niña events, characterised by negative sea surface temperature anomalies in the equatorial Pacific, are considered to result in increased frequency of major (sustained wind speeds > 180 km/h) hurricanes in the Atlantic Basin (Goldenberg and Shapiro, 1996; Goldenberg *et al.*, 1997).

The NAO has been linked to a number of winter climatological phenomena on both sides of the North Atlantic basin. In Europe, decreasing winter temperatures have been correlated with downward trends in the NAOI and the current positive phase in the index contributes to winters drier than normal in central and southern Europe and wetter than normal in Scandinavia (Hurrel, 1995). Sea-level variations in the North and Baltic Seas may be related to the NAO (Plag and Tsimplis, 1999) and water mass redistributions across the Atlantic Basin may result in coincidence of the NAOI and decadal polar motion, the geographic variation in the position of the Earth's rotational axis (Zhou *et al.*, 1998; Iwabuchi *et al.*, 1997). In the western Atlantic, the NAOI has been correlated to the latitude of the Gulf Stream (Taylor and Stephens, 1998); more northerly positions occur approximately 2 years after high NAOI winters. Also during high NAOI winters, westerly wind speeds increase across the Atlantic, anomalous northerly flow develops over the Canadian Arctic, and anomalous southerly flow develops over the southeastern United States (Hurrel, 1995). The effect of these anomalies on storms impacting the Eastern Shore remains unclear and is the subject of this section.

The above discussion illustrates that both the Southern Oscillation and the North Atlantic Oscillation may contribute to the climate of eastern North America, yet comparisons of portions of the NAOI and SOI since 1950 do not readily reveal any strong evidence for correlation. The SOI is a monthly index of zonal flow; the 12 month running mean shows an irregular periodicity of approximately 3-5 years. Negative values of the 12 month running mean indicate El Niño conditions while positive values indicate La Niña conditions. The 11 year running mean shows some irregular low-amplitude oscillations since 1920 (before which the Tahiti air pressure record is discontinuous) but amplitudes became larger after 1970. After 1980 the 11 year mean of the SOI was the lowest it has been since 1920.

In contrast to the SOI, the NAOI is an annual index of winter months from meridional aligned stations and should be considered only with winter phenomena. The 3 year running mean oscillates irregularly with a period of 5-7 years and has varied considerably since 1860. From approximately 1860 to 1896 shorter period variations were dominant but after 1896 longer period and higher amplitude asymmetric oscillations occurred until a low point in the index was reached in 1964. After 1964 high amplitude and regular oscillations became dominant. The 11 year running mean shows a pattern of low amplitude irregular oscillations and positive values prior to 1896. Values increased to 1910 when oscillation periods became longer with a downward trend to a minimum in 1964. The 11 year mean shows an upward trend since that time.

El Niño or La Niña events may coincide with either peaks or depressions in the NAOI. Strong El Niño events such as occurred in 1972, 1982, and 1992 coincided with peaks on the NAOI, that is, to higher relative air pressures in the Azores. The 1997 event, however, the strongest in recent history (McFadden, 1999), corresponded to a depression in the NAOI or higher relative air pressure in Iceland. Strong La Niña events such as 1973, 1988, and 1998 tend to correspond to peaks in the NAOI but the strong 1964 La Niña corresponds to negative NAOI values.

On annual time scales, winter storm frequencies are roughly in phase with the SOI between 1970 and 1990 and may correspond to El Niño events in 1972, 1976, 1982, and 1987 but there is no relation prior to 1970 or after 1990. Summer storm frequencies, an indicator of hurricane frequency, show two peaks in 1989 and 1995 loosely correlating with peaks in the wave record (Figure 5.5) but there is no close relation to similar peaks in the NAOI and SOI. Peaks in the three year running mean of summer wind frequency post-date the SOI and NAOI peaks and are closer together in time.

Annual wave frequencies and heights show little relation to annual wind frequencies and speeds, though the wave record is relatively short and does not include the 1954 to 1964 stormy period (Figure 5.6). Increased frequencies of waves of mean daily significant wave height greater than 3 m, corresponding to mean daily southeasterly to southwesterly winds, show elevated frequencies and heights in 1978, 1983, and 1995. Annual summer frequencies show several short peaks while annual winter frequencies show fewer peaks of longer duration. Three year running means of summer frequencies may be associated with La Niña years (*e.g.* 1975, 1989) and three year running mean of winter frequencies may be associated with El Niño years (*e.g.* 1982, 1992). No association of waves and the NAOI is apparent. The lack of obvious correlation of local winds and waves indicates the influence of distant storms. If these originate in the tropics, correlation with the SOI, an indicator of hurricane frequency, might be expected,

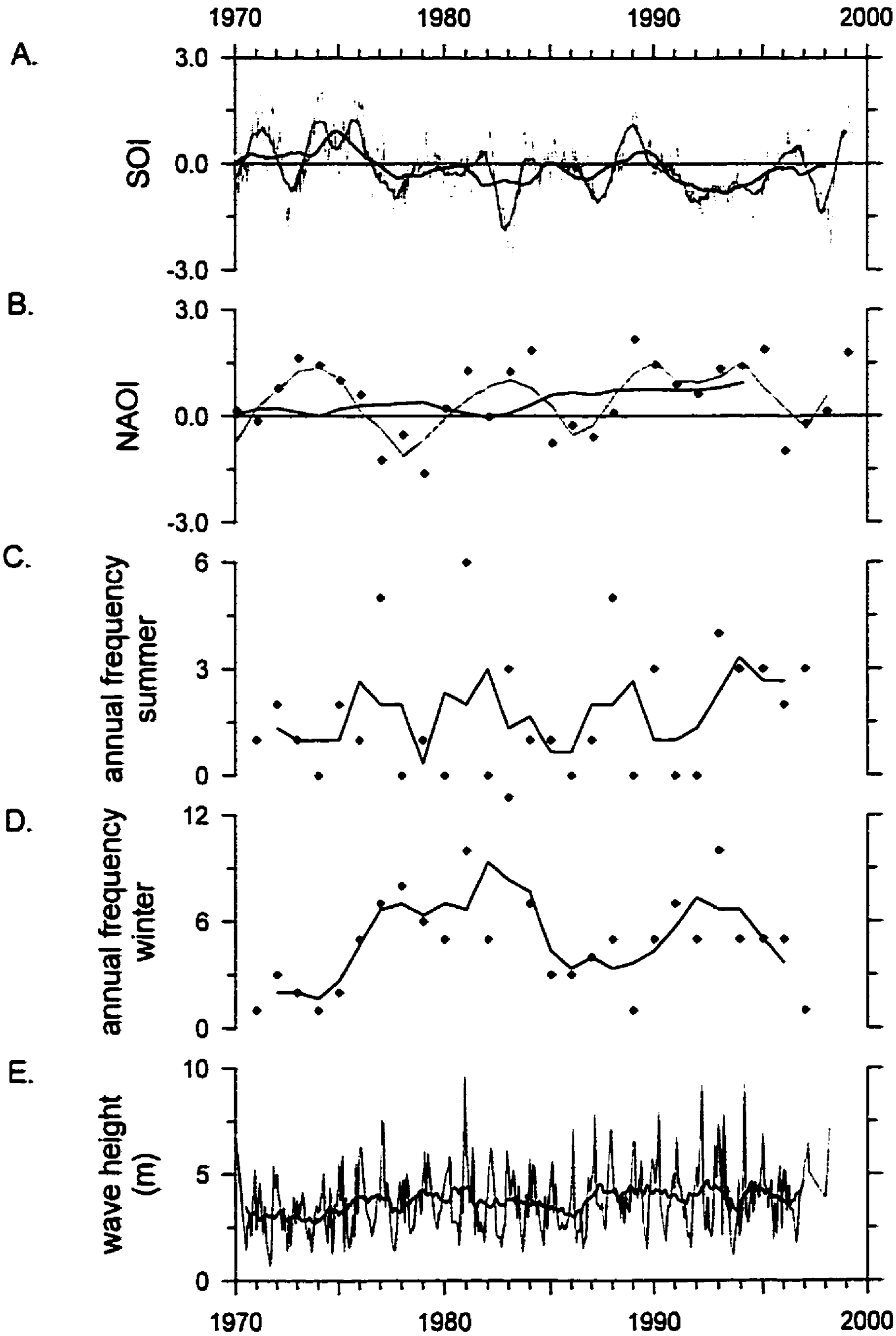


Figure 5.5 Wave climate at Halifax between 1970 and March 1999. A) SOI. Monthly values (light grey line), 12 month running mean (dark grey line) and 3 year running mean (thin black line) are shown. B) NAOI. Annual values (points), 3 year running mean (grey line), and 11 year running mean (black line) are shown. C) Annual frequency of mean daily significant wave heights greater than 3 m during southeasterly to southwesterly winds from June to November of each calendar year. The solid line indicates the 3 year running mean. D) As in C but from January to May and December of each calendar year. E) Maximum monthly significant wave height during southeasterly to southwesterly winds. The dark line indicates 12 month running mean.

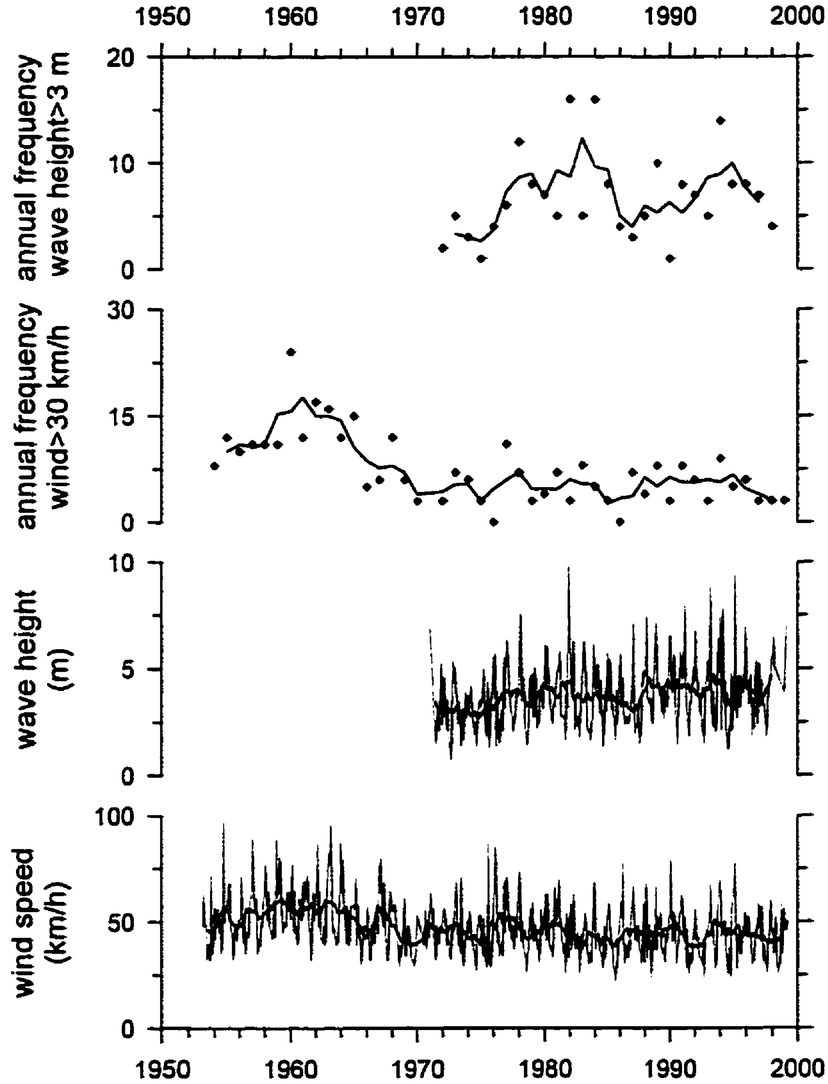


Figure 5.6 Comparison of wind and wave climates at Halifax. Maximum monthly speeds of southeasterly to southwesterly winds, maximum monthly significant wave heights during southeasterly to southwesterly winds, annual frequencies of mean daily southeasterly to southwesterly winds greater than 30 km/h and annual frequencies of mean daily significant wave heights greater than 3 m during southeasterly to southwesterly winds are shown. Dark lines on the lower two graphs show 12 month running means, and on the upper two graphs they show 3 year running means.

yet the relationship of hurricanes to the SOI is weak. Elevated equatorial sea-surface temperatures (*i.e.* El Niño conditions) reduce hurricane activity, but no strong relationship is demonstrated with La Niña conditions. Hurricane formation may be more related to precipitation in the Sahel area of Africa (Goldenberg and Shapiro, 1996).

In Florida, the period from 1870 to 1900 was an active hurricane period in contrast to the period from 1900 to 1920 (Doehring et al., 1994). During the 1920s and 1930s hurricane activity increased and reached a maximum during the 1940s. Hurricane activity began to decline in the 1950s, although tropical storm activity remained high. A slight increase in hurricane activity occurred in the 1960s but activity was very low in the 1970s and only slightly higher in the 1980s. Activity is considered to have increased in the mid-1990s (Goldenberg, *et al.*, 1997). This pattern appears to relate to neither the SOI nor the NAOI.

The lack of evident correlation between the NAOI, SOI, and annual weather patterns in the Maritimes indicates the complexity and nonlinearity of weather (*e.g.* Essex *et al.*, 1987), and over larger spatial and temporal scales, climate systems (*e.g.* Bluemle *et al.*, 1999). Gyakum *et al.* (1996) reported the number of rapidly intensifying cyclones southwest of Newfoundland since 1975 were highest during the winters of 1978, 1980, and 1992. The active period in 1992 was associated with a westward shift and deepening of the Icelandic Low and anomalous temperatures over Hudson Bay. These years show no correlation with the NAOI and are not shown as significant peaks in the annual frequencies of southerly winter winds greater than 30 km/h at Halifax. The meridional structure of the NAO may not be highly indicative of the annual weather of the Maritimes, which has a strong influence from zonal continental flow. Topliss (1997) suggested climate variability in the Maritimes indicates the influence of an additional climatic system. It is not known if this reflects an influence from the Southern Oscillation, possibly in some dynamic relationship with the NAO, or an altogether different climatic system. Future research on annual storminess variability might consider other indices using continental North American air pressures and the Icelandic Low. The relative temperature differences between air masses and water masses, particularly the Gulf Stream, may be important in cyclogenesis (Gyakum *et al.*, 1996); future research should additionally include investigation of sea surface temperatures of major currents affecting the Maritimes.

The NAO over decadal time scales seems to be an indicator of storminess. Just prior to the historical low of the NAOI in 1964, the frequency and strength of winter and summer storms increased. Delure (1983) proposed that the periods from approximately 1635 to 1723 and 1798 to 1873 were also stormy periods; a lengthy NAOI derived from Greenland ice cores (Appenzeller *et al.*, 1998) indicates lows in the NAOI deeper than the low in the early 1960s during both of these periods.

5.4 Relative Sea-Level Rise at Halifax

The major cause of relative sea-level (RSL) rise at Halifax over geological time scales is related to the glacio-isostatic subsidence of Halifax. Approximately 11.6 ± 0.1 ka, sea level at Halifax was 65 m below present (Stea *et al.*, 1994) and the Halifax Peninsula was situated atop a peripheral bulge (Quinlan and Beaumont, 1981) that formed in response to asthenospheric flow away from a center of ice accumulation in Quebec (Rampton *et al.*, 1984; Stea, 1995). Following ablation at the accumulation centre, the bulge has been migrating west and decaying in elevation resulting in subsidence of Halifax and relative sea-level rise. During the late mid-Holocene, changes in the volume of seawater in the oceans following melting of the ice sheets may have added significantly to relative sea-level rise in Nova Scotia (Scott *et al.*, 1995).

Over decadal time scales, however, significant variability in rates of sea-level rise occurred. Since 1896, the Halifax tide gauge records stepwise relative sea-level rise between 0.8 and 8.0 mm/a with a cumulative rate of 3.0 mm/a to 1998 (Figure 2.16). As decadal variability may contribute to coastal erosion and instability over decadal time scales (IPCC, 1995; Forbes *et al.*, 1997; Carter *et al.*, 1989; Orford *et al.*, 1995; Kaplin and Selivanov, 1995), further discussion of possible causes of decadal variability is merited.

Decadal changes in the rate of RSL rise occur over the background of glacio-isostatic RSL rise and either accelerate or decelerate this rate of change. Two processes may result in stepwise changes in the rate of RSL rise on the East Coast of North America. The first is steric or thermal change in sea level, which is generally thought to occur over longer than decadal time scales (van de Plassche *et al.*, 1998), and the second is the decadal oscillation of sea level across the North Atlantic, resulting in out of phase but coincident sea level changes in Europe and eastern North America (Gröger and Plag, 1993; Iwabuchi *et al.*, 1997).

Gröger and Plag (1993), using data from the Permanent Service for Mean Sea Level set of tide gauges, noticed strong regional variability in sea-level trends, particularly in the North Atlantic, between 1951 and 1989. Iwabuchi *et al.* (1997) further demonstrated this variability. Between 1967 and 1972 and 1978 and 1984 sea level was dominantly rising on the eastern coast of North America and falling in Europe, while between 1972 and 1978 and 1984 and 1990 sea level was dominantly falling on the east coast of North America and rising in Europe. Rise and fall occurred at rates up to approximately 5 mm/a, which approaches the magnitude of sea level change required to suppress 10 cm of rise over 25 years at Halifax. Iwabuchi *et al.* (1997) further showed that mass redistributions caused by this pattern of sea level change could cause decadal polar wobble and Zhou *et al.* (1998) found significant coincidence of the NAOI and polar wobble.

In a more detailed study, Plag and Tsimplis (1999) investigated the annual and sub-annual variability in modeled sea levels in northern Europe. A change in variability occurs after 1970, corresponding to the decrease in the rate of RSL rise at Halifax. Plag and Tsimplis (1999) concluded that annual variability in sea level may be caused by atmospheric forcing.

The NAOI, SOI and historical sea level at Halifax are shown in Figure 5.7. Sea level appears to rise rapidly as the 11 year running mean of the NAO decreases after 1920 and the rate of RSL rise appears to decrease as the NAO reaches a minimum in 1964. A time lag of approximately 5 years is apparent. No association of sea level trend and the SOI is apparent.

This treatment of a complex process is admittedly simple, yet may illustrate the dependence of decadal changes in the rate of RSL rise on atmospheric processes. As will be further discussed, this has important implications for studies of shorelines. Decadal trends in storms and storminess have usually been considered independent of decadal sea-level rise, however, if both are related to the NAOI, it is no coincidence that they occur

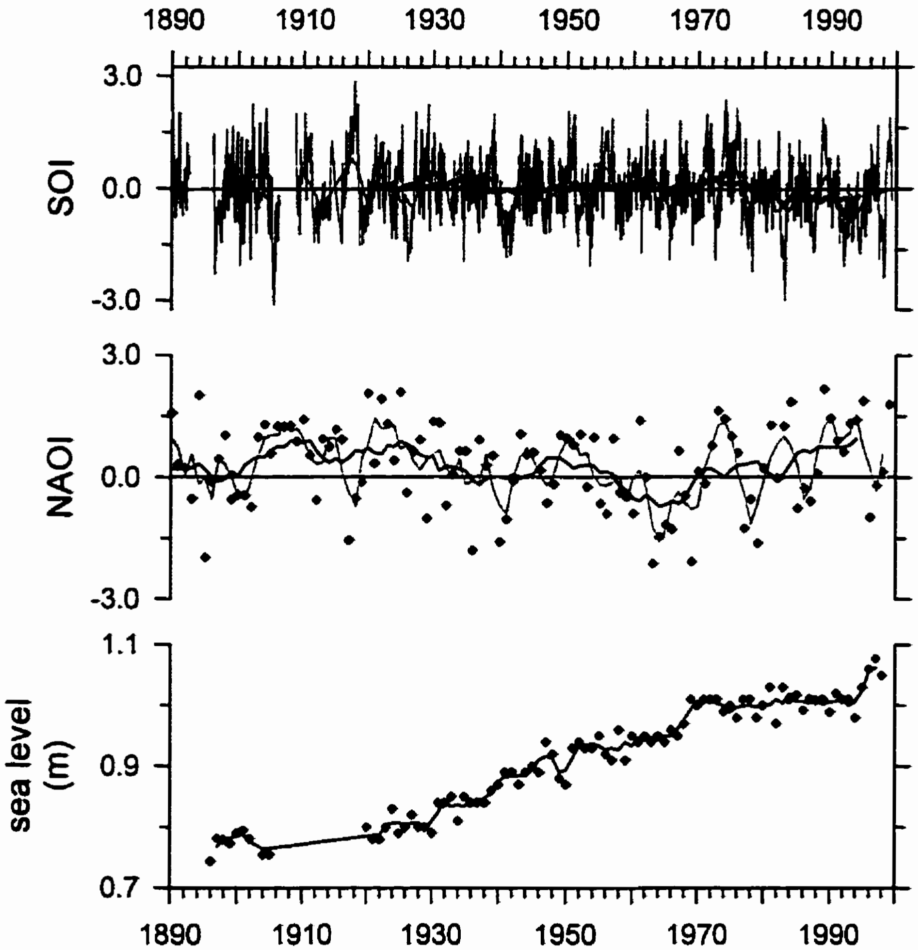


Figure 5.7 Monthly (grey line), 3 year running mean (thin black line), and 11 year running mean (heavy black line) values of the SOI. Annual (points), 3 year running mean (grey line) and 11 year running mean (black line) values of the NAOI. Mean annual sea level (points) and 3 year running mean (black line) at Halifax.

together. The rate of RSL is apparently again accelerating at Halifax; it will be interesting to see if future trends are consistent with those noted here.

5.5 The Historical Evolution of the Thrumcaps

The evolution of Thrumcap Hook, Thrumcap Shoal, Big Thrumcap and Little Thrumcap has been outlined in Chapters 3 and 4 and will be reviewed here. Historical charts and airphotos are shown in Figure 4.2, and summarized in Figure 5.8. Retreat rates and volumes supplied are given in Figure 5.1.

Charts from 1758 and 1759 (Cook, 1758; Morris and Jeffries, 1759) show subaerial exposures of either glacial or beach deposits on Thrumcap Shoal and an adjacent stony beach. Little Thrumcap was nearly connected to Thrumcap Shoal and Big Thrumcap was rounded at its seaward end. By 1776, if the chart by Des Barres (1776) is accurate, Thrumcap shoal had ceased to support subaerial deposits, which had been reworked to two transverse ridges. Erosion of Little Thrumcap since 1759 was significant, but, though low bluffs are charted at Big Thrumcap, little change in shape had occurred. Thrumcap Hook downdrift of Little Thrumcap was well-developed by 1776.

By 1853 (Bayfield, 1853), retreat at Big Thrumcap had transformed the rounded seaward end to an asymmetric needle-like promontory and Little Thrumcap had been eroded on its western flank to a long, thin remnant drumlin. The two transverse ridges were still present at Thrumcap Shoal and were delivering sediment to a beach that developed between Little Thrumcap and Big Thrumcap. A tidal channel cut this beach near Little Thrumcap, and several more were present at the northern, landward end of Thrumcap Hook, although these were dry at low water.

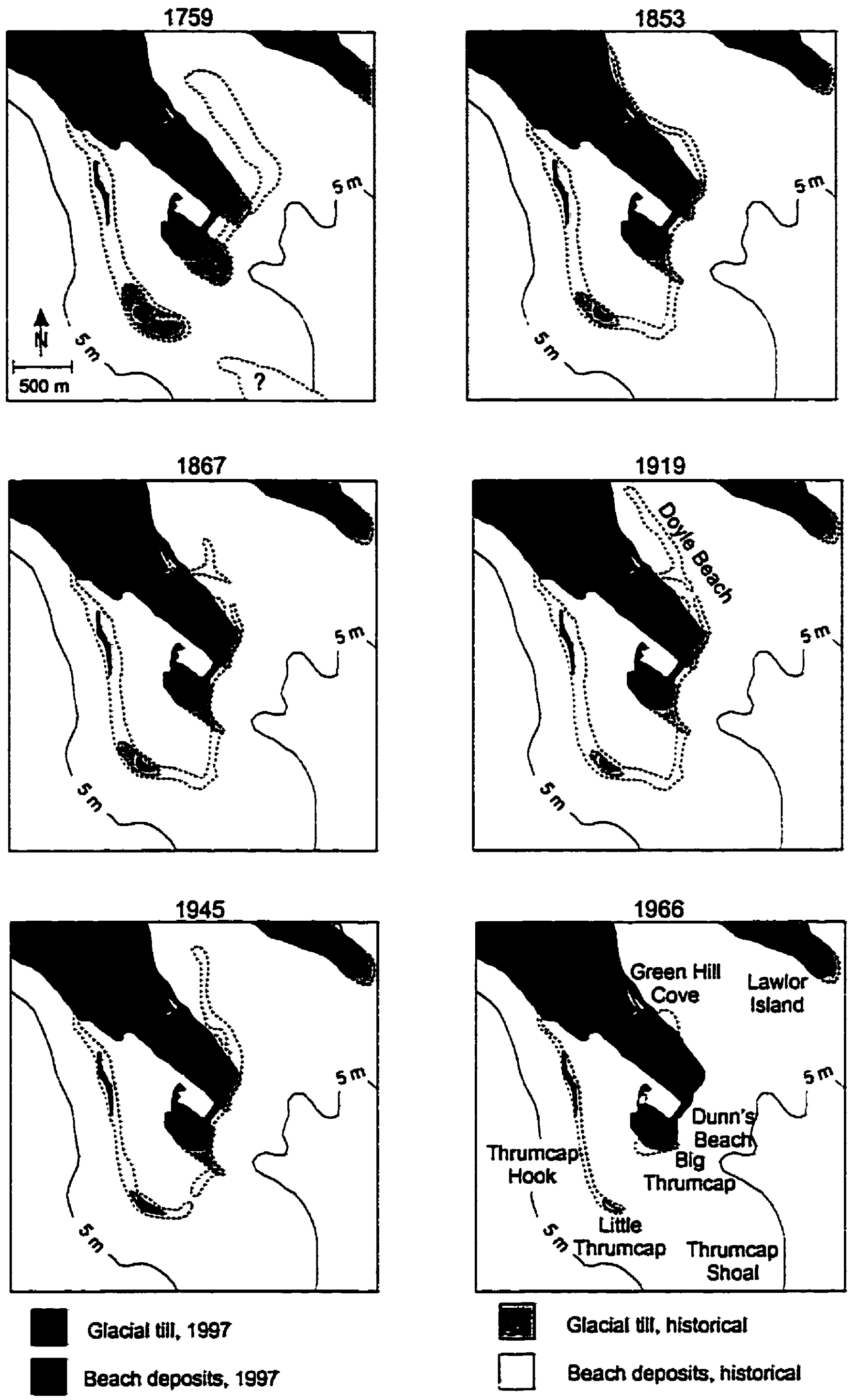


Figure 5.8 Schematic diagram of the historical evolution of the Thrumcaps and Doyle Beach since 1759 relative to the 1997 shoreline.

Maps and charts from 1867 (Rowe, 1867), 1886 (Akers, 1886) and 1915 (War Department, 1915) show the beach between Little and Big Thrumcap to have two prominent points where the transverse ridges connected to it (see also Figure 4.3a). By 1945 these had been eroded and rather than a tidal channel near Little Thrumcap, a new tidal channel had formed in the central portion of the beach between the former points. The beach had retreated approximately 150 m since 1919. Little change is apparent between 1853 and 1945 at the northern portion of Thrumcap Hook aside from a gradual infilling of the tidal channels. Between 1853 and 1945 little change occurred at either Big or Little Thrumcap prior to 1954.

Retreat at Big Thrumcap began again between 1945 and 1954 (Figure 5.1) as the eastern portion of the beach between Big and Little Thrumcap migrated rapidly north along the flank of Big Thrumcap exposing the promontory to wave attack. Lines M15A and B were still not directly exposed and show only small increases in retreat rate. The average rate of M14, M15A and M15B shows even less increase (Figure 5.1) because M14 did not retreat significantly until after 1992. Dunn's Beach migrated rapidly landward during this period. Thrumcap Hook appears to have developed larger overwash channels since 1945.

By 1960 the beach between Little and Big Thrumcap had been almost completely submerged. Rate of retreat at Big Thrumcap increased as a ness migrated north of M15A and B. By 1966, the promontory had retreated considerably, become more rounded and spit formation had begun at the north end of Big Thrumcap. Little Thrumcap was exposed to direct wave attack from the south; Little Thrumcap and the northern end of Thrumcap Hook eroded considerably between 1960 and 1966.

By 1982, two of the washover channels in northern Thrumcap Hook were infilled, the washover channel north of Little Thrumcap became well established, and Little Thrumcap was completely eroded. Retreat at M15A and B reached a maximum while, due to slumping and an indistinct bluff edge, retreat at M14 was negative. Spit progradation continued at the north end of Big Thrumcap across a shallow till shore platform. After 1982 a period of stability ensued to 1997, characterised by decreasing bluff and beach retreat rates. After 1997, however, bluff retreat accelerated, mainly at M14 although also at M15A and B.

Accelerated retreat after 1997 was measured at several locations on McNab's Island, but this result should be interpreted with caution. Field measurements were made over a period of only two years, as opposed to measurements from airphotos, which represent averages over ten years or more. Because bluff retreat occurs episodically, longer time averages give more representative retreat rates.

5.6 Discussion: Causes of Coastal Change at the Thrumcaps

The following discussion considers the historical records of storminess, sea level change and sediment supply, as they relate to rates of coastal change. The impacts and relative importance of storminess, sea-level rise and sediment supply on rates of coastal change are discussed.

After the submergence of what was most likely beach deposits (see Section 4.4) on Thrumcap Shoal between 1759 and 1776, sediment was fed to the beach landward of Thrumcap Shoal by transverse ridges. In response to initially abundant sediment supply a stable barrier beach formed. The presence of washover channels at the north end of

Thrumcap Hook indicates that no significant sediment from Thrumcap Shoal or the erosion of Little Thrumcap was being deposited here. As this was a period of fair-weather (DeIure, 1983), the relative stability during this time period is thought to reflect abundant sediment supply to Thrumcap Hook under conditions of low storminess; decadal rates of sea-level rise are unknown prior to 1896.

Between 1776 and 1853, the eastern side of Big Thrumcap (near M14) was not protected by the abundant beach sediment of Thrumcap Hook, and retreat that occurred there was likely caused by increasing storminess between 1798 and 1873 (Table 2.5; DeIure, 1983). As the stormy period ended, the bluffs on the east side of Big Thrumcap became inactive. Well-vegetated bluffs are shown in Figure 4.3a and no change in morphology is apparent at Big Thrumcap until the 1950s. The south end of Thrumcap Hook formed between Big and Little Thrumcap prior to 1853, indicating continuing abundant sediment supply from Thrumcap Shoal. Increasing storminess may have also played a role in the formation of the beach and resulted in depletion of the sediment reservoir over Thrumcap Shoal.

Increasing storminess causes higher waves and greater incident wave energy on both the beach face and the bluff toe resulting in increased erosion and retreat (see also Chapter 3). All other things being equal, according to solitary wave theory, higher waves also increase wave-generated near-bed shear stress in the nearshore and increase the potential for nearshore particle movement (Munk, 1949; Denny, 1995). Increasing storminess thus causes increased sediment supply from submerged sources over decadal time scales. Increased supply to a barrier occurs at the expense of future supply, and, if the sediment source is discrete (such as Thrumcap Shoal), can cause future supply limitation. It is in this manner that the south end of Thrumcap Hook likely developed and the sediment reservoir at Thrumcap Shoal became depleted.

The period after 1886 was characterised by low storminess and, at least after 1896, low rates of sea-level rise. These are, as demonstrated by the period of little morphologic change at Thrumcap Hook between 1853 and 1919, ideal conditions for the stability of subaerial portions of beaches. Conversely, landward transport of the submerged portion of barriers, that is, the shoreface sand sheet, may occur.

The seasonal movements of sediment in sandy beaches are well known; sand is moved offshore by short, steep waves generated by local storms in winter, and, is moved onshore by long period waves generated by distant storms during summer. This cycle may provide an analogy for the decadal-scale depletion of the shoreface sand sheet. During fairweather periods with few local storms, sand may be moved onshore and during periods of local storminess, sand is moved offshore resulting in a less steep beach profile and possibly more extensive sand sheet.

It is thought that the buildup of the south end of Thrumcap Hook reduced the gravel sediment reservoir submerged on Thrumcap Shoal. With reduction of the reservoir, less gravel was overpassing the sand sheet and without protection of overpassing clasts, near-bed shear stress generated by long period waves during a fairweather period between approximately 1886 and 1954 acted directly on the sand sheet and caused increased mobility. After 1886, sand began infilling at Maugher's Beach. It has been proposed in Section 4.4 that the most likely source of sand is from the shoreface sand sheet adjacent to Thrumcap Hook. The above discussion presents a possible mechanism for enhanced transportation to Maugher's Beach beginning at the time of increased deposition observed on historic charts.

No apparent retreat of the subaerial portions of Thrumcap Hook occurred until after 1920. For reasons discussed in Section 5.4, after 1920, sea level began rapidly rising. This possibly resulted in overstepping and further decreased sediment supply. Rapid retreat and morphologic change occurred at the south end of Thrumcap Hook until 1954. Retreat at this beach was accompanied by moderate progradation at the northern end of Thrumcap Hook indicating some landward movement of gravel sediment from the south end of Thrumcap Hook under rapidly rising sea-level.

Storminess increased between 1954 and 1966 (Section 5.3). With continuing decreasing sediment supply and rapidly rising sea level, retreat at the south end of Thrumcap Hook proceeded rapidly until it was destroyed between 1960 and 1966. The northern end of Thrumcap Hook again prograded with landward migration of the sediment liberated from the south end of Thrumcap Hook.

The period of storminess ended in 1964 and sea-level rise decreased in rate in 1970 resulting in a shift from instability back to stability. With decreasing rate of RSL rise, wave-generated shear stress over the remnant south end of Thrumcap Hook increased, resulting in increased sediment supply to the north end of Thrumcap Hook and progradation and stability through the 1980s and 1990s. Although this was a period of relatively low storminess, the wave climate appeared to become more energetic (and apparently continues to do so), further increasing wave shear stress on offshore sources and maintaining sediment supply. Counteracting increased sediment supply, however, is rise in sea level which accelerated after 1993. Overstepping of potential sediment sources may result.

With loss of the protective beach fronting Big Thrumcap, bluff retreat at M15A and B accelerated after 1954 and after 1992 at M14. The volume of sediment delivered by bluff retreat also accelerated after 1954 and peaked between 1966 and 1982 at 6465 m^3 of gravel and coarser material and 6845 m^3 of sand. The gravel and coarser sediment formed a migrating ness and the spit trailing Big Thrumcap but likely did not contribute significantly to subsequent development of Thrumcap Hook. The sand delivered by bluff retreat may have, however, in being added to the shoreface sand sheet, played an important role in subsequent stabilization.

Three mechanisms forcing decadal-scale coastal change have been discussed: sediment supply, sea-level rise, and storminess. Major coastal change occurs when at least two mechanisms coincide, and is most rapid when all three coincide. The destruction of Thrumcap Hook was conditioned by dwindling sediment supply after 1853 and became rapid when sea level began rising rapidly after 1920. The final phase of destruction occurred suddenly when dwindling supply, rapid sea-level rise, and increasing storminess coincided between 1954 and 1964. With relaxation of all three factors, a stable barrier was re-established but at a more landward location. In the vernacular of nonlinear dynamical systems, over decadal time scales the basin of attraction and the state of the system is controlled by a combination of climate, related sea-level rise, and sediment supply.

Section 5.3 suggested that rapidly rising sea-level and increased storminess may both be atmospherically controlled. The previous discussion of wave shear stress under different rates of RSL rise suggests that decreasing sediment supply and rapid sea-level rise may also not be independent. The interaction of dependent factors, possibly sharing feedback relationships, introduces nonlinear behaviour to the coastal system. These factors, due in part to relationships to the nonlinear climate system, all show some degree of nonlinear cyclicity. Cyclicity in behaviour of barrier beaches along the coast of Nova Scotia may result and may be related to the NAO.

This cyclicity depends on the position of the dynamical equilibrium between the inter-dependent forcing mechanisms controlling the state of the system. Because of the relationships between forcing mechanisms, however, their relative importance is difficult to ascertain and may change at a particular location over time and be different between locations. At Thrumcap Hook, the behaviour of the barrier was first influenced by decreasing sediment supply; subsequent rapid sea-level rise exacerbated this and coincident increasing storminess pushed the basin of attraction of the system past a threshold of stability to a state beyond which negative feedback failed or positive feedback occurred, and bifurcation of the barrier occurred.

The potential impacts of global climate change appear, on the Atlantic Coast of Nova Scotia, to not be restricted to sea-level rise alone; the relationship of storminess to the NAOI indicates changing storminess may result from global climate change. The relationships between sea-level rise, storminess and the NAOI result in coincidence of forcing mechanisms or controlling factors. Furthermore, sea-level change impacts sediment mobility and sediment supply to barrier beaches. Change in global climate could result in rapid change in barrier beaches and bluffs on the Atlantic Coast of Nova Scotia.

5.7 Conclusions

1) Storminess, as indicated by wind and wave measurements, is variable over decadal time scales. The most recent episode of increased storminess between 1954 and 1964 corresponds to an historical low in the 11 year mean of the NAOI, and was characterised by increasing strengths and frequencies of winter and summer storm winds and a slight change in modal storm direction. Frequencies and strengths of summer storm winds have increased during the 1990s and significant wave heights may show a similar pattern.

2) The rate of sea-level rise is also variable over decadal time scales. Rapid sea level rise (4.0 mm/a) occurred from 1920 to 1970 when it tapered to a rate of 0.3 mm/a. Rapid rise may have started again in the late 1990s. Rapid sea-level rise may correspond to a period of decreasing values in the 11 year mean of the NAOI from approximately 1915 to 1965.

3) At Thrumcap Hook, decreasing sediment supply from sources offshore and loss of the shoreface sand sheet preceded rapid sea-level rise in contributing to barrier beach overwash and destruction. Subsequent rapid sea-level rise and associated increased storminess caused rapid destruction of the subaerial barrier.

4) The transition from barrier stability to barrier instability occurs not in response to a single forcing mechanism, but in response to a change in the position of the dynamical equilibrium between factors affecting stability. The factors of decreasing sediment supply, rapid sea-level rise and increasing storminess are not independent of each other

and may be related through nonlinear feedback. Coincidence of factors may produce a bifurcation of the system.

5) The decadal scale impacts of climate change may manifest as accelerated sea-level rise, changing storminess, and decreasing sediment supply. These are all shown to affect the behaviour of barrier beaches in the study area; climate change may cause rapid and widespread coastal change on the Atlantic coast of Nova Scotia.

Chapter 6

Summary

Bluffs in the McNab's Island area are formed in drumlins composed mainly of facies of Lawrencetown Till. Shear strength of the Lawrencetown Till was shown to be dependent on water content through power curve relationships. Small increases in natural till water content cause large decreases in till shear strength, the property resisting erosion, and, in part, control the sub-annual to annual retreat and erosion of bluffs. Retreat and erosion also depend on the incident wave energy, the assailing force which promotes erosion.

Over sub-annual to annual time scales, storms were found to be a major cause of bluff retreat and erosion. Storms are accompanied by precipitation, high winds, high waves and storm surges. Bluffs fail through episodic rotational failure and flow processes, often during storms. Precipitation increases water content thus reducing shear strength, a process that may be exacerbated by increasing water content during periods of thaw. Wave attack at the bluff toe indirectly promotes bluff failure by oversteepening slopes and removing toe support; reduction in shear strength at the bluff top can then cause failure. Precipitation and spray elevate water content at the bluff toe and render the till more susceptible to erosion by waves during storms. Foreshore erosion is a major contributor to bluff retreat. Where low shear strength till is exposed in the foreshore, it is eroded by waves and mobile sand and gravel. Foreshore lowering results in increased wave energy and erosion at the bluff toe promoting bluff instability, whereas beaches protect the bluff toe and foreshore from direct wave attack and promote bluff stability.

Slowly retreating bluffs have high beaches while rapidly retreating bluffs have low beaches and exposures of till in the foreshore. Rapidly retreating bluffs appear to have been recently reactivated after periods of stability in the 1980s. During periods of stability, subaerial processes result in decreased shear strength of the bluff and the development of face-parallel tension cracks and zones of weakness, rendering the drumlin susceptible to rapid retreat when wave attack is re-initiated or intensified.

Over decadal time scales natural and anthropogenic changes in sediment supply, changing storminess and sea-level rise have caused variable rates of coastal change in the McNab's Island area. The period from 1759 to 1853 was characterised mostly by bluff retreat and landward movement of sediment resulting in progradation of beaches. Between 1853 and approximately 1920, little coastal change occurred except at Barrie Beach, Noonan's Beach, and Doyle Beach which were mined repeatedly for gravel. After 1920, coastal change began to accelerate, and peaked, in particular at the Thrumcaps, between 1954 and 1966. After 1966 little change occurred although possible increasing storminess and accelerated sea-level rise may contribute to an apparent increase in coastal change in the 1990s.

Sediment is supplied to gravel beaches mainly by retreating bluffs, barriers subject to overwash, and beach deposits submerged offshore during transgression. Bluffs supply the only new source of sediment, which usually forms small migrating nesses adjacent to the retreating bluff; all other sediment is reworked onshore during transgression. Where sediment is plentiful, beaches form and protect till bluffs and foreshores and reduce rates of coastal change. Beach mining is considered a loss from the sediment budget and beach and bluff retreat in the study area significantly accelerated after mining. Sediment supply at the Thrumcaps at the southwestern end of McNab's Island, is arguably limited not due to direct loss of sediment by mining, but by slowly dwindling sediment supply from Thrumcap Shoal. Beginning before 1853, progradation of Thrumcap Hook decreased the sediment reserve on Thrumcap Shoal and with less protective gravel overpassing the shoreface sand sheet, waves were able to transport the sand sheet from the front of the beach, increasing, in a positive feedback cycle, the susceptibility of the barrier to future destruction.

Relative sea-level rise is occurring at Halifax in response to global eustatic sea-level rise and isostatic subsidence following deglaciation. Considerable decadal variability in the rate of sea-level rise may be related to the 11 year running mean of the North Atlantic Oscillation Index. Sea-level was rising rapidly between approximately 1920 and 1970, causing accelerating retreat during that period. At the Thrumcaps, which by this time were disposed to retreat due to loss of the shoreface sand sheet, barrier retreat accelerated first in response to accelerated sea-level rise between approximately 1920 and 1955, and second in response to increasing storminess and continued rapid sea-level rise from approximately 1955 to 1964.

Increasing storminess is also important in causing accelerated coastal change. Incident energy is increased at the shoreline, resisting force is decreased, and water levels are elevated. Storminess, like relative sea-level rise, is also related to the 11 year running mean of the NAO. Between 1954 and 1966, the frequency and strength of winter and summer storms increased. At the Thrumcaps, rapid bluff retreat and the final destruction of a barrier resulted. Following 1964, storminess decreased, and the remnant south end of Thrumcap Hook supplied enough sediment to support a smaller barrier beach.

Stability resulted but may be short-lived as sea-level rise appears to have accelerated and storminess may have increased through the 1990s; bluffs appear to have been reactivated. At least two other stormy periods have occurred on the Atlantic coast of Nova Scotia, one between approximately 1635 and 1723 and one between approximately 1798 and 1873. Historical charts show the latter may have caused significant coastal change. Both periods are represented by deep lows in a proxy NAOI derived from oxygen isotope records from Greenland ice cores. Estimation of bluff retreat rates based on extrapolation of historical retreat rates measured from airphotos is, however, problematic because of the effects of vegetation and freezing on bluff retreat rates. McNab's Island has been deforested repeatedly since the mid-1700s and retreat likely accelerated following deforestation suggesting historical retreat rates may be higher than prior to the mid-1700s. Cooler temperatures may increase the effects of freeze and thaw cycles on bluff retreat and cause accelerated retreat relative to the warmer periods during which historical retreat rates are measured. Retreat during the cool 1800s and the Little Ice Age in the mid-1600s may have been accelerated.

Decadal scale coastal change is not caused by the variation of a single factor but occurs through the interaction of sediment supply, sea-level rise and storminess which all vary over diverse time scales. Sediment supply is indirectly related to sea-level rise and storminess. Near-bed wave-generated shear stress acts on submerged sources longer under slowly rising sea level and is highest under large waves. Periods with low rates of sea-level rise, as occurred from at least 1896 to 1920, cause depletion of sediment in offshore reserves because waves can act on sediment reserves for a longer period of time than under rapidly rising sea level. As it is sediment supply that determines the elevation of the beach crest and hence susceptibility to washover, decreasing supply increases the sensitivity of the barrier to accelerated sea-level rise and increasing storminess. A slow process of morphodynamic development during slow sea-level rise may be terminated by rapid destruction and retreat of barriers under increased storminess and accelerated sea-level rise. Morphodynamic conditioning to rapid beach retreat includes depletion of reserves of offshore sediment and loss of the sand sheet, while bluffs are morphodynamically conditioned by subaerial processes which raise water content and lower shear strength of the bluff-forming till.

Sediment supply, sea-level rise and storminess are not independent. Both sea-level rise and storminess are related to the North Atlantic Oscillation and display changes in behaviour during the historical minimum in the NAO Index. At the time of this minimum in 1964, storminess was high and sea-level rise rapid, but both decreased after 1970. Additionally, both storminess and sea-level rise affect sediment supply by increasing the rate of bluff retreat and the transport of sediment from offshore sources. It is usually when supply limitation, rapid sea-level rise, and increased storminess occur together that natural rapid coastal change and barrier beach destruction results.

Beach mining or dredging causes anthropogenic change of barrier beaches by lowering the elevation of the beach crest. The barrier becomes susceptible to overwash by small waves and is rapidly destroyed. Rapid sea-level rise and increased storminess are, in this case, not required to induce rapid coastal change, but beach mining and dredging can be considered a reduction in sediment supply. Coincidence of rapid sea-level rise, increased storminess and sediment supply limitation is not required for barrier beaches that have been subject to mining or dredging to experience rapid destruction.

The relationships between sediment supply, sea-level rise and storminess produce nonlinear and cyclical behaviour in the evolution of drumlin shorelines. As these three factors are variable and interact over diverse time scales some cyclicity in behaviour of barrier beaches may result. The period from 1873 to 1964 may represent a recent complete cycle of slow morphodynamic evolution terminating in rapid coastal change. Investigation of longer records containing multiple cycles of storminess and coastal change are required to address questions concerning the cyclicity and periodicity of episodes of rapid coastal change. The dependence of coastal evolution on climate indicates the importance of global climate change as a control on future rates of shoreline change.

While precise prediction of future coastal change is difficult, first because of the number of factors that control coastal evolution, and second because of their inter-relationships, the results of this study indicate that accelerated sea level rise and increasing storminess, if associated with global climate change, will cause rapid retreat of drumlin shorelines limited in sediment supply. Beaches may experience overwash and landward migration causing rates of bluff retreat to locally increase or decrease. Where bluffs are protected by migrating barriers stability will result, but with continued landward barrier migration, bluffs may become exposed to direct wave action and retreat rates may accelerate.

Appendix A
Survey Benchmark Locations

All positions are NAD83 with elevations given in metres above geodetic datum.

Identifier	Type	Easting	Northing	Elevation	Method
NS-5719	Provincial Benchmark	456966.93	4941154.29	7.15	RTK
NS-4354	Provincial Benchmark	463740.26	4938267.57	21.16	RTK
GSC152 TOP	Reference Station	459685.54	4938852.48	2.01	RTK
GSC247 TOP	Reference Station	459766.11	4938773.65	2.46	RTK
GSC-363 TOP	Reference Station	464086.36	4937713.00	8.40	RTK
GSC153 TOP	M1-AP	459786.32	4938678.31	8.72	RTK
GSC153 BASE	M1-AP	459786.36	4938678.37	8.42	RTK
M1-1B	base wood stake	459789.88	4938678.37	7.00	Emery
M2-AP	base wood stake	459778.37	4938647.08	12.89	RTK
M2-1	base rebar	459781.56	4938647.22	12.77	RTK
M3-AP	base rebar	459784.61	4938593.02	11.62	RTK
M3-1	base wood stake	459793.97	4938595.22	11.31	Emery
GSC154 TOP	M4-AP	459796.37	4938562.95	9.82	Emery
GSC154 BASE	M4-AP	459796.37	4938562.95	9.55	Emery
M4-1	base wood stake	459802.47	4938566.06	9.48	RTK
M5-AP	base rebar	460106.28	4938110.96	9.40	RTK
M5-1	base wood stake	460114.90	4938116.66	7.63	RTK
M6-AP	base rebar	460134.25	4938091.27	8.76	RTK
M6-1A	base wood stake	460138.12	4938095.02	7.73	RTK
M6-1B	base wood stake	460136.25	4938093.21	7.64	Emery
M7-AP	base rebar	460146.93	4938081.74	7.75	RTK
M7-1	base wood stake	460152.51	4938091.03	4.70	Emery
GSC155 TOP	M8-AP	460225.29	4937998.64	9.38	RTK
GSC155 BASE	M8-AP	460225.23	4937998.68	8.90	RTK
M8-1	base wood stake	460234.23	4938002.42	7.89	RTK
GSC156 TOP	M9-AP	460284.85	4937898.65	10.34	RTK
GSC156 BASE	M9-AP	460284.84	4937898.69	9.89	RTK
M9-1	base wood stake	460289.69	4937902.59	8.85	RTK
GSC157T	M10-AP	460349.78	4937807.23	11.44	RTK
GSC157B	M10-AP	460349.81	4937807.27	11.04	RTK
M10-1	base wood stake	460358.75	4937813.89	9.76	RTK
GSC158 BASE	M11-AP	460362.61	4937723.02	11.32	Emery
M11-1A	base wood stake	460367.95	4937720.07	11.42	RTK
M11-1B	base wood stake	460365.56	4937721.39	11.37	Emery
GSC159 TOP	M12-AP	460314.39	4937683.86	13.99	RTK
GSC159 BASE	M12-AP	460312.43	4937681.79	15.18	Emery
M12-1	base wood stake	460317.11	4937678.40	14.46	RTK
GSC160 TOP	M13-AP	460299.61	4937642.94	14.58	RTK
GSC160 BASE	M13-AP	460299.66	4937642.86	14.09	RTK
M13-1	base wood stake	460306.18	4937639.52	13.65	RTK
GSC161 TOP	M14-AP	460181.38	4937336.59	10.65	RTK
GSC161 BASE	M14-AP	460181.46	4937336.61	10.49	RTK
M14-1	base wood stake	460186.12	4937336.41	9.95	RTK
M14-2	base wood stake	460191.13	4937335.97	7.36	RTK
M15A-AP TOP	top rebar	460131.39	4937289.44	13.63	RTK
M15A-AP Base	base rebar	460131.30	4937289.38	13.26	RTK
M15A-1	base wood stake	460133.76	4937282.64	12.90	Emery
M15B-AP	base wood stake	460125.48	4937285.75	13.13	RTK
M15B-1	base wood stake	460125.55	4937281.22	12.85	RTK
GSC164 TOP	M17-AP	459129.87	4938562.38		RTK (pproc)
GSC164 BASE	M17-AP	459130.02	4938562.55		RTK (pproc)
M17-1	base wood stake	459125.97	4938556.50		RTK (pproc)
GSC166 TOP	M18-AP	458696.91	4938865.99		RTK (pproc)
GSC166 BASE	M18-AP	458696.91	4938865.98		RTK (pproc)
M18-1	base wood stake	458689.17	4938859.99		RTK (pproc)

Identifier	Type	Easting	Northing	Elevation	Method
GSC165 TOP	M19-AP	458647.40	4938925.69		RTK (pproc)
GSC165 BASE	M19-AP	458647.41	4938925.70		RTK (pproc)
M19-1	base wood stake	458640.30	4938917.76		RTK (pproc)
L1-AP	stump, landward side	461222.09	4938455.08	11.48	RTK (pproc)
L1-1	base wood stake	461224.65	4938451.61	10.92	RTK (pproc)
L2-AP	stump, seaward side	461223.52	4938464.07	11.76	RTK (pproc)
L2-1	base wood stake	461229.99	4938457.79	11.24	RTK (pproc)
L3-AP	stump, landward side	461228.90	4938469.94	11.86	RTK (pproc)
L3-1	base wood stake	461234.71	4938464.25	11.08	RTK (pproc)
L3-2	base wood stake	461231.97	4938466.88	11.44	RTK (pproc)
L4-AP	base wood stake	460482.09	4938833.83	7.31	RTK (pproc)
L4-1	base wood stake	460479.80	4938827.36	6.83	RTK (pproc)
L5-AP	base wood stake	460878.03	4938636.88		RTK (pproc)
L5-1	base wood stake	460877.10	4938633.20		RTK (pproc)

Appendix B
Field Water Content and Shear Strength Data

sampling date	Sample #	mass in grams M(wet)	M(dry)	% water interior	exterior	foreshore	shear strength (kPa) interior	exterior	foreshore
11/11/97	M14+2A	26.23	22.73		15.44			29.41	
11/11/97	M14+2B	29.38	26.00	13.00			54.75		
12/01/98	M14+15	33.76	29.58	14.14			40.43		
10/02/98	M14-15	41.86	36.91			13.41			48.88
10/02/98	M14+0	45.71	40.74		12.21			68.72	
10/02/98	M14+0b	34.32	30.86	11.23			93.00		
19/04/98	M14+5A	61.81	56.11	10.17			132.99		
19/04/98	M14+5B	56.36	50.20			12.27			67.38
29/04/98	M14+1B	50.90	45.46	11.98			73.49		
29/04/98	M14+1A	55.24	48.47		13.96			42.24	
10/05/98	M14+2A	53.98	45.43		18.82			14.37	
10/05/98	M14+2B	51.15	45.55	12.29			67.11		
21/06/98	M14+5A	67.60	59.93		12.78			58.13	
21/06/98	M14+5B	52.94	47.87	10.58			115.18		
05/08/98	M14+5A	41.03	40.37		1.63			99976.39	
05/08/98	M14+5B	45.77	41.57	10.10			136.22		
26/08/98	M14+5A	72.18	64.15		12.51			62.85	
26/08/98	M14+5B	51.77	46.93	10.30			126.83		
26/08/98	M14-20	67.53	60.89			10.90			103.43
02/09/98	M14+5A	33.05	31.75		4.10			3529.72	
02/09/98	M14+5B	44.96	40.93	9.85			149.34		
02/09/98	M14-2	63.04	55.16			14.28			39.00
20/09/98	M14+5A	35.72	34.37		3.91			4193.74	
20/09/98	M14+5B	45.34	41.27	9.88			147.68		
13/10/98	M14+5A	79.81	70.68		12.93			55.80	
13/10/98	M14+5B	65.49	59.68	9.73			155.83		
27/10/98	M14+5A	30.01	28.36		5.84			984.65	
27/10/98	M14+5B	48.84	44.33	10.18			132.44		
27/10/98	M14-30	64.63	57.21			12.97			55.20
05/11/98	M14+25	26.38	22.75			15.97			26.01
05/11/98	M14+25	20.65	17.88			15.51			28.93
05/11/98	M14+30	30.82	27.58			11.76			78.52
05/11/98	M14+30	25.89	23.22			11.48			85.71
09/11/98	M14+2A	70.02	61.60		13.67			45.69	
09/11/98	M14+2B	46.15	41.45	11.36			89.02		
14/11/98	M14 +15A	52.29	46.74		11.87			76.01	
14/11/98	M14+15B	46.93	42.80	9.65			160.64		
22/11/98	M14+10A	74.72	63.88		16.97			20.89	
22/11/98	M14+10B	52.02	47.22	10.15			133.61		
08/12/98	M14+5A	69.46	58.93		17.88			17.30	
08/12/98	M14+5B	56.16	51.18	9.72			156.62		
13/12/98	M14+5A	69.12	59.70		15.78			27.17	
13/12/98	M14+5B	46.69	42.64	9.50			170.23		
13/12/98	M14-30-1A	29.56	26.53			11.43			87.01
13/12/98	M14-30-1B	27.37	24.54			11.53			84.30
13/12/98	M14-30-2A	35.57	31.49			12.95			55.55
13/12/98	M14-30-2B	39.88	35.64			11.92			74.92
17/12/98	M14+5A	53.27	47.17		12.94			55.68	
17/12/98	M14+5B	45.02	40.94	9.97			142.57		
11/01/99	M14+5A	62.24	53.05		17.33			19.37	
11/01/99	M14+5B	68.68	61.17	12.28			67.19		
18/01/99	M14+0A	78.11	68.40		14.20			39.81	
18/01/99	M14+0B	68.15	60.51	12.63			60.72		
30/01/99	M14+2A	62.34	53.70		16.09			25.33	
30/01/99	M14+2B	57.60	50.67	13.67			45.60		
30/01/99	M14-30A	55.31	49.11			12.62			60.90
30/01/99	M14-30B	55.48	50.12			10.70			110.64
12/02/99	M14+10A	58.33	50.94		14.52			36.67	
12/02/99	M14+10B	42.65	38.59	10.53			117.34		
03/03/99	M14-5A	48.44	42.96		12.77			58.37	
03/03/99	M14-5B	43.45	39.24	10.73			109.54		
23/03/99	M14-15A	55.09	48.63		13.29			50.56	
23/03/99	M14-15B	61.78	55.93	10.44			120.68		

sampling date	Sample #	mass in grams		% water			shear strength (kPa)		
		M(wet)	M(dry)	interior	exterior	foreshore	interior	exterior	foreshore
23/03/99	M14-10A	40.64	36.78			10.51			117.80
23/03/99	M14-10B	64.13	57.06			12.39			65.03
02/05/99	M14-10A	47.08	45.72		2.97			11359.97	
02/05/99	M14-10B	36.87	34.05	8.27			280.94		
10/02/98	M15A-24	38.09	34.17	11.45			86.65		
10/02/98	M15A-25	33.34	31.54	5.71			1069.58		
28/02/98	M15A+0	35.01	30.99	13.00			54.67		
28/02/98	M15A+20	47.80	43.31	10.35			124.59		
19/04/98	M15A-24	51.27	46.56	10.12			135.11		
29/04/98	M15A-23B	44.47	40.52	9.76			154.23		
29/04/98	M15A-23A	35.40	32.87		7.71			361.64	
10/05/98	M15A-23A	42.59	38.65		10.19			131.82	
10/05/98	M15A-23B	38.03	34.62	9.85			149.17		
21/06/98	M15A-24A	33.28	31.07		7.12			482.10	
21/06/98	M15A-24B	48.57	44.15	10.01			140.49		
05/08/98	M15A-20A	32.86	32.23		1.96			50962.58	
05/08/98	M15A-20B	51.42	49.91	3.03			10604.85		
26/08/98	M15A-24A	49.03	44.32		10.61			114.00	
26/08/98	M15A-24B	40.78	37.03	10.15			133.99		
02/09/98	M15A-30	47.01	42.98			9.38			178.28
02/09/98	M15A-24A	36.43	35.31		3.17			8956.32	
02/09/98	M15A-24B	59.13	53.72	10.07			137.80		
20/09/98	M15A-23A	38.46	37.60		2.28			29462.48	
20/09/98	M15A-23B	41.87	38.21	9.58			164.63		
20/09/98	M15B-5	45.08	40.77			10.58			115.22
13/10/98	M15A-24A	60.65	53.42		13.54			47.20	
13/10/98	M15A-24B	64.29	58.40	10.08			137.04		
27/10/98	M15A-24A	48.35	45.66		5.89			958.75	
27/10/98	M15A-24B	31.85	29.87	6.62			626.65		
09/11/98	M15A-24A	34.32	32.99		4.03			3754.97	
09/11/98	M15A-24B	43.34	39.82	8.85			219.57		
14/11/98	M15A-24A	42.36	41.50		2.07			42263.73	
14/11/98	M15A-24B	43.34	40.19	7.82			342.71		
22/11/98	M15A-24A	66.10	56.90		16.17			24.84	
22/11/98	M15A-24B	52.31	47.54	10.04			139.28		
08/12/98	M15A-24A	32.92	31.56		4.33			2911.74	
08/12/98	M15A-24B	56.09	51.16	9.63			161.81		
13/12/98	M15A-24A	37.92	36.96		2.61			18167.94	
13/12/98	M15A-24B	46.93	43.08	8.93			213.01		
13/12/98	M15A-25A	61.27	54.09			13.27			50.75
13/12/98	M15A-25B	49.90	45.24			10.29			127.21
13/12/98	M15B+0A	24.21	22.15			9.30			183.51
13/12/98	M15B+0B	23.41	21.32			9.80			152.13
17/12/98	M15A-24A	42.51	40.81		4.16			3374.80	
17/12/98	M15A-24B	51.40	46.69	10.08			136.99		
11/01/99	M15A-24A	54.69	48.04		13.85			43.49	
11/01/99	M15A-24B	50.78	45.58	11.40			87.85		
18/01/99	M15A-24A	32.85	31.55		4.10			3530.49	
18/01/99	M15A-24B	39.18	35.35	10.82			106.22		
30/01/99	M15A-26A	68.45	61.33			11.60			82.63
30/01/99	M15A-26B	79.07	69.59			13.62			46.18
30/01/99	M15A-24A	38.32	37.84		1.28			238624.72	
30/01/99	M15A-24B	51.07	46.31	10.27			128.08		
12/02/99	M15A-24A	41.26	39.94		3.32			7636.62	
12/02/99	M15A-24B	46.59	42.35	10.00			141.36		
03/03/99	M15A-24A	38.52	35.15		9.60			163.88	
03/03/99	M15A-24B	51.18	46.45	10.19			131.82		
23/03/99	M15A-24A	46.84	42.39		10.49			118.67	
23/03/99	M15A-24B	45.85	41.66	10.08			137.20		
23/03/99	M15A-30A	65.71	58.50			12.32			66.46
23/03/99	M15A-30B	55.73	48.37			15.21			31.04
02/05/99	M15A-25A	37.01	36.57		1.19			313057.63	
02/05/99	M15A-25B	41.83	38.90	7.53			393.99		
11/11/97	M11-10	25.22	22.59		11.63			81.75	
12/01/98	M12+50	29.73	27.16	9.44			174.23		
10/02/98	M10+50	37.85	32.98	14.74			34.74		
10/02/98	M11-18	35.91	32.28	11.25			92.35		
10/02/98	M11-20A	23.75	22.82			4.07			3652.21

sampling date	Sample #	mass in grams		% water			shear strength (kPa)		
		M(wet)	M(dry)	interior	exterior	foreshore	interior	exterior	foreshore
10/02/98	M13+35A	36.41	32.85		10.81			106.42	
10/02/98	M13+35B	37.97	33.93	11.92			74.92		
10/02/98	M11-20B	35.47	32.07	10.59			114.85		
28/02/98	M10+50	47.51	43.17	10.07			137.71		
28/02/98	M13+30	44.72	40.62	10.10			136.21		
19/04/98	M13+10	40.63	37.00	9.80			152.11		
29/04/98	M10+50A	52.06	44.38		17.32			19.39	
29/04/98	M10+50B	43.42	38.84	11.80			77.68		
10/05/98	M10+50A	47.52	42.90		10.76			108.39	
10/05/98	M10+50B	50.63	45.63	10.96			101.24		
21/06/98	M10+50A	40.93	37.78		8.34			272.73	
21/06/98	M10+50B	60.54	54.77	10.52			117.51		
05/08/98	M10+50A	53.22	51.96		2.43			23441.18	
05/08/98	M10+50B	31.06	29.12	6.64			620.20		
26/08/98	M10+50A	58.31	51.71		12.76			58.56	
26/08/98	M10+50B	50.64	46.05	9.96			143.35		
20/09/98	M10+50A	28.80	27.48		4.82			1976.25	
20/09/98	M10+50B	52.95	47.71	10.99			100.34		
13/10/98	M10+50A	88.27	77.09		14.50			36.91	
13/10/98	M10+50B	50.65	45.85	10.49			119.01		
27/10/98	M10+50A	36.06	33.63		7.23			455.52	
27/10/98	M10+50B	55.55	50.89	9.15			194.34		
09/11/98	M10+50A	46.64	41.60		12.12			70.56	
09/11/98	M10+50B	52.60	48.02	9.53			168.27		
14/11/98	M10+50A	57.12	51.58		10.75			108.92	
14/11/98	M10+50B	40.97	37.22	10.07			137.85		
22/11/98	M10+50A	59.18	51.69		14.50			36.84	
22/11/98	M10+50B	59.82	54.65	9.47			172.22		
08/12/98	M10+50A	59.94	53.61		11.81			77.40	
08/12/98	M10+50B	47.32	43.02	9.99			141.83		
13/12/98	M10+50A	60.14	52.65		14.22			39.55	
13/12/98	M10+50B	54.76	49.89	9.76			154.06		
13/12/98	M11+40A	23.32	17.10			36.41			1.32
13/12/98	M11+40B	15.54	11.92			30.35			2.56
17/12/98	M10+50A	52.49	46.80		12.15			69.88	
17/12/98	M10+50B	56.54	51.11	10.61			114.19		
11/01/99	M10+50A	64.71	55.46		16.66			22.30	
11/01/99	M10+50B	52.46	47.16	11.25			92.36		
18/01/99	M10+50A	57.17	50.39		13.45			48.33	
18/01/99	M10+50B	42.88	38.70	10.81			106.70		
30/01/99	M10+50A	44.35	43.39		2.21			33053.31	
30/01/99	M10+50B	40.64	36.73	10.63			113.07		
12/02/99	M10+50A	65.94	56.06		17.61			18.27	
12/02/99	M10+50B	50.38	43.77	15.12			31.68		
03/03/99	M10+50A	45.01	40.11		12.22			68.44	
03/03/99	M10+50B	55.93	50.23	11.36			89.01		
23/03/99	M10+50A	72.53	64.54		12.38			65.37	
23/03/99	M10+50B	63.91	57.67	10.83			106.00		
23/03/99	M12+20A	79.33	70.59			12.38			65.26
23/03/99	M12+20B	75.35	65.45			15.12			31.71
02/05/99	M10+50A	36.98	36.01		2.69			16175.73	
02/05/99	M10+50B	36.46	33.50	8.81			223.17		
11/11/97	M11-5A	26.35	23.61		11.60			25.15	
11/11/97	M11-5B	31.00	28.13	10.21			34.53		
12/01/98	M11+08	35.33	31.72	11.39			26.40		
26/08/98	M11+10A	29.13	26.77		8.82			47.25	
26/08/98	M11+10B	35.72	33.17	7.69			61.07		
13/12/98	M11+5A	47.20	41.74		13.07			18.00	
13/12/98	M11+5B	41.00	36.15	13.43			16.61		
17/12/98	M11+5A	53.82	47.10		14.27			13.73	
17/12/98	M11+5B	43.11	38.76	11.22			27.41		
11/01/99	M11+3A	36.14	31.03		16.45			8.36	
11/01/99	M11+3B	41.16	36.19	13.74			15.48		
18/01/99	M11+5A	48.32	42.86		12.75			19.39	
18/01/99	M11+5B	56.82	50.73	12.00			22.97		
30/01/99	M11+1A	33.35	29.18		14.29			13.67	
30/01/99	M11+1B	41.03	34.58	18.65			5.08		
12/02/99	M11+2A	37.47	28.95		29.43			0.44	

sampling date	Sample #	mass in grams M(wet)	M(dry)	% water interior	exterior	foreshore	shear strength (kPa) interior	exterior	foreshore
12/02/99	M11+2B	51.20	45.38	12.83			19.04		
03/03/99	M11+1A	55.78	49.61		12.44			20.79	
03/03/99	M11+1B	49.01	44.21	10.85			29.81		
23/03/99	M11+1A	59.48	52.78		12.71			19.57	
23/03/99	M11+1B	61.60	55.35	11.30			26.92		
02/05/99	M11+1A	38.27	33.81		13.20			17.48	
02/05/99	M11+1B	30.55	25.81	18.36			5.43		
11/11/97	M8+50A	34.84	30.89		12.79			19.21	
11/11/97	M8+50B	32.32	29.43	9.82			37.68		
12/01/98	M8+10	30.96	27.31	13.37			16.85		
10/02/98	M9+10	40.25	35.69	12.78			19.26		
28/02/98	M8+50	42.50	37.85	12.27			21.58		
19/04/98	M8+50	59.89	52.55	13.96			14.72		
19/04/98	M9+0	66.48	58.97	12.73			19.45		
29/04/98	M8+50B	57.84	51.22	12.93			18.59		
29/04/98	M8+50A	83.58	72.80		14.80			12.16	
10/05/98	M8+50A	62.29	54.05		15.26			10.95	
10/05/98	M8+50B	44.05	38.90	13.23			17.37		
21/06/98	M8+50A	52.20	44.77		16.60			8.07	
21/06/98	M8+50B	64.53	55.39	16.51			8.25		
05/08/98	M8+50A	45.19	39.92		13.21			17.44	
05/08/98	M8+50B	56.54	49.47	14.28			13.70		
26/08/98	M8+60A	79.15	70.43		12.39			21.05	
26/08/98	M8+60B	57.57	51.39	12.03			22.84		
20/09/98	M9+10A	60.26	53.96		11.67			24.76	
20/09/98	M9+10B	39.36	35.42	11.11			28.15		
13/10/98	M9+20A	75.94	67.17		13.06			18.07	
13/10/98	M9+20B	61.61	55.26	11.49			25.77		
27/10/98	M8+50A	67.92	59.63		13.89			14.95	
27/10/98	M8+50B	66.79	59.59	12.09			22.49		
27/10/98	M9+10A	44.06	38.58		14.22			13.87	
27/10/98	M9+10B	35.32	31.59	11.81			23.97		
09/11/98	M9+10A	42.08	37.12		13.36			16.87	
09/11/98	M9+10B	42.53	37.84	12.41			20.91		
14/11/98	M9+10A	56.21	49.17		14.31			13.61	
14/11/98	M9+10B	57.05	50.35	13.32			17.02		
22/11/98	M9+10A	78.93	67.69		16.61			8.06	
22/11/98	M9+10B	47.52	42.10	12.88			18.82		
08/12/98	M9+10A	55.49	49.01		13.23			17.39	
08/12/98	M9+10B	30.92	27.96	10.58			31.69		
13/12/98	M9+10A	66.20	57.71		14.70			12.43	
13/12/98	M9+10B	47.32	42.53	11.26			27.18		
17/12/98	M9+10A	51.36	43.65		17.66			6.36	
17/12/98	M9+10B	46.52	40.92	13.69			15.65		
11/01/99	M9+10A	56.85	49.15		15.65			10.03	
11/01/99	M9+10B	43.42	38.46	12.89			18.76		
18/01/99	M9+10A	30.67	24.57		24.81			1.25	
18/01/99	M9+10B	36.62	29.11	25.80			1.00		
30/01/99	M9+10A	30.64	20.62		48.62			0.01	
30/01/99	M9+10B	40.55	25.87	56.78			0.00		
12/02/99	M9+5A	72.05	62.19		15.86			9.56	
12/02/99	M9+5B	47.29	38.53	22.73			2.01		
03/03/99	M9+10A	58.99	50.69		16.37			8.52	
03/03/99	M9+10B	18.65	15.43	20.85			3.08		
23/03/99	M9+10A	52.46	44.20		18.67			5.05	
23/03/99	M9+10B	67.47	58.43	15.46			10.47		
02/05/99	M9+10A	44.97	39.81		12.96			18.46	
02/05/99	M9+10B	36.44	32.95	10.60			31.54		
11/11/97	M6-10A	36.70	32.98		11.28			91.46	
11/11/97	M6-10B	37.86	34.38	10.10			136.20		
10/02/98	M5+20	55.46	47.22	17.45			18.88		
10/02/98	M5+0	32.50	27.89			16.54			22.92
28/02/98	M6-2	41.66	37.44	11.28			91.49		
19/04/98	M6+0	58.70	51.79	13.34			49.80		
29/04/98	M5+10A	52.18	46.65		11.87			76.00	
29/04/98	M5+10B	46.41	41.69	11.32			90.34		
10/05/98	M5+10A	55.67	49.66		12.09			71.22	
10/05/98	M5+10B	42.69	38.46	10.99			100.39		

sampling date	Sample #	mass in grams		% water			shear strength (kPa)		
		M(wet)	M(dry)	interior	exterior	foreshore	interior	exterior	foreshore
21/06/98	M5+3A	64.17	56.56		13.45			48.34	
21/06/98	M5+3B	47.65	42.94	10.96			101.25		
05/08/98	M5+5A	46.81	43.64		7.26			448.93	
05/08/98	M5+5B	39.44	36.10	9.25			187.31		
26/08/98	M5+5A	57.41	50.54		13.59			46.57	
26/08/98	M5+5B	44.24	40.04	10.48			119.23		
02/09/98	M5+2A	49.88	44.69		11.62			82.15	
02/09/98	M5+2B	62.18	55.80	11.42			87.32		
02/09/98	M5+20	57.61	49.53			16.32			24.07
20/09/98	M5+1A	46.89	42.11		11.34			89.52	
20/09/98	M5+1B	65.66	58.79	11.69			80.36		
20/09/98	M5+0	65.48	58.40			12.12			70.58
13/10/98	M5+2A	60.86	52.70		15.47			29.15	
13/10/98	M5+2B	58.23	52.51	10.90			103.60		
27/10/98	M5+1A	45.28	39.46		14.73			34.83	
27/10/98	M5+1B	44.64	40.43	10.41			122.26		
09/11/98	M5+2A	60.39	53.65		12.56			62.00	
09/11/98	M5+2B	46.17	41.77	10.53			117.00		
14/11/98	M5+1A	58.94	51.46		14.55			36.39	
14/11/98	M5+1B	54.89	48.99	12.04			72.28		
22/11/98	M5+1A	68.56	58.94		16.32			24.04	
22/11/98	M5+1B	52.30	46.07	13.53			47.33		
08/12/98	M5+2A	43.79	37.21		17.69			17.98	
08/12/98	M5+2B	53.82	48.10	11.89			75.51		
13/12/98	M5+1A	49.16	41.25		19.15			13.48	
13/12/98	M5+1B	56.87	48.01	18.46			15.42		
17/12/98	M5+1A	61.06	51.89		17.67			18.04	
17/12/98	M5+1B	56.41	50.63	11.41			87.57		
11/01/99	M5+2A	70.72	60.01		17.85			17.39	
11/01/99	M5+2B	52.61	46.01	14.35			38.31		
18/01/99	M5+1A	52.30	44.39		17.82			17.51	
18/01/99	M5+1B	38.43	32.00	20.09			11.36		
30/01/99	M5+0A	34.49	33.54		2.84			13281.58	
30/01/99	M5+0B	37.26	30.32	22.89			7.08		
12/02/99	M5-2A	41.73	37.14		12.36			65.70	
12/02/99	M5-2B	54.86	45.17	21.44			8.97		
03/03/99	M5+1A	55.20	48.37		14.11			40.65	
03/03/99	M5+1B	43.07	37.66	14.36			38.19		
23/03/99	M5-5A	65.59	56.99		15.10			31.88	
23/03/99	M5-5B	53.80	48.55	10.80			106.78		
02/05/99	M5+1A	52.50	47.50		10.54			116.79	
02/05/99	M5+1B	46.14	42.30	9.09			199.69		
11/11/97	M5+20A	27.82	23.58	17.99			3.65		
10/02/98	M5+20B	25.01	18.93	32.12			-0.59		
12/01/98	M3+20	38.12	33.03	15.41			29.58		
10/02/98	M2+30	39.44	35.69	10.49			118.71		
28/02/98	M2+10	31.94	28.98	10.19			131.81		
19/04/98	M1+0	46.50	41.85	11.10			96.71		
19/04/98	M1+30	46.10	41.74	10.44			121.07		
29/04/98	M1+5A	42.38	38.70		9.50			170.11	
29/04/98	M1+5B	44.11	40.07	10.10			136.19		
10/05/98	M1+5A	59.75	53.33		12.04			72.20	
10/05/98	M1+5B	51.98	46.34	12.17			69.42		
21/06/98	M1+5A	26.34	24.14		9.11			198.12	
21/06/98	M1+5B	37.92	34.06	11.33			89.90		
05/08/98	M1+5A	42.96	42.37		1.40			170278.10	
05/08/98	M1+5B	30.41	28.18	7.88			334.07		
26/08/98	M1+5A	79.98	70.84		12.89			56.39	
26/08/98	M1+5B	54.47	49.26	10.58			115.23		
20/09/98	M1+5A	35.74	34.59		3.32			7606.15	
20/09/98	M1+5B	38.11	34.65	9.98			142.47		
13/10/98	M1+5A	82.36	72.21		14.05			41.30	
13/10/98	M1+5B	59.01	53.32	10.67			111.76		
27/10/98	M1+3A	33.12	31.66		4.61			2322.63	
27/10/98	M1+3B	40.13	36.77	9.13			195.90		
09/11/98	M1+10A	34.60	32.10		7.79			347.66	
09/11/98	M1+10B	54.77	49.74	10.11			135.65		
14/11/98	M1+2A	41.98	37.77		11.17			94.81	

sampling date	Sample #	mass in grams M(wet)	M(dry)	% water interior	exterior	foreshore	shear strength (kPa) interior	exterior	foreshore
14/11/98	M1+2B	54.28	48.74	11.35			89.27		
22/11/98	M1+1A	75.21	65.62		14.62			35.77	
22/11/98	M1+1B	50.74	45.57	11.36			89.18		
08/12/98	M1+10A	54.43	49.18		10.68			111.33	
08/12/98	M1+10B	55.91	50.65	10.39			122.84		
08/12/98	M2+0A	20.59	16.89			21.91			8.29
08/12/98	M2+0B	20.69	16.52			25.27			4.95
13/12/98	M1+5A	72.06	64.03		12.55			62.21	
13/12/98	M1+5B	46.18	42.00	9.96			143.38		
13/12/98	M3+0A	43.58	37.57			15.99			25.91
13/12/98	M3+0B	25.87	21.88			18.19			16.24
17/12/98	M1+20A	57.61	50.72		13.59			46.59	
17/12/98	M1+20B	59.95	54.81	9.38			178.16		
11/01/99	M1+5A	72.39	62.79		15.29			30.47	
11/01/99	M1+5B	50.52	44.81	12.76			58.46		
11/01/99	M1+10A	45.41	40.44			12.30			66.76
11/01/99	M1+10B	66.51	59.22			12.30			66.73
18/01/99	M1+5A	78.15	67.48		15.81			26.95	
18/01/99	M1+5B	51.43	45.34	13.42			48.77		
30/01/99	M1+5A	33.48	31.12		7.56			387.48	
30/01/99	M1+5B	59.53	51.14	16.40			23.63		
12/02/99	M1+5A	59.61	49.79		19.71			12.15	
12/02/99	M1+5B	71.90	63.25	13.67			45.66		
03/03/99	M1+5A	56.33	49.96		12.73			58.97	
03/03/99	M1+5B	72.11	63.37	13.78			44.28		
23/03/99	M1+10A	55.54	49.79		11.56			83.69	
23/03/99	M1+10B	63.30	56.96	11.12			96.07		
23/03/99	M1+1A	57.37	51.33			11.75			78.74
23/03/99	M1+1B	67.60	61.59			9.77			153.79
02/05/99	M1+5A	30.82	29.90		3.08			9959.07	
02/05/99	M1+5B	41.24	37.21	10.81			106.56		
10/02/98	M4+0	14.76	12.19	21.11			2.90		
10/02/98	M4+2	36.74	32.36						
10/05/98	M2+20B	59.37	52.32	13.47			16.46		
21/06/98	M2+70A	48.44	38.57		25.61			1.04	
21/06/98	M2+70B	48.05	41.56	15.60			10.15		
26/08/98	M1+20A	37.20	36.09		3.07			174.64	
26/08/98	M1+20B	29.54	27.88	5.97			90.27		
13/10/98	M2+10A	43.22	37.06		16.63			8.02	
13/10/98	M2+10B	42.97	38.24	12.36			21.19		
27/10/98	M2+20A	40.27	35.48		13.52			16.25	
27/10/98	M2+20B	45.55	40.97	11.20			27.57		
09/11/98	M2 +20A	55.46	48.01		15.52			10.32	
09/11/98	M2+20B	54.56	48.70	12.03			22.82		
14/11/98	M2+10A	44.43	38.79		14.56			12.84	
14/11/98	M2+10B	47.21	41.81	12.90			18.74		
22/11/98	M2+10A	55.30	48.90		13.07			18.00	
22/11/98	M2+10B	48.09	41.99	14.51			13.00		
08/12/98	M2+10A	64.94	57.24		13.46			16.50	
08/12/98	M2+10B	61.21	53.97	13.41			16.67		
13/12/98	M2+10A	58.92	50.99		15.55			10.26	
13/12/98	M2+10B	60.90	53.79	13.23			17.37		
17/12/98	M2+10A	35.35	30.81		14.73			12.35	
17/12/98	M2+10B	44.89	39.49	13.67			15.72		
11/01/99	M2+20A	27.29	21.61		26.27			0.90	
11/01/99	M2+20B	38.15	30.52	24.99			1.20		
18/01/99	M2+10A	40.62	30.45		33.40			0.18	
18/01/99	M2+10B	24.88	19.71	26.25			0.90		
30/01/99	M2+10A	34.36	28.56		20.32			3.47	
30/01/99	M2+10B	26.55	15.01	76.84					
12/02/99	M2+10A	47.22	39.96		18.17			5.66	
12/02/99	M2+10B	53.09	41.23	28.77			0.51		
03/03/99	M2+10A	52.99	44.66		18.65			5.07	
03/03/99	M2+10B	40.72	33.64	21.05			2.94		
23/03/99	M2+10A	75.97	65.91		15.26			10.96	
23/03/99	M2+10B	50.33	44.11	14.11			14.21		
02/05/99	M2+10A	40.28	35.80		12.51			20.45	
02/05/99	M2+10B	41.71	37.66	10.75			30.48		

sampling date	Sample #	mass in grams		% water			shear strength (kPa)		
		M(wet)	M(dry)	interior	exterior	foreshore	interior	exterior	foreshore
11/11/97	L4-10	34.69	31.27	10.93			102.31		
12/01/98	L4+1	37.83	34.21	10.59			114.63		
19/04/98	L4+35A	49.39	43.93		12.43			64.41	
19/04/98	L4+35B	45.35	41.17	10.14			134.54		
29/04/98	L4+35B	42.64	38.73	10.09			136.51		
29/04/98	L4+35A	66.73	56.38		18.37			15.69	
10/05/98	L4+35B	32.52	29.38	10.68			111.33		
10/05/98	L4+35A	61.20	52.24		17.15			20.10	
21/06/98	L4+34A	71.13	61.90		14.91			33.31	
21/06/98	L4+34B	42.72	38.51	10.94			101.95		
05/08/98	L4+35A	31.12	30.41		2.33			27391.58	
05/08/98	L4+35B	35.89	33.27	7.89			331.96		
26/08/98	L4+35A	35.17	31.91		10.24			129.65	
26/08/98	L4+35B	39.57	36.14	9.49			170.66		
02/09/98	L4-5	55.11	48.90			12.70			59.49
02/09/98	L4+35A	37.29	34.54		7.97			320.46	
02/09/98	L4+35B	39.49	36.13	9.28			185.07		
20/09/98	L4+36A	23.16	22.36		3.59			5715.59	
20/09/98	L4+36B	42.99	39.55	8.70			233.92		
20/09/98	L4+0	46.13	41.47			11.24			92.45
13/10/98	L4+35A	62.53	51.89		20.50			10.55	
13/10/98	L4+35B	60.57	55.45	9.23			188.38		
27/10/98	L4+35A	29.34	27.93		5.03			1687.50	
27/10/98	L4+35B	38.60	35.48	8.79			225.23		
05/11/98	L4+10	24.49	22.12			10.75			108.66
09/11/98	L4+38A	43.76	38.96		12.30			66.81	
09/11/98	L4+38B	44.65	40.94	9.07			200.80		
14/11/98	L4+38A	59.17	53.07		11.49			85.48	
14/11/98	L4+38B	55.45	50.79	9.17			192.80		
22/11/98	L4+38A	58.94	51.34		14.81			34.16	
22/11/98	L4+38B	45.51	41.26	10.31			126.43		
08/12/98	L4+35A	59.69	53.18		12.24			68.02	
08/12/98	L4+35B	47.80	43.14	10.80			106.98		
13/12/98	L4+35A	40.75	37.00		10.13			134.60	
13/12/98	L4+35B	49.16	44.82	9.68			158.55		
13/12/98	L4-40A	32.53	28.44			14.41			37.73
13/12/98	L4-40B	27.21	24.45			11.29			91.17
17/12/98	L4+35A	38.82	33.88		14.59			36.06	
17/12/98	L4+35B	36.80	33.46	9.98			142.43		
17/12/98	L4-5A	44.88	40.00			12.22			68.51
17/12/98	L4-5B	44.15	40.21			9.80			151.90
11/01/99	L4-10A	48.40	42.53			13.80			44.08
11/01/99	L4-10B	46.82	41.96			11.58			83.12
11/01/99	L4+35A	62.79	52.21		20.25			11.03	
11/01/99	L4+35B	51.79	46.41	11.59			82.90		
18/01/99	L4+35A	45.23	40.93		10.50			118.36	
18/01/99	L4+35B	49.68	44.26	12.25			67.91		
30/01/99	L4+10A	67.65	57.68			17.29			19.54
30/01/99	L4+10B	55.90	49.89			12.04			72.24
30/01/99	L4+30A	73.79	63.24		16.68			22.22	
30/01/99	L4+30B	68.86	62.08	10.92			102.65		
12/02/99	L4+35A	49.70	42.17		17.87			17.34	
12/02/99	L4+35B	45.57	40.84	11.60			82.66		
03/03/99	L4+35A	56.71	48.12		17.85			17.40	
03/03/99	L4+35B	61.62	54.87	12.31			66.72		
23/03/99	L4+35A	75.94	67.31		12.82			57.57	
23/03/99	L4+35B	72.35	65.98	9.65			160.67		
23/03/99	L4-30A	53.65	47.28			13.46			48.25
23/03/99	L4-30B	43.12	38.31			12.56			62.04
02/05/99	L4+35A	30.94	29.03		6.59			639.03	
02/05/99	L4+35B	34.73	32.12	8.12			299.16		
11/11/97	L5-25	27.46	25.50	7.67					
12/01/98	L4+200	40.08	34.55	16.00					
12/01/98	L1-100	46.11	39.78	15.92					
29/04/98	L1-40B	32.06	29.69	8.00					
29/04/98	L1-40A	27.90	25.73		8.41				
29/04/98	L5-10B	37.93	35.70	6.22					
10/05/98	L5+5	36.96	35.37		4.49				

Appendix C
Bluff and Foreshore Erosion Data

Bluff Erosion

	erosion (cm) btw survey			days btw survey	erosion rate (m/a)			erosion rate (m/a)
survey date	**upper**	**mid**	**lower**		**upper**	**mid**	**lower**	**avg.**
M5+5								
26/11/97								
16/12/97		3.9		20		0.712		0.71
12/01/98	12.4	9.1	13.8	27	1.676	1.230	1.866	1.59
28/01/98								
03/02/98	16.1		18.0	6	9.794		10.950	10.37
28/02/98								
08/03/98	36.4	38.1	39.2	8	16.608	17.383	17.885	17.29
10/05/98								
21/06/98	0.3	0.2	0.0	42	0.026	0.017	0.000	0.01
05/08/98	1.8	18.4		45	0.146	1.492		0.82
26/08/98	4.8	0.7		21	0.834	0.122		0.48
01/09/98	0.3	0.1		6	0.183	0.061		0.12
20/09/98	0.2			19	0.038			0.04
13/10/98	1.1	1.7		23	0.175	0.270		0.22
29/10/98	0.0	0.0		16	0.000	0.000		0.00
09/11/98	0.0	0.0		11	0.000	0.000		0.00
14/11/98	0.0	0.1		5	0.000	0.073		0.04
22/11/98	6.5	0.9		8	2.943	0.411		1.68
08/12/98				16				
13/12/98		0.0		5		0.000		0.00
17/12/98		0.0		4		0.000		0.00
11/01/99	36.6	33.6	32.5	25	5.344	4.906	4.745	5.00
18/01/99				7				
30/01/99		19.2		12		5.840		5.84
12/02/99		1.0		13		0.281		0.28
03/03/99		8.8		19		1.691		1.69
23/03/99		17.5		20		3.194		3.19
02/05/99	50.0	50.0	50.0	40	4.563	4.563	4.563	4.56
M14+1								
26/11/97								
16/12/97	8.1	12.1		20	1.478	2.208		1.84
12/01/98	12.3	13.4	13.5	27	1.663	1.811	1.825	1.77
28/01/98				16				
03/02/98	14.9	18.8		6	9.064	11.437		10.25
10/02/98	16.1	17.8	18.1	7	8.395	9.281	9.438	9.04
17/02/98	13.3			7	6.935			6.94
28/02/98	18.7		16.1	11	6.205		5.342	5.77
08/03/98	0.1	0.4	7.0	8	0.046	0.183	3.194	1.14
29/03/98	7.3	8.4		21	1.269	1.460		1.36
19/04/98	3.2	0.2	0.6	21	0.556	0.035	0.104	0.23
29/04/98		0.0	0.2	10		0.000	0.073	0.04
10/05/98				11				
21/06/98	2.0	2.2		42	0.174	0.191		0.18
05/08/98	3.1	1.5	1.8	45	0.251	0.122	0.146	0.17
26/08/98				21				

01/09/98			0.9	6			0.548	0.55
20/09/98	0.3		5.4	19	0.058		1.037	0.55
13/10/98	23.8	27.5	23.7	23	3.777	4.364	3.761	3.97
15/10/98								
29/10/98		0.5		14		0.117	0.000	0.06
05/11/98			8.6	7			4.484	4.48
09/11/98	0.0	0.0	0.1	4	0.000	0.000	0.091	0.03
14/11/98	2.0	0.0		5	1.460	0.000		0.73
22/11/98	0.6	0.0	3.6	8	0.297	0.000	1.643	0.65
08/12/98	1.0	0.3	0.5	16	0.217	0.068	0.114	0.13
13/12/98		0.3	0.0	5		0.219		0.22
17/12/98	0.2			4	0.183			0.18
11/01/99	44.6			25	6.512			6.51
18/01/99	38.5			7	20.075			20.08
30/01/99	5.9	17.7		12	1.795	5.384		3.59
12/02/99	35.0			13	9.827			9.83
03/03/99	23.6			19	4.534			4.53
23/03/99	26.4	50.0	50.0	20	4.818	9.125	9.125	7.69
02/05/99		2.2		40		0.201		0.20
M15A-25								
26/11/97								
16/12/97	0.8	3.2	3.9	20	0.146	0.584	0.712	0.48
12/01/98	12.3	13.5	13.8	27	1.663	1.825	1.866	1.78
28/01/98								
03/02/98	10.9	14.2	3.6	6	6.631	8.638	2.190	5.82
10/02/98	0.5	1.7		7	0.261	0.886		0.57
17/02/98	0.9	3.6	10.7	7	0.469	1.877	5.579	2.64
28/02/98	17.7	15.5	8.6	11	5.873	5.143	2.854	4.62
08/03/98	0.7		2.3	8	0.319		1.049	0.68
29/03/98								
19/04/98	0.6	2.3	4.6	21	0.104	0.400	0.800	0.43
29/04/98		0.8	5.7	10		0.292	2.081	1.19
10/05/98	0.0	0.2		11	0.000	0.066		0.03
21/06/98		3.9		42		0.339		0.34
05/08/98	1.7			45	0.138			0.14
26/08/98		3.8		21		0.660		0.66
01/09/98	0.1	6.8	4.1	6	0.061	4.137	2.494	2.23
20/09/98	1.0	1.2	10.5	19	0.192	0.231	2.017	0.81
13/10/98		1.9		23		0.302		0.30
29/10/98	2.1	0.6		16	0.479	0.137	0.000	0.21
05/11/98	0.2	0.0	3.1	7	0.104	0.000	1.616	0.57
09/11/98		0.1		4		0.091		0.09
14/11/98	1.0	0.5		5	0.730	0.365		0.55
22/11/98	2.8	0.4		8	1.278	0.183		0.73
08/12/98		0.2	1.4	16		0.046	0.319	0.18
13/12/98	0.3	0.5		5	0.219	0.365		0.29
17/12/98	0.0		1	4	0.000		0.913	0.46
11/01/99	29.0	23.0		25	4.234	3.358		3.80
18/01/99	10.9			7	5.684			5.68
30/01/99	4.9			12	1.490			1.49
12/02/99	8.8			13	2.471			2.47
03/03/99	7.6	11.6		19	1.460	2.228		1.84
23/03/99	7.1	8.4		20	1.296	1.533		1.41
02/05/99	0.5	11.2	5.9	40	0.046	1.022	0.538	0.54
L4+40								
12/01/98								
28/01/98	12.6	13.0	13.9	16	2.874	2.966	3.171	3.00

10/02/98	18.4	17.5	19.3	13	5.166	4.913	5.419	5.17
17/02/98	18.2	18.6	17.8	7	9.490	9.699	9.281	9.49
28/02/98	17.9	18.1	19.5	11	5.940	6.006	6.470	6.14
08/03/98	0.0			8	0.000			0.00
29/03/98	28.2			21	4.901			4.90
19/04/98				21				
29/04/98	0.1			10	0.037			0.04
10/05/98	0.0		1.1	11	0.017		0.348	0.18
21/06/98	0.9	0.5		42	0.074	0.043		0.06
05/08/98	4.5	3.3	1.9	45	0.365	0.268	0.154	0.26
26/08/98				21				
01/09/98	0.5		0.1	6	0.304		0.061	0.18
20/09/98		0.8		19		0.154		0.15
13/10/98	2.4	0.5		23	0.381	0.079		0.23
29/10/98	0.2	0.0		16	0.046	0.000		0.02
09/11/98		0.0		11		0.000		0.00
14/11/98	0.0			5	0.000			0.00
22/11/98	0.2	0.0		8	0.091	0.000		0.05
08/12/98	0.5	0.8		16	0.114	0.183		0.15
13/12/98		2.7		5		1.971		1.97
17/12/98	0.1	0.5		4	0.091	0.456		0.27
11/01/99	17.4	12.8	3.5	25	2.540	1.869	0.511	1.64
18/01/99		0.1	2.0	7		0.052	1.043	0.55
30/01/99	0.0			12	0.000			0.00
12/02/99	21.9	13.5	5.6	13	6.149	3.790	1.572	3.84
03/03/99	22.8			19	4.380			4.38
23/03/99	26.0	7.6	9.3	20	4.745	1.387	1.697	2.61

Foreshore Erosion

survey date	erosion (cm) btw survey			days btw survey	erosion rate (mm/a)			mean erosion rate (m/a)
	A	B	C		A	B	C	
M5+20								
10/05/98								
21/06/98	3.45	2.55	2.90	42	299.82	221.61	252.02	0.26
05/08/98	-0.32	3.00	1.30	45		243.33	105.44	0.17
01/09/98	0.60	0.01	0.63	27	81.11	1.35	85.17	0.06
20/09/98	0.64	0.69	0.71	19	122.95	132.55	136.39	0.13
M5+15								
21/06/98								
05/08/98	0.50	1.50	1.35	45	40.56	121.67	109.50	0.09
01/09/98	-2.12	-2.50	-1.27	27				
20/09/98	2.17	3.10	1.66	19	416.87	595.53	318.89	0.44
05/11/98	-11.58	-7.75	-11.79	46				
L4-5								
29/04/98								
10/05/98	0.30	0.00	0.32	11	99.55	0.00	106.18	0.07
21/06/98	2.78	2.76	1.38	42	241.60	239.86	119.93	0.20
05/08/98	0.02	-0.06	0.00	45	1.62		0.00	0.00

26/08/98	-0.33	-0.36	-0.38	21				
01/09/98	0.34	1.51	0.19	6	206.83	918.58	115.58	0.41
20/09/98	3.59	3.18	2.40	19	689.66	610.89	461.05	0.59
05/11/98	1.40	2.92	3.69	46	111.09	231.70	292.79	0.21
14/11/98	1.75	-0.20	3.15	9	709.72		1277.50	0.99
17/12/98	-4.30	-2.72	-5.50	33				
11/01/99	2.70	0.52	-1.65	25	394.20	75.92		0.24
18/01/99	-0.85	0.00	-0.05	7		0.00		0.00
30/01/99	1.00	0.05	0.05	12	304.17	15.21	15.21	0.11
02/05/99	-8.00	-0.65	-3.40	92				
L4+0								
29/03/98								
31/03/98	0.00	0.00	0.00	2	0.00	0.00	0.00	0.00
29/04/98	2.12	1.97	1.10	29	266.83	247.95	138.45	0.22
10/05/98	0.22	0.15	0.02	11	73.00	49.77	6.64	0.04
21/06/98	0.68	0.32	1.75	42	59.10	27.81	152.08	0.08
05/08/98	2.30	3.23	2.20	45	186.56	261.99	178.44	0.21
26/08/98	0.50	-0.05	0.35	21	86.90		60.83	0.07
01/09/98	-1.50	-1.23	-2.20	6				
20/09/98	0.25	0.10	1.19	19	48.03	19.21	228.61	0.10
05/11/98	0.05	2.10	2.93	46	3.97	166.63	232.49	0.13
14/11/98	0.10	-0.65	-1.70	9	40.56			0.04
17/12/98	-0.90	-4.97	-5.30	33				
11/01/99	0.40	3.30	2.68	25	58.40	481.80	391.28	0.31
18/01/99	0.50	0.80	0.40	7	260.71	417.14	208.57	0.30
30/01/99	-1.95	-1.18	-0.30	12				
02/05/99	-7.00	-7.52	-7.75	92				
L4+30								
05/11/98								
14/11/98	0.59	0.92	0.50	9	239.28	373.11	202.78	0.27
17/12/98	0.88	1.35	1.20	33	97.33	149.32	132.73	0.13
11/01/99	-6.30	-7.66	-5.80	25				
18/01/99	3.10	4.26	0.12	7	1616.43	2221.29	62.57	1.30
30/01/99	-0.60	0.33	-0.02	12		100.38		0.10
02/05/99	-7.10	-8.68	-3.59	92				

Appendix D
Bluff Sediment Volume Data

line	retreat (m)	bluff length (m)	elevation AP (m)	elevation wood stake (m)	distance (m)	bluff height (m)	volume delivered (m^3)	% > 256 mm	% gravel	%sand	%mud	volume coarse (m^3)	volume gravel (m^3)	volume sand (m^3)	volume mud (m^3)	total (m^3)	E_s (m)	RMS error (m)	E_v (m^3)
1934 to 1945																			
M1	0.00	91.89	8.42	7.00	3.52	0.00	0.00	4.1	9.0	33.7	52.8	0.0	0.0	0.0	0.0	0.0	1.94	1.89	0.00
M2	0.00	0.00	12.89	12.77	3.19	0.00	0.00	4.1	8.9	33.6	52.9	0.0	0.0	0.0	0.0	0.0	1.94	1.89	0.00
M3	0.00	0.00	11.62	11.31	9.63	0.00	0.00	4.1	9.0	33.7	52.8	0.0	0.0	0.0	0.0	0.0	1.94	1.89	0.00
M4	0.00	0.00	9.55	9.48	6.85	0.00	0.00	4.0	9.2	33.9	52.5	0.0	0.0	0.0	0.0	0.0	1.94	1.89	0.00
M5	3.24	22.65	9.40	7.63	10.34	1.68	122.95	5.9	10.8	32.3	50.2	7.3	13.3	39.7	61.7	122.0	2.69	2.70	204.54
M6	0.00	0.00	8.76	7.64	2.79	5.64	0.00	5.4	9.9	36.5	47.5	0.0	0.0	0.0	0.0	0.0	2.69	2.70	0.00
M7	0.00	0.00	7.75	4.70	10.84	2.72	0.00	5.9	10.8	32.3	50.2	0.0	0.0	0.0	0.0	0.0	2.69	2.70	0.00
M8	0.00	0.00	8.90	7.89	9.75	4.67	0.00	5.5	11.7	32.8	49.6	0.0	0.0	0.0	0.0	0.0	2.69	2.70	0.00
M9	4.47	98.28	9.89	8.85	6.22	4.97	2,184.52	5.7	11.7	32.2	50.0	123.6	255.6	703.6	1093.1	2175.9	2.69	2.70	2,634.13
M10	3.71	186.54	11.04	9.76	11.13	6.66	4,611.52	5.8	11.7	31.7	50.4	268.3	538.4	1462.4	2323.8	4592.9	2.69	2.70	6,699.76
M11	15.70	93.21	11.32	11.37	3.37	7.51	10,994.41	5.0	16.2	33.5	44.4	554.9	1781.7	3686.2	4885.8	10908.5	2.69	2.70	3,774.51
M12	0.00	110.91	15.18	14.46	5.78	10.44	0.00	5.2	15.8	33.3	44.9	0.0	0.0	0.0	0.0	0.0	2.69	2.70	6,241.08
M13	3.89	82.94	14.09	13.65	7.33	10.39	3,351.06	5.2	15.8	33.3	44.9	173.9	530.4	1115.5	1504.0	3323.8	2.69	2.70	4,643.25
M14	9.36	168.64	10.49	7.36	9.70	2.28	3,606.35	3.9	13.0	26.1	57.0	140.5	468.6	939.5	2056.6	3605.2	2.69	2.70	2,076.73
M15A	0.00	0.00	13.26	12.90	7.18	11.80	0.00	13.7	11.6	23.0	51.6	0.0	0.0	0.0	0.0	0.0	2.69	2.70	0.00
M15B	0.00	0.00	13.13	12.85	4.54	11.31	0.00	4.0	12.9	25.6	57.5	0.0	0.0	0.0	0.0	0.0	2.69	2.70	0.00
L1			11.48	10.92	4.31	9.01	0.00	5.6	12.2	32.7	49.0	0.0	0.0	0.0	0.0	0.0	2.88	1.61	0.00
L2			11.76	11.24	9.02	9.07	0.00	5.6	12.2	32.7	49.1	0.0	0.0	0.0	0.0	0.0	2.88	1.61	0.00
L3			11.85	11.44	4.34	8.66	0.00	5.6	12.3	32.8	48.9	0.0	0.0	0.0	0.0	0.0	2.88	1.61	0.00
L4	0.00		7.31	6.83	6.63	4.98	0.00	5.1	11.1	32.5	50.8	0.0	0.0	0.0	0.0	0.0	2.88	1.61	0.00
L5			9.37	9.19	3.87	5.84	0.00	44.5	27.2	20.4	7.6	0.0	0.0	0.0	0.0	0.0	2.88	1.61	0.00
1945 to 1954																			
M1	0	0.00	8.42	7.00	3.52	0.00	0.00	4.1	9.0	33.7	52.8	0.0	0.0	0.0	0.0	0.0	3.93	3.22	0
M2	0	36.64	12.89	12.77	3.19	9.05	0.00	4.1	8.9	33.6	52.9	0.0	0.0	0.0	0.0	0.0	3.93	3.22	2373.303
M3	0	46.11	11.62	11.31	9.63	7.18	0.00	4.1	9.0	33.7	52.8	0.0	0.0	0.0	0.0	0.0	3.93	3.22	2369.246
M4	0	0.00	9.55	9.48	6.85	0.00	0.00	4.0	9.2	33.9	52.5	0.0	0.0	0.0	0.0	0.0	3.93	3.22	0
M5	12.09	31.82	9.40	7.63	10.34	1.00	384.70	5.9	10.8	32.3	50.2	22.7	41.6	124.3	193.0	381.6	4.10	2.07	196.3546
M6	11.57	32.69	8.76	7.64	2.79	1.00	378.22	5.4	9.9	36.5	47.5	20.3	37.3	138.1	179.5	375.2	4.10	2.07	201.7232
M7	11.13	21.48	7.75	4.70	10.84	1.00	239.07	5.9	10.8	32.3	50.2	14.1	25.9	77.3	119.9	237.2	4.10	2.07	132.5486
M8	11.67	129.29	8.90	7.89	9.75	1.18	1786.75	5.5	11.7	32.8	49.6	97.8	209.6	585.8	886.7	1780.0	4.10	2.07	944.7846
M9	6.99	97.12	9.89	8.85	6.22	0.23	157.78	5.7	11.7	32.2	50.0	8.9	18.5	50.8	78.9	157.2	4.10	2.07	139.286
M10	0	0.00	11.04	9.76	11.13	3.05	0.00	5.8	11.7	31.7	50.4	0.0	0.0	0.0	0.0	0.0	4.10	2.07	0
M11	20.67	124.51	11.32	11.37	3.37	7.87	20241.57	5.0	16.2	33.5	44.4	1021.5	3280.2	6786.6	8995.1	20083.4	4.10	2.07	6042.891
M12	52.97	75.88	15.18	14.46	5.78	1.38	5557.57	5.2	15.8	33.3	44.9	288.1	880.4	1850.5	2493.3	5512.3	4.10	2.07	647.4346
M13	34.92	62.30	14.09	13.65	7.33	7.50	16321.12	5.2	15.8	33.3	44.9	846.9	2583.3	5432.9	7325.0	16188.1	4.10	2.07	2884.142
M14	0	165.39	10.49	7.36	9.70	0.28	0.00	3.9	13.0	26.1	57.0	0.0	0.0	0.0	0.0	0.0	4.10	2.07	289.9415
M15A	0	0.00	13.26	12.90	7.18	8.43	0.00	13.7	11.6	23.0	51.6	0.0	0.0	0.0	0.0	0.0	4.10	2.07	0
M15B	0	0.00	13.13	12.85	4.54	8.18	0.00	4.0	12.9	25.6	57.5	0.0	0.0	0.0	0.0	0.0	4.10	2.07	0
L1	9.61	367.56	11.48	10.92	4.31	2.89	10222.96	5.6	12.2	32.7	49.0	575.7	1250.1	3343.4	5014.1	10183.2	3.76	2.76	6933.392
L2	10.17	18.05	11.76	11.24	9.02	6.37	1169.17	5.6	12.2	32.7	49.1	65.9	142.9	382.1	573.7	1164.6	3.76	2.76	749.2878
L3	10.75	58.71	11.85	11.44	4.34	4.29	2706.32	5.6	12.3	32.8	48.9	151.5	331.7	888.4	1324.3	2695.9	3.76	2.76	1640.828
L4	0	497.27	7.31	6.83	6.63	3.93	0.00	5.1	11.1	32.5	50.8	0.0	0.0	0.0	0.0	0.0	3.76	2.76	12745.07
L5	0	123.33	9.37	9.19	3.87	5.08	0.00	44.5	27.2	20.4	7.6	0.0	0.0	0.0	0.0	0.0	3.76	2.76	4080.064
1954 to 1966																			
M1	0	28.38	8.42	7.00	3.52	0.00	0.00	4.1	9.0	33.7	52.8	0.0	0.0	0.0	0.0	0.0	3.41	2.26	0
M2	0	26.80	12.89	12.77	3.19	9.05	0.00	4.1	8.9	33.6	52.9	0.0	0.0	0.0	0.0	0.0	3.41	2.26	1377.022
M3	12.26	49.86	11.62	11.31	9.63	7.18	4390.48	4.1	9.0	33.7	52.8	178.3	395.7	1480.6	2317.0	4371.6	3.41	2.26	2032.243
M4	14.25	32.08	9.55	9.48	6.85	6.08	2779.64	4.0	9.2	33.9	52.5	111.6	255.1	942.9	1458.2	2767.9	3.41	2.26	1106.952
M5	0	0.00	9.40	7.63	10.34	0.00	0.00	5.9	10.8	32.3	50.2	0.0	0.0	0.0	0.0	0.0	4.31	3.54	0
M6	0	0.00	8.76	7.64	2.79	1.48	0.00	5.4	9.9	36.5	47.5	0.0	0.0	0.0	0.0	0.0	4.31	3.54	0

line	retreat (m)	bluff length (m)	elevation AP (m)	elevation wood stake (m)	distance (m)	bluff height (m)	volume delivered (m^3)	% > 256 mm	% gravel	%sand	%mud	volume coarse (m^3)	volume gravel (m^3)	volume sand (m^3)	volume mud (m^3)	total (m^3)	E_s (m)	RMS error (m)	E_v (m^3)
M7	0	0.00	7.75	4.70	10.84	1.36	0.00	5.9	10.8	32.3	50.2	0.0	0.0	0.0	0.0	0.0	4.31	3.54	0
M8	7.73	129.29	8.90	7.89	9.75	2.39	2391.69	5.5	11.7	32.8	49.6	131.0	280.6	784.1	1187.0	2382.6	4.31	3.54	2429.073
M9	7.21	97.12	9.89	8.85	6.22	1.40	981.14	5.7	11.7	32.2	50.0	55.5	114.8	316.0	490.9	977.3	4.31	3.54	1068.343
M10	22.6	201.06	11.04	9.76	11.13	3.05	13879.46	5.8	11.7	31.7	50.4	807.4	1620.4	4401.4	6994.1	13823.3	4.31	3.54	4821.475
M11	0	49.15	11.32	11.37	3.37	7.56	0.00	6.0	16.2	33.6	44.4	0.0	0.0	0.0	0.0	0.0	4.31	3.54	2916.521
M12	5.19	64.57	15.18	14.46	5.78	7.98	2674.59	5.2	15.8	33.3	44.9	138.6	423.7	890.5	1199.9	2652.8	4.31	3.54	4045.809
M13	5.9	69.47	14.09	13.65	7.33	9.60	3934.10	5.2	15.8	33.3	44.9	204.2	622.7	1309.6	1765.6	3902.0	4.31	3.54	5234.901
M14	4.61	170.45	10.49	7.36	9.70	0.28	223.23	3.9	13.0	26.1	57.0	8.7	29.0	58.2	127.3	223.2	4.31	3.54	380.1653
M15A	25.52	65.00	13.26	12.90	7.18	8.43	13984.75	13.7	11.6	23.0	51.6	1921.7	1618.8	3217.5	7223.1	13981.1	4.31	3.54	4302.186
M15B	0	0.00	13.13	12.85	4.54	8.18	0.00	4.0	12.9	25.6	57.5	0.0	0.0	0.0	0.0	0.0	4.31	3.54	0
L1	21.93	386.12	11.48	10.92	4.31	4.14	35079.68	5.6	12.2	32.7	49.0	1975.5	4289.5	11472.6	17205.5	34943.2	3.92	2.55	10352.91
L2	21.65	13.62	11.76	11.24	9.02	6.96	2050.96	5.6	12.2	32.7	49.1	115.6	250.7	670.3	1006.3	2043.0	3.92	2.55	613.1198
L3	20.48	86.30	11.85	11.44	4.34	5.30	9373.69	5.6	12.3	32.8	48.9	524.7	1148.7	3077.1	4586.9	9337.5	3.92	2.55	2962.281
L4	14.47	506.17	7.31	6.83	6.63	3.93	28801.99	5.1	11.1	32.5	50.8	1465.0	3202.6	9362.3	14626.4	28656.3	3.92	2.55	12882.48
L5	11.22	117.13	9.37	9.19	3.87	5.08	6670.63	44.5	27.2	20.4	7.6	2967.8	1815.1	1360.9	506.1	6649.9	3.92	2.55	3847.861
1966 to 1982																			
M1	4.67	21.75	8.42	7.00	3.52	0.00	0.00	4.1	9.0	33.7	52.8	0.0	0.0	0.0	0.0	0.0	3.74	2.56	0
M2	32.92	22.54	12.89	12.77	3.19	9.05	6718.39	4.1	8.9	33.6	52.9	274.5	599.6	2258.6	3556.6	6689.3	3.74	2.56	1286.235
M3	26.03	41.00	11.62	11.31	9.63	7.58	8086.46	4.1	9.0	33.7	52.8	328.4	728.8	2727.0	4267.5	8051.7	3.74	2.56	1957.937
M4	22.22	45.51	9.55	9.48	6.85	6.23	6296.06	4.0	9.2	33.9	52.5	252.8	577.9	2135.7	3303.0	6269.4	3.74	2.56	1785.829
M5	7.95	32.40	9.40	7.63	10.34	0.00	0.00	5.9	10.8	32.3	50.2	0.0	0.0	0.0	0.0	0.0	3.20	2.46	0
M6	0	0.00	8.76	7.64	2.79	1.48	0.00	5.4	9.9	36.5	47.5	0.0	0.0	0.0	0.0	0.0	3.20	2.46	0
M7	0	0.00	7.75	4.70	10.84	1.36	0.00	5.9	10.8	32.3	50.2	0.0	0.0	0.0	0.0	0.0	3.20	2.48	0
M8	14.26	132.24	8.90	7.89	9.75	3.19	6018.55	5.5	11.7	32.8	49.6	329.5	706.2	1973.1	2986.9	5995.7	3.20	2.46	2388.755
M9	18.82	104.61	9.89	8.85	6.22	2.61	5077.41	5.7	11.7	32.2	50.0	287.3	594.2	1635.3	2540.7	5057.5	3.20	2.48	1542.258
M10	12.49	135.10	11.04	9.76	11.13	5.65	9539.87	5.8	11.7	31.7	50.4	554.9	1113.8	3025.3	4807.3	9501.3	3.20	2.46	4319.911
M11	12.32	57.68	11.32	11.37	3.37	7.56	5361.78	5.0	16.2	33.5	44.4	270.6	868.9	1797.7	2382.7	5319.9	3.20	2.46	2461.46
M12	5.35	59.92	15.18	14.46	5.78	8.63	2765.75	5.2	15.8	33.3	44.9	143.4	438.1	920.9	1240.8	2743.2	3.20	2.46	2923.841
M13	11.12	60.26	14.09	13.65	7.33	9.95	6669.08	5.2	15.8	33.3	44.9	346.1	1055.6	2220.0	2993.1	6614.7	3.20	2.46	3392.001
M14	0	131.04	10.49	7.36	9.70	1.77	0.00	3.9	13.0	26.1	57.0	0.0	0.0	0.0	0.0	0.0	3.20	2.48	1313.036
M15A	29.46	67.36	13.26	12.90	7.18	9.71	19269.16	13.7	11.6	23.0	51.6	2647.9	2230.6	4433.3	9952.4	19264.1	3.20	2.48	3699.345
M15B	37.98	30.34	13.13	12.85	4.54	8.18	9425.88	4.0	12.9	25.6	57.5	372.6	1214.4	2412.2	5424.1	9423.1	3.20	2.46	1403.659
L1	15.53	400.59	11.48	10.92	4.31	6.99	43499.50	5.6	12.2	32.7	49.0	2449.7	5319.1	14226.3	21335.2	43330.3	4.23	2.98	20191.05
L2	15.03	12.41	11.76	11.24	9.02	8.20	1530.14	5.6	12.2	32.7	49.1	86.3	187.0	500.1	750.8	1524.2	4.23	2.98	733.869
L3	15.07	88.75	11.85	11.44	4.34	7.24	9681.00	5.6	12.3	32.8	48.9	541.9	1186.4	3178.0	4737.3	9643.6	4.23	2.98	4630.772
L4	0	421.68	7.31	6.83	6.63	4.98	0.00	5.1	11.1	32.5	50.8	0.0	0.0	0.0	0.0	0.0	4.23	2.98	15137.65
L5	5.21	131.04	9.37	9.19	3.87	5.60	3821.64	44.5	27.2	20.4	7.6	1700.3	1039.9	779.7	289.9	3809.8	4.23	2.98	5267.59
1982 to 1992																			
M1	3.59	19.96	8.42	7.00	3.52	1.54	110.18	4.1	9.0	33.7	52.8	4.5	9.9	37.1	58.2	109.7	3.10	2.73	178.9394
M2	4.45	25.80	12.89	12.77	3.19	10.20	1181.69	4.1	8.9	33.6	52.9	48.3	105.5	397.3	625.6	1176.6	3.10	2.73	1548.314
M3	6.99	50.66	11.62	11.31	9.63	8.41	2979.86	4.1	9.0	33.7	52.8	121.0	268.6	1004.9	1572.6	2967.1	3.10	2.73	2485.608
M4	4.58	40.77	9.55	9.48	6.85	6.45	1204.98	4.0	9.2	33.9	52.5	48.4	110.6	408.8	632.1	1199.9	3.10	2.73	1534.016
M5	5.31	19.06	9.40	7.63	10.34	1.32	133.70	5.9	10.8	32.3	50.2	7.9	14.5	43.2	67.1	132.6	3.62	2.04	142.5033
M6	10.36	29.54	8.76	7.64	2.79	1.48	453.28	5.4	9.9	36.5	47.5	24.4	44.7	165.5	215.1	449.7	3.62	2.04	247.6261
M7	4.84	20.93	7.75	4.70	10.84	1.36	137.59	5.9	10.8	32.3	50.2	8.1	14.9	44.5	69.0	136.5	3.62	2.04	160.886
M8	0	115.15	8.90	7.89	9.75	4.67	0.00	5.5	11.7	32.8	49.6	0.0	0.0	0.0	0.0	0.0	3.62	2.04	3043.467
M9	0	96.06	9.89	8.85	6.22	5.72	0.00	5.7	11.7	32.2	50.0	0.0	0.0	0.0	0.0	0.0	3.62	2.04	3109.757
M10	0	124.88	11.04	9.76	11.13	7.09	0.00	5.8	11.7	31.7	50.4	0.0	0.0	0.0	0.0	0.0	3.62	2.04	5011.029
M11	6.44	55.65	11.32	11.37	3.37	7.38	2643.29	5.0	16.2	33.5	44.4	133.4	428.4	886.2	1174.6	2622.6	3.62	2.04	2322.99
M12	9.2	56.94	15.18	14.46	5.78	9.29	4868.63	5.2	15.8	33.3	44.9	252.4	771.3	1621.1	2184.3	4829.0	3.62	2.04	2995.07
M13	0	72.76	14.09	13.65	7.33	10.82	0.00	5.2	15.8	33.3	44.9	0.0	0.0	0.0	0.0	0.0	3.62	2.04	4373.257
M14	0	54.86	10.49	7.36	9.70	1.77	0.00	3.9	13.0	26.1	57.0	0.0	0.0	0.0	0.0	0.0	3.62	2.04	550.0744
M15A	12.22	81.06	13.26	12.90	7.18	11.19	11081.61	13.7	11.6	23.0	51.6	1522.8	1282.8	2549.5	5723.6	11078.7	3.62	2.04	6132.39
M15B	12.82	47.47	13.13	12.85	4.54	10.52	6403.53	4.0	12.9	25.6	57.5	253.0	825.0	1638.8	3684.9	6401.7	3.62	2.04	2826.958
L1	0	366.43	11.48	10.92	4.31	9.01	0.00	5.6	12.2	32.7	49.0	0.0	0.0	0.0	0.0	0.0	4.68	3.82	28058
L2	0	15.34	11.76	11.24	9.02	9.07	0.00	5.6	12.2	32.7	49.1	0.0	0.0	0.0	0.0	0.0	4.68	3.82	1182.637
L3	0	115.77	11.85	11.44	4.34	8.66	0.00	5.6	12.3	32.8	48.9	0.0	0.0	0.0	0.0	0.0	4.68	3.82	8522.265

line	retreat (m)	bluff length (m)	elevation AP (m)	elevation wood stake (m)	distance (m)	bluff height (m)	volume delivered (m^3)	% > 256 mm	% gravel	%sand	%mud	volume coarse (m^3)	volume gravel (m^3)	volume sand (m^3)	volume mud (m^3)	total (m^3)	E_s (m)	RMS error (m)	E_v (m^3)
L4	0	419.59	7.31	6.83	6.63	4.98	0.00	5.1	11.1	32.5	50.8	0.0	0.0	0.0	0.0	0.0	4.68	3	16044.61
L5	0	126.82	9.37	9.19	3.87	5.84	0.00	44.5	27.2	20.4	7.6	0.0	0.0	0.0	0.0	0.0	4.68	3	5686.897
1992 to 1997																			
M1	3.58	29.05	8.42	7.00	3.52	2.98	310.52	4.1	9.0	33.7	52.8	12.6	27.9	104.7	163.9	309.2	2.43	1.47	338.2757
M2	0	29.97	12.89	12.77	3.19	10.46	0.00	4.1	8.9	33.6	52.9	0.0	0.0	0.0	0.0	0.0	2.43	1.47	1222.596
M3	0	46.98	11.62	11.31	9.63	8.64	0.00	4.1	9.0	33.7	52.8	0.0	0.0	0.0	0.0	0.0	2.43	1.47	1583.038
M4	0	50.50	9.55	9.48	6.85	6.50	0.00	4.0	9.2	33.9	52.5	0.0	0.0	0.0	0.0	0.0	2.43	1.47	1280.175
M5	0	20.52	9.40	7.63	10.34	2.23	0.00	5.9	10.8	32.3	50.2	0.0	0.0	0.0	0.0	0.0	4.02	2.99	320.7748
M6	0	31.90	8.76	7.64	2.79	5.64	0.00	5.4	9.9	36.5	47.5	0.0	0.0	0.0	0.0	0.0	4.02	2.99	1261.211
M7	0	21.64	7.75	4.70	10.84	2.72	0.00	5.9	10.8	32.3	50.2	0.0	0.0	0.0	0.0	0.0	4.02	2.99	412.6142
M8	0	105.73	8.90	7.89	9.75	4.67	0.00	5.5	11.7	32.8	49.6	0.0	0.0	0.0	0.0	0.0	4.02	2.99	3461.251
M9	0	88.71	9.89	8.85	6.22	5.72	0.00	5.7	11.7	32.2	50.0	0.0	0.0	0.0	0.0	0.0	4.02	2.99	3557.023
M10	0	132.12	11.04	9.76	11.13	7.09	0.00	5.8	11.7	31.7	50.4	0.0	0.0	0.0	0.0	0.0	4.02	2.99	6566.483
M11	0	64.99	11.32	11.37	3.37	7.28	0.00	5.0	16.2	33.5	44.4	0.0	0.0	0.0	0.0	0.0	4.02	2.99	3316.622
M12	0	63.46	15.18	14.46	5.78	10.44	0.00	5.2	15.8	33.3	44.9	0.0	0.0	0.0	0.0	0.0	4.02	2.99	4644.282
M13	0	88.74	14.09	13.65	7.33	10.62	0.00	5.2	15.8	33.3	44.9	0.0	0.0	0.0	0.0	0.0	4.02	2.99	6606.356
M14	10.95	68.76	10.49	7.36	9.70	1.77	1333.91	3.9	13.0	26.1	57.0	52.0	173.3	347.5	760.7	1333.5	4.02	2.99	853.9485
M15A	0	89.18	13.26	12.90	7.18	11.80	0.00	13.7	11.6	23.0	51.6	0.0	0.0	0.0	0.0	0.0	4.02	2.99	7376.791
M15B	0	70.35	13.13	12.65	4.54	11.31	0.00	4.0	12.9	25.6	57.5	0.0	0.0	0.0	0.0	0.0	4.02	2.99	5579.046
L1	0	384.96	11.48	10.92	4.31	9.01	0.00	5.6	12.2	32.7	49.0	0.0	0.0	0.0	0.0	0.0	4.60	3.59	28406.93
L2	0	15.56	11.76	11.24	9.02	9.07	0.00	5.6	12.2	32.7	49.1	0.0	0.0	0.0	0.0	0.0	4.60	3.59	1155.848
L3	0	100.88	11.85	11.44	4.34	8.66	0.00	5.6	12.3	32.8	48.9	0.0	0.0	0.0	0.0	0.0	4.60	3.59	7156.607
L4	0	424.56	7.31	6.83	6.63	4.98	0.00	5.1	11.1	32.5	50.8	0.0	0.0	0.0	0.0	0.0	4.60	3.59	17316.19
L5	0	128.72	9.37	9.19	3.87	5.84	0.00	44.5	27.2	20.4	7.6	0.0	0.0	0.0	0.0	0.0	4.60	3.59	6156.626

1997 to 1999

line	cum. retreat (m)	bluff length (m)	elevation bluff edge (m)	elevation bluff toe (m)	bluff height (m)	volume delivered (m^3)	% > 256 mm	% gravel	%sand	%mud	volume coarse (m^3)	volume gravel (m^3)	volume sand (m^3)	volume mud (m^3)	total (m^3)	RMS error	E_v
M1	1.79	19.90	6.74	2.31	4.43	157.80	4.06	9.00	33.71	52.80	6.41	14.20	53.19	83.31	157.12	1.94	179.84
M2	1.98	28.59	12.37	1.91	10.46	592.12	4.09	8.93	33.62	52.94	24.19	52.85	199.06	313.46	589.56	1.94	610.06
M3	1.00	44.66	11.16	2.52	8.64	385.86	4.06	9.01	33.72	52.77	15.67	34.78	130.12	203.63	384.20	1.94	787.16
M4	0.67	58.96	9.24	2.74	6.50	256.77	4.02	9.18	33.92	52.46	10.31	23.57	87.10	134.70	255.68	1.94	781.81
M5	1.95	30.13	3.94	1.71	2.23	131.02	5.90	10.82	32.31	50.17	7.73	14.18	42.34	65.73	129.98	2.69	187.46
M6	2.21	29.74	6.80	1.16	5.64	370.69	5.38	9.86	36.52	47.45	19.93	36.56	135.37	175.90	367.77	2.69	467.98
M7	1.82	58.80	4.29	1.57	2.72	291.08	5.90	10.82	32.31	50.17	17.17	31.51	94.06	146.02	288.76	2.69	446.22
M8	0.66	127.72	7.80	3.13	4.67	393.66	5.48	11.73	32.78	49.63	21.55	46.19	129.05	195.37	392.16	2.69	1,664.10
M9	0.28	76.17	7.83	2.11	5.72	121.99	5.66	11.70	32.21	50.04	6.90	14.28	39.29	61.04	121.51	2.69	1,215.58
M10	0.85	96.12	9.30	2.21	7.09	579.27	5.82	11.68	31.71	50.39	33.70	67.63	183.70	291.90	576.92	2.69	1,901.36
M11	2.64	64.48	11.28	4.00	7.28	1,239.25	5.05	16.21	33.53	44.44	62.54	200.83	415.50	550.71	1,229.57	2.69	1,309.67
M12	0.49	63.79	13.61	3.17	10.44	326.32	5.18	15.84	33.30	44.86	16.92	51.70	108.65	146.40	323.67	2.69	1,858.05
M13	0.84	92.51	13.49	2.87	10.62	825.26	5.19	15.83	33.29	44.88	42.83	130.62	274.71	370.38	818.54	2.69	2,741.05
M14	8.89	72.22	7.08	1.78	5.31	3,406.00	3.90	12.99	26.05	57.03	132.71	442.59	887.31	1,942.34	3,404.95	2.69	1,068.92
M15A	2.76	104.61	12.74	0.94	11.80	3,406.94	13.74	11.58	23.01	51.65	468.17	394.38	783.83	1,759.67	3,406.05	2.69	3,443.97
M15B	4.29	69.85	12.66	1.35	11.31	3,390.01	3.95	12.88	25.59	57.54	133.95	436.75	867.56	1,950.77	3,389.03	2.69	2,204.69
L1	0.30	330.61	10.85	1.84	9.01	893.64	5.63	12.23	32.70	49.05	50.33	109.27	292.26	438.30	890.16	2.88	8,876.81
L2	0.36	12.81	11.03	1.96	9.07	41.83	5.64	12.22	32.68	49.07	2.36	5.11	13.67	20.52	41.66	2.88	346.24
L3	0.07	111.09	11.08	2.42	8.66	67.36	5.60	12.25	32.83	48.93	3.77	8.25	22.11	32.96	67.10	2.88	2,867.54
L4	2.74	448.82	6.53	1.55	4.98	6,124.24	5.09	11.12	32.51	50.78	311.50	680.98	1,990.74	3,110.05	6,093.26	2.88	6,660.67
L5	0.10	140.21	9.02	3.18	5.84	81.88	44.49	27.21	20.40	7.59	36.43	22.28	16.71	6.21	81.63	2.88	2,440.10

Appendix E
Bluff Retreat Data

airphoto date	central date	RMS error (m)	X (m)	E_x (m)	T (yrs)	R (m/a)	E_r (m)
M1							
22/06/34		1.89					
28/07/45	09/01/40	3.22	-24.41	3.73	11.107	-2.20	0.34
04/07/54	14/01/50	2.26	-4.84	3.93	8.940	-0.54	0.44
03/06/66	18/06/60	2.56	-1.30	3.41	11.923	-0.11	0.29
08/05/82	21/05/74	2.73	4.67	3.74	15.940	0.29	0.23
25/07/92	16/06/87	1.47	3.59	3.10	10.222	0.35	0.30
15/05/97	19/12/94	1.94	3.58	2.43	4.808	0.74	0.51
11/06/98	27/11/97	0.05	0.44	0.10	0.553	0.79	0.09
12/06/99	29/05/98	0.05	1.35	0.10	1.003	1.34	0.05
M2							
22/06/34		1.89					
28/07/45	09/01/40	3.22	-1.52	3.73	11.107	-0.14	0.34
04/07/54	14/01/50	2.26	-5.95	3.93	8.940	-0.67	0.44
03/06/66	18/06/60	2.56	-2.28	3.41	11.923	-0.19	0.29
08/05/82	21/05/74	2.73	32.92	3.74	15.940	2.07	0.23
25/07/92	16/06/87	1.47	4.45	3.10	10.222	0.44	0.30
15/05/97	19/12/94	1.94	-1.52	2.43	4.808	-0.32	0.51
11/06/98	27/11/97	0.05	1.44	0.10	0.553	2.59	0.09
12/06/99	29/05/98	0.05	0.54	0.10	1.003	0.54	0.05
M3							
22/06/34		1.89					
28/07/45	09/01/40	3.22	-1.44	3.73	11.107	-0.13	0.34
04/07/54	14/01/50	2.26	-1.17	3.93	8.940	-0.13	0.44
03/06/66	18/06/60	2.56	12.26	3.41	11.923	1.03	0.29
08/05/82	21/05/74	2.73	26.03	3.74	15.940	1.63	0.23
25/07/92	16/06/87	1.47	6.99	3.10	10.222	0.68	0.30
15/05/97	19/12/94	1.94	-0.40	2.43	4.808	-0.08	0.51
11/06/98	27/11/97	0.05	0.13	0.10	0.553	0.23	0.09
12/06/99	29/05/98	0.05	0.87	0.10	1.003	0.87	0.05
M4							
22/06/34		1.89					
28/07/45	09/01/40	3.22	-1.87	3.73	11.107	-0.17	0.34
04/07/54	14/01/50	2.26	-1.30	3.93	8.940	-0.15	0.44
03/06/66	18/06/60	2.56	14.25	3.41	11.923	1.20	0.29
08/05/82	21/05/74	2.73	22.22	3.74	15.940	1.39	0.23
25/07/92	16/06/87	1.47	4.58	3.10	10.222	0.45	0.30
15/05/97	19/12/94	1.94	0.46	2.43	4.808	0.10	0.51
11/06/98	27/11/97	0.05	0.43	0.10	0.553	0.78	0.09
12/06/99	29/05/98	0.05	0.24	0.10	1.003	0.24	0.05
M5							
22/06/34		2.70					
28/07/45	09/01/40	2.07	3.24	3.40	11.107	0.29	0.31
16/07/54	20/01/50	3.54	12.09	4.10	8.973	1.35	0.46
03/06/66	24/06/60	2.46	0.60	4.31	11.890	0.05	0.36
08/05/82	21/05/74	2.04	7.95	3.20	15.940	0.50	0.20
25/07/92	16/06/87	2.99	5.31	3.62	10.222	0.52	0.35
15/05/97	19/12/94	2.69	-1.87	4.02	4.808	-0.39	0.84
11/06/98	27/11/97	0.05	0.99	0.10	0.485	2.04	0.09
12/06/99	29/05/98	0.05	0.96	0.10	1.003	0.96	0.05
M6							
22/06/34		2.70					
28/07/45	09/01/40	2.07	2.61	3.40	11.107	0.23	0.31
16/07/54	20/01/50	3.54	11.57	4.10	8.973	1.29	0.46
03/06/66	24/06/60	2.46	1.27	4.31	11.890	0.11	0.36
08/05/82	21/05/74	2.04	0.13	3.20	15.940	0.01	0.20
25/07/92	16/06/87	2.99	10.36	3.62	10.222	1.01	0.35
15/05/97	19/12/94	2.69	1.40	4.02	4.808	0.29	0.84
11/06/98	27/11/97	0.05	1.65	0.10	0.485	3.40	0.09

12/06/99	29/05/98	0.05	0.56	0.10	1.003	0.56	0.05
M7							
22/06/34		2.70					
28/07/45	09/01/40	2.07	1.17	3.40	11.107	0.11	0.31
16/07/54	20/01/50	3.54	11.13	4.10	8.973	1.24	0.46
03/06/66	24/06/60	2.46	1.38	4.31	11.890	0.12	0.36
08/05/82	21/05/74	2.04	0.77	3.20	15.940	0.05	0.20
25/07/92	16/06/87	2.99	4.84	3.62	10.222	0.47	0.35
15/05/97	19/12/94	2.69	2.47	4.02	4.808	0.51	0.84
11/06/98	27/11/97	0.05	1.20	0.10	0.485	2.47	0.09
12/06/99	29/05/98	0.05	0.62	0.10	1.003	0.62	0.05
M8							
22/06/34		2.70					
28/07/45	09/01/40	2.07	3.17	3.40	11.107	0.29	0.31
16/07/54	20/01/50	3.54	11.67	4.10	8.973	1.30	0.46
03/06/66	24/06/60	2.46	7.73	4.31	11.890	0.65	0.36
08/05/82	21/05/74	2.04	14.25	3.20	15.940	0.89	0.20
25/07/92	16/06/87	2.99	2.66	3.62	10.222	0.26	0.35
15/05/97	19/12/94	2.69	-1.82	4.02	4.808	-0.38	0.84
09/11/98	10/02/98	0.05	0.40	0.10	0.899	0.45	0.07
12/06/99	29/05/98	0.05	0.26	0.10	0.589	0.44	0.05
M9							
22/06/34		2.70					
28/07/45	09/01/40	2.07	4.47	3.40	11.107	0.40	0.31
16/07/54	20/01/50	3.54	6.99	4.10	8.973	0.78	0.46
03/06/66	24/06/60	2.46	7.21	4.31	11.890	0.61	0.36
08/05/82	21/05/74	2.04	18.62	3.20	15.940	1.17	0.20
25/07/92	16/06/87	2.99	2.65	3.62	10.222	0.26	0.35
15/05/97	19/12/94	2.69	-0.11	4.02	4.808	-0.02	0.84
11/06/98	27/11/97	0.05	0.07	0.10	0.485	0.14	0.09
12/06/99	29/05/98	0.05	0.21	0.10	1.003	0.21	0.05
M10							
22/06/34		2.70					
28/07/45	09/01/40	2.07	3.71	3.40	11.107	0.33	0.31
16/07/54	20/01/50	3.54	0.41	4.10	8.973	0.05	0.46
03/06/66	24/06/60	2.46	22.60	4.31	11.890	1.90	0.36
08/05/82	21/05/74	2.04	12.49	3.20	15.940	0.78	0.20
25/07/92	16/06/87	2.99	-0.66	3.62	10.222	-0.06	0.35
15/05/97	19/12/94	2.69	-1.28	4.02	4.808	-0.27	0.84
11/06/98	27/11/97	0.05	0.39	0.10	0.485	0.80	0.09
12/06/99	29/05/98	0.05	0.46	0.10	1.003	0.46	0.05
M11							
22/06/34		2.70					
28/07/45	09/01/40	2.07	15.70	3.40	11.107	1.41	0.31
16/07/54	20/01/50	3.54	20.67	4.10	8.973	2.30	0.46
03/06/66	24/06/60	2.46	4.12	4.31	11.890	0.35	0.36
08/05/82	21/05/74	2.04	12.32	3.20	15.940	0.77	0.20
25/07/92	16/06/87	2.99	6.44	3.62	10.222	0.63	0.35
15/05/97	19/12/94	2.69	1.07	4.02	4.808	0.22	0.84
11/06/98	27/11/97	0.05	0.15	0.10	0.485	0.31	0.09
12/06/99	29/05/98	0.05	2.49	0.10	1.003	2.48	0.05
M12							
22/06/34		2.70					
28/07/45	09/01/40	2.07	2.78	3.40	11.107	0.25	0.31
16/07/54	20/01/50	3.54	52.97	4.10	8.973	5.90	0.46
03/06/66	24/06/60	2.46	5.19	4.31	11.890	0.44	0.36
08/05/82	21/05/74	2.04	5.35	3.20	15.940	0.34	0.20
25/07/92	16/06/87	2.99	9.20	3.62	10.222	0.90	0.35
15/05/97	19/12/94	2.69	-2.67	4.02	4.808	-0.56	0.84
11/06/98	27/11/97	0.05	0.20	0.10	0.485	0.41	0.09
12/06/99	29/05/98	0.05	0.29	0.10	1.003	0.29	0.05
M13							
22/06/34		2.70					
28/07/45	09/01/40	2.07	3.89	3.40	11.107	0.35	0.31
16/07/54	20/01/50	3.54	34.92	4.10	8.973	3.89	0.46
03/06/66	24/06/60	2.46	5.90	4.31	11.890	0.50	0.36
08/05/82	21/05/74	2.04	11.12	3.20	15.940	0.70	0.20
25/07/92	16/06/87	2.99	1.76	3.62	10.222	0.17	0.35

15/05/97	19/12/94	2.69	-0.82	4.02	4.808	-0.17	0.84
11/06/98	27/11/97	0.05	0.65	0.10	0.545	1.19	0.09
12/06/99	29/05/98	0.05	0.19	0.10	0.942	0.20	0.05
M14							
22/06/34		2.70					
28/07/45	09/01/40	2.07	9.36	3.40	11.107	0.84	0.31
16/07/54	20/01/50	3.54	3.82	4.10	8.973	0.43	0.46
03/06/66	24/06/60	2.46	4.61	4.31	11.890	0.39	0.36
08/05/82	21/05/74	2.04	-11.23	3.20	15.940	-0.70	0.20
25/07/92	16/06/87	2.99	-3.82	3.62	10.222	-0.37	0.35
15/05/97	19/12/94	2.69	10.95	4.02	4.808	2.28	0.84
03/07/98	08/12/97	0.05	3.42	0.10	0.545	6.27	0.09
12/06/99	29/05/98	0.05	5.47	0.10	0.942	5.81	0.05
M15A							
22/06/34		2.70					
28/07/45	09/01/40	2.07	-4.86	3.40	11.107	-0.44	0.31
16/07/54	20/01/50	3.54	-0.87	4.10	8.973	-0.10	0.46
03/06/66	24/06/60	2.46	25.52	4.31	11.890	2.15	0.36
08/05/82	21/05/74	2.04	29.46	3.20	15.940	1.85	0.20
25/07/92	16/06/87	2.99	12.22	3.62	10.222	1.20	0.35
15/05/97	19/12/94	2.69	1.87	4.02	4.808	0.39	0.84
03/07/98	08/12/97	0.05	2.10	0.10	0.545	3.85	0.09
12/06/99	29/05/98	0.05	0.66	0.10	0.942	0.70	0.05
M15B							
22/06/34		2.70					
28/07/45	09/01/40	2.07	-7.74	3.40	11.107	-0.70	0.31
16/07/54	20/01/50	3.54	-0.56	4.10	8.973	-0.06	0.46
03/06/66	24/06/60	2.46	-6.15	4.31	11.890	-0.52	0.36
08/05/82	21/05/74	2.04	37.98	3.20	15.940	2.38	0.20
25/07/92	16/06/87	2.99	12.82	3.62	10.222	1.25	0.35
15/05/97	19/12/94	2.69	-0.39	4.02	4.808	-0.08	0.84
03/07/98	08/12/97	0.05	2.59	0.10	0.545	4.75	0.09
12/06/99	29/05/98	0.05	1.70	0.10	0.942	1.80	0.05
M17							
22/06/34		1.89					
28/07/45	09/01/40	3.22		3.73	11.107		0.34
04/07/54	14/01/50	2.26	11.70	3.93	8.940	1.31	0.44
03/06/66	18/06/60	2.56	8.81	3.41	11.923	0.74	0.29
08/05/82	21/05/74	2.73	2.46	3.74	15.940	0.15	0.23
25/07/92	16/06/87	1.47	-0.38	3.10	10.222	-0.04	0.30
15/05/97	19/12/94	1.94	4.81	2.43	4.808	1.00	0.51
09/12/98	25/02/98	0.05	0.77	0.10	0.899	0.86	0.06
02/05/99	08/05/98	0.05	0.29	0.10	0.477	0.61	0.05
M18							
22/06/34		1.89					
28/07/45	09/01/40	3.22	2.46	3.73	11.107	0.22	0.34
04/07/54	14/01/50	2.26	8.91	3.93	8.940	1.00	0.44
03/06/66	18/06/60	2.56	5.01	3.41	11.923	0.42	0.29
08/05/82	21/05/74	2.73	2.13	3.74	15.940	0.13	0.23
25/07/92	16/06/87	1.47	3.78	3.10	10.222	0.37	0.30
15/05/97	19/12/94	1.94	4.24	2.43	4.808	0.88	0.51
03/07/98	08/12/97	0.05	0.49	0.10	0.899	0.55	0.09
02/05/99	08/05/98	0.05	0.01	0.10	0.477	0.02	0.05
M19							
22/06/34		1.89					
28/07/45	09/01/40	3.22	2.29	3.73	11.107	0.21	0.34
04/07/54	14/01/50	2.26	4.20	3.93	8.940	0.47	0.44
03/06/66	18/06/60	2.56	5.38	3.41	11.923	0.45	0.29
08/05/82	21/05/74	2.73	1.19	3.74	15.940	0.07	0.23
25/07/92	16/06/87	1.47	4.00	3.10	10.222	0.39	0.30
15/05/97	19/12/94	1.94	5.76	2.43	4.808	1.20	0.51
09/12/98	25/02/98	0.05	0.30	0.10	0.899	0.33	0.06
02/05/99	08/05/98	0.05	0.01	0.10	0.477	0.02	0.05
L1							
22/06/34		1.61					
28/07/45	09/01/40	2.76		3.20	11.107		0.29
04/07/54	14/01/50	2.55	9.61	3.76	8.940	1.07	0.42
03/06/66	18/06/60	2.98	21.93	3.92	11.923	1.84	0.33

08/05/82	21/05/74	3.00	15.53	4.23	15.940	0.97	0.27
25/07/92	16/06/87	3.59	1.77	4.68	10.222	0.17	0.46
15/05/97	19/12/94	2.88	1.32	4.60	4.808	0.27	0.96
14/11/98	13/02/98	0.05	0.23	0.10	0.277	0.85	0.07
20/06/99	02/06/98	0.05	0.07	0.10	1.337	0.05	0.05
L2							
22/06/34		1.61					
28/07/45	09/01/40	2.76		3.20	11.107		0.29
04/07/54	14/01/50	2.55	10.17	3.76	8.940	1.14	0.42
03/06/66	18/06/60	2.98	21.65	3.92	11.923	1.82	0.33
08/05/82	21/05/74	3.00	15.03	4.23	15.940	0.94	0.27
25/07/92	16/06/87	3.59	0.46	4.68	10.222	0.05	0.46
15/05/97	19/12/94	2.88	0.92	4.60	4.808	0.19	0.96
14/11/98	13/02/98	0.05	0.28	0.10	0.649	0.43	0.07
20/06/99	02/06/98	0.05	0.08	0.10	0.597	0.13	0.05
L3							
22/06/34		1.61					
28/07/45	09/01/40	2.76		3.20	11.107		0.29
04/07/54	14/01/50	2.55	10.75	3.76	8.940	1.20	0.42
03/06/66	18/06/60	2.98	20.48	3.92	11.923	1.72	0.33
08/05/82	21/05/74	3.00	15.07	4.23	15.940	0.95	0.27
25/07/92	16/06/87	3.59	0.37	4.68	10.222	0.04	0.46
15/05/97	19/12/94	2.88	0.69	4.60	4.808	0.14	0.96
20/06/99	29/08/98	0.05	0.07	0.10	1.614	0.04	0.04
L4							
22/06/34		1.61					
28/07/45	09/01/40	2.76	-3.85	3.20	11.107	-0.35	0.29
04/07/54	14/01/50	2.55	0.12	3.76	8.940	0.01	0.42
03/06/66	18/06/60	2.98	14.47	3.92	11.923	1.21	0.33
08/05/82	21/05/74	3.00	1.31	4.23	15.940	0.08	0.27
25/07/92	16/06/87	3.59	-0.11	4.68	10.222	-0.01	0.46
15/05/97	19/12/94	2.88	2.27	4.60	4.808	0.47	0.96
09/11/98	10/02/98	0.05	2.17	0.10	0.244	8.90	0.07
20/06/99	02/06/98	0.05	0.57	0.10	1.118	0.51	0.05
L5							
22/06/34		6.92					
28/07/45	09/01/40	5.31		8.72	11.107		0.79
04/07/54	14/01/50	2.55	1.04	5.89	8.940	0.12	0.66
03/06/66	18/06/60	2.98	11.22	3.92	11.923	0.94	0.33
08/05/82	21/05/74	3.00	5.21	4.23	15.940	0.33	0.27
25/07/92	16/06/87	3.59	-0.08	4.68	10.222	-0.01	0.46
15/05/97	19/12/94	2.88	0.42	4.60	4.808	0.09	0.96
20/06/99	23/11/98	0.05	0.10	0.10	1.142	0.09	0.05

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