ANALYSIS OF COASTAL GEOMORPHOLOGICAL PROCESSES ON A BOREAL COARSE CLASTIC BARRIER: LONG POND BARACHOIS, CONCEPTION BAY, NEWFOUNDLAND

DONALD PAUL PITTMAN

Analysis of Coastal Geomorphological Processes on a Boreal Coarse Clastic Barrier: Long Pond Barachois, Conception Bay, Newfoundland

By

©Donald Paul Pittman

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Abstract

Long Pond Barachois is a single-ridged open-work gravel-dominated baymouth barrier adjacent to an asymmetric double-basined lagoon. Sea level rise, climate, and inherited geology have controlled long term barrier evolution but human activities have modified littoral processes and barrier morphology. Updrift shoreline armouring induced barrier stretching and breaching, generating a curved planform and a permanent tidal inlet. Tidal exchange generated strong currents in the channel, scouring the backbarrier. This induced in-place narrowing, which was exacerbated when shore-normal breakwater construction in 1973 formed a sediment sink, allowing the inlet-adjacent beach segment to prograde. The narrowed barrier segment breached during a 1976 storm which also induced sluicing overwash north of Burnt Island and cusp-related overwash between the island and the channel. The breach was repaired with silt-rich dredge spoil, placing the barrier in a state of arrested breakdown. The breach repair site has proven very erosion-prone. The barrier breached at the same site in 1992, without overwashing elsewhere on the barrier. The breach was again repaired with silt-rich dredge spoil. Erosion problems have persisted and the barrier is probably not sustainable in its current form in the long term.

Sluicing overwash occurred due to cyclic barrier narrowing and barrier overstepping onto an impermeable substrate. The crest was low and the barrier has narrowed since 1976. Access road construction has placed a flat impermeable surface on the northern backbarrier and narrowed the berm. Two residences have been constructed in hazard zones. These activities have limited potential management options.

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1.0 Introduction

Coarse clastic (gravel) barrier shorelines have received little scientific attention as compared to their sandy counterparts. Gravel barriers are often perceived as stable, with little associated risk of barrier failure. Gravel barrier stability makes them attractive as natural breakwaters, and port facilities have been developed at some sites. Gravel barriers can maintain stability for extended periods but may be prone to sudden, catastrophic adjustment due to severe storm events or the passing of some environmental threshold (Forbes *et al.*, 1991). Catastrophic barrier failure may pose a significant hazard for local infrastructure and property.

While coarse clastic shorelines have been studied in Nova Scotia (Forbes & Taylor, 1987), New England (Duffy *et al.*, 1989), the U. S. Pacific northwest (McKay & Terich, 1992), the British Isles (Bray, 1997), New Zealand (Soons *et al.*, 1997), Argentina (Isla & Bujalesky, 2000), and the Mediterranean (Postma & Nemec, 1990; Sanders, 2000), there have been comparatively few studies on boreal gravel coastlines. The more extreme climatic regime may be characterized by distinct process mechanisms which do not occur on more temperate gravel barriers.

Gravel barrier evolution is driven by the interplay of sediment supply, wave climate, terrestrial basement, and the rate of Relative Sea Level Rise (RSLR) (Carter *et al.*, 1989), along with any number of site-specific secondary and tertiary controls. Gravel barriers often display extended periods of stability, followed by a period of rapid adjustment that occurs as some environmental threshold is met and exceeded (Forbes *et al.*, 1995).

1.1 Objectives

Different climatic regimes may be capable of inducing process variations that affect gravel barrier evolution. A multi-seasonal study of Long Pond Barachois, a coarse clastic gravel barrier beach, was conducted between January 1997 and July 1999.

The study objectives included:

- Description and assessment of barrier evolution based upon barrier morphology, sedimentary structures, and historical records;
- Assessment of the influence of the climate regime on barrier morphology;
- Identification and assessment of sedimentary transport processes based upon barrier morphology, position, sedimentary structures, and geological inheritance;
- Assessment of alongshore variations in morphology and sedimentary structures;
- Assessment of human-induced impacts, particularly coastal armouring, port development, and residential expansion, on sedimentary transport processes;
- Forecasting future evolutionary patterns based upon process interactions and probable human intervention.

1.2 Regional Setting

Long Pond (47°31' N, 52° 58' W) was a double-basined saltwater lagoon located on a narrow coastal plain abutting southeastern Conception Bay, Newfoundland (Fig. 1.1). The plain was backed by steep 200 m high hills from which four small streams debouched into the lagoon. The basins were connected by a narrow tidal channel bounded by the

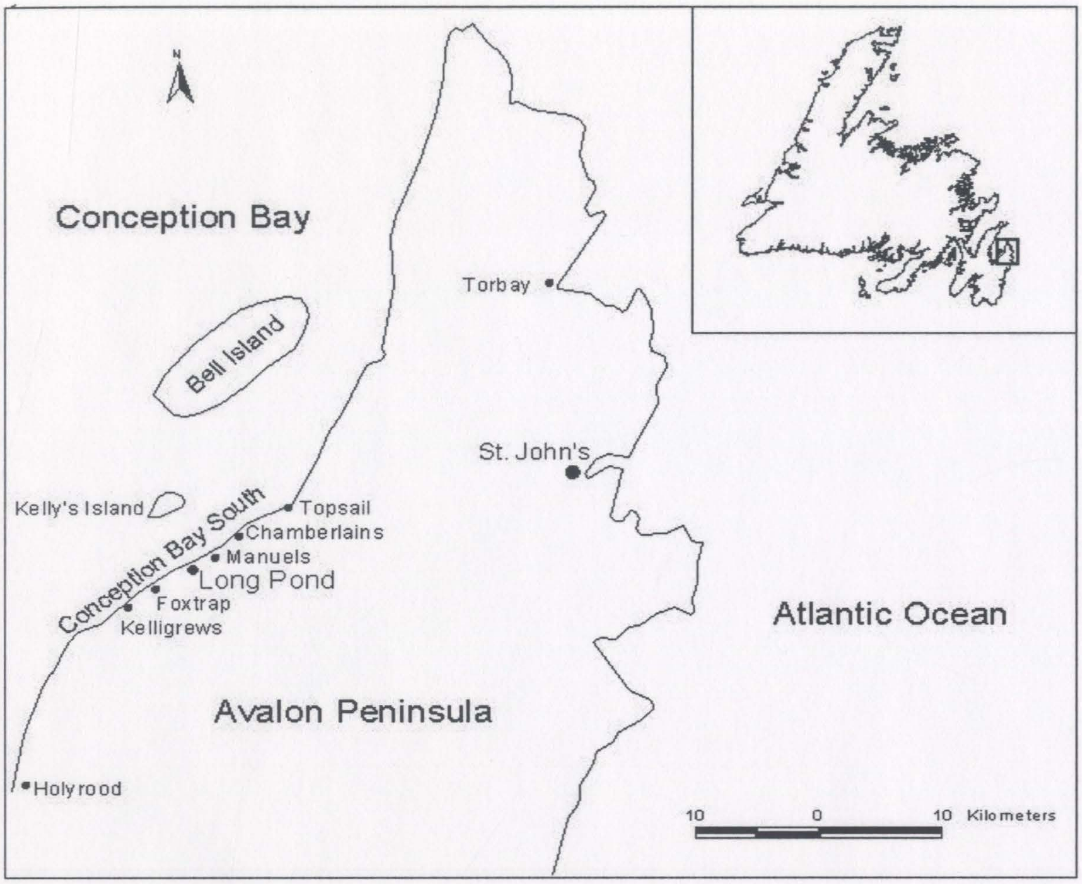


Figure 1.1. Long Pond and northeastern Avalon Peninsula, Newfoundland.

barrier and the Long Pond Peninsula (Fig. 1.2). The southern basin (Appendix 1) was connected to Conception Bay by a 90 m wide tidal inlet. The inlet facilitated the development of an industrial and recreational port facility (Fig. 1.3).

Long Pond was separated from Conception Bay by a narrow, single ridged, baymouth gravel barrier (or barachois) approximately 1.75 km in length and 20 - 40 m in width. The barachois was aligned approximately parallel to the coast, trending from southwest to northeast. The barrier planform was arcuate (concave seaward) over most of its length, averaging 040° azimuth north of the stress point (Fig. 1.2) and 055° azimuth to the south

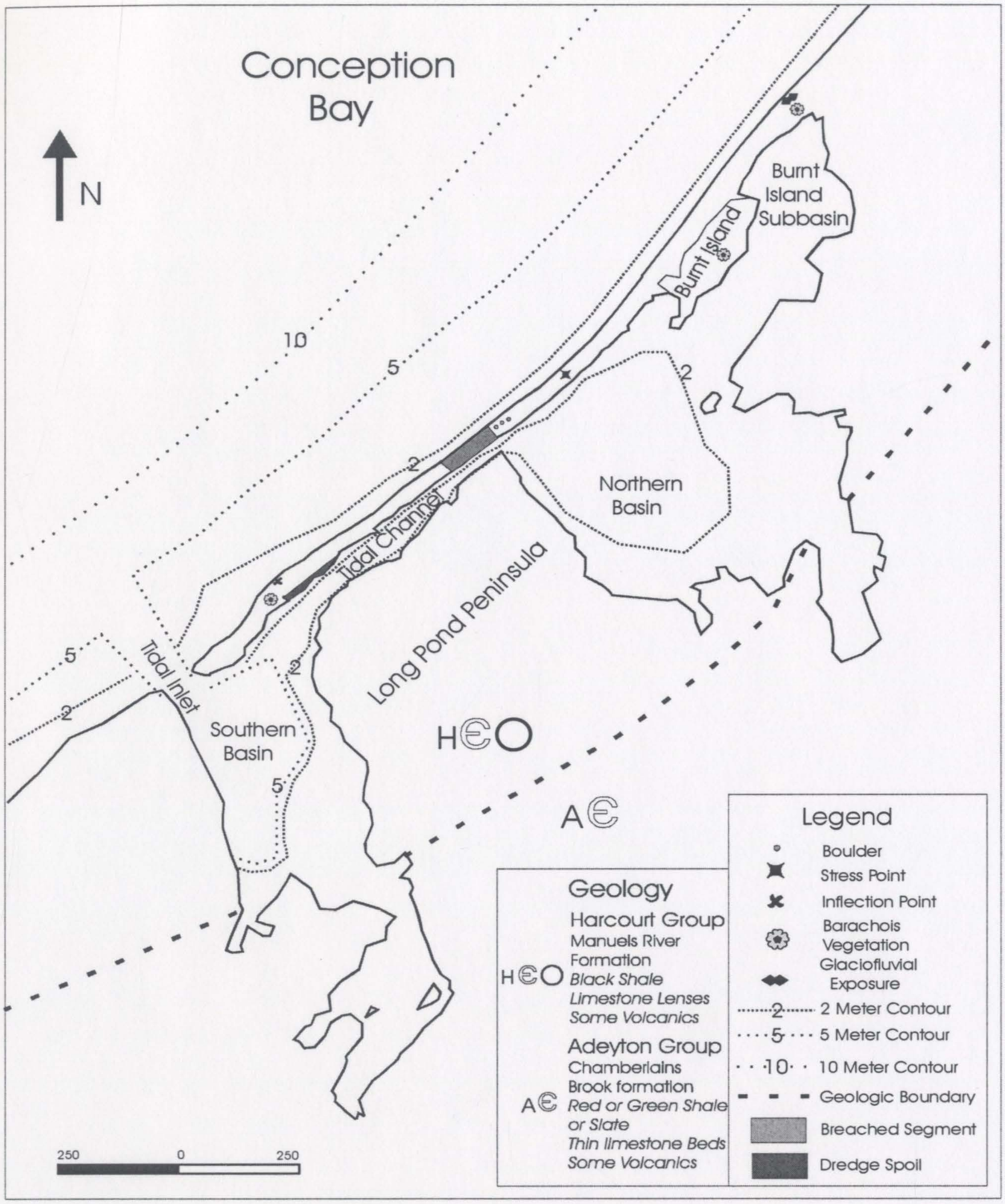


Figure 1.2. Long Pond: Biophysical Features. Geological features from King (1988). Bathymetric features from Canadian Hydrographic Service (1987).

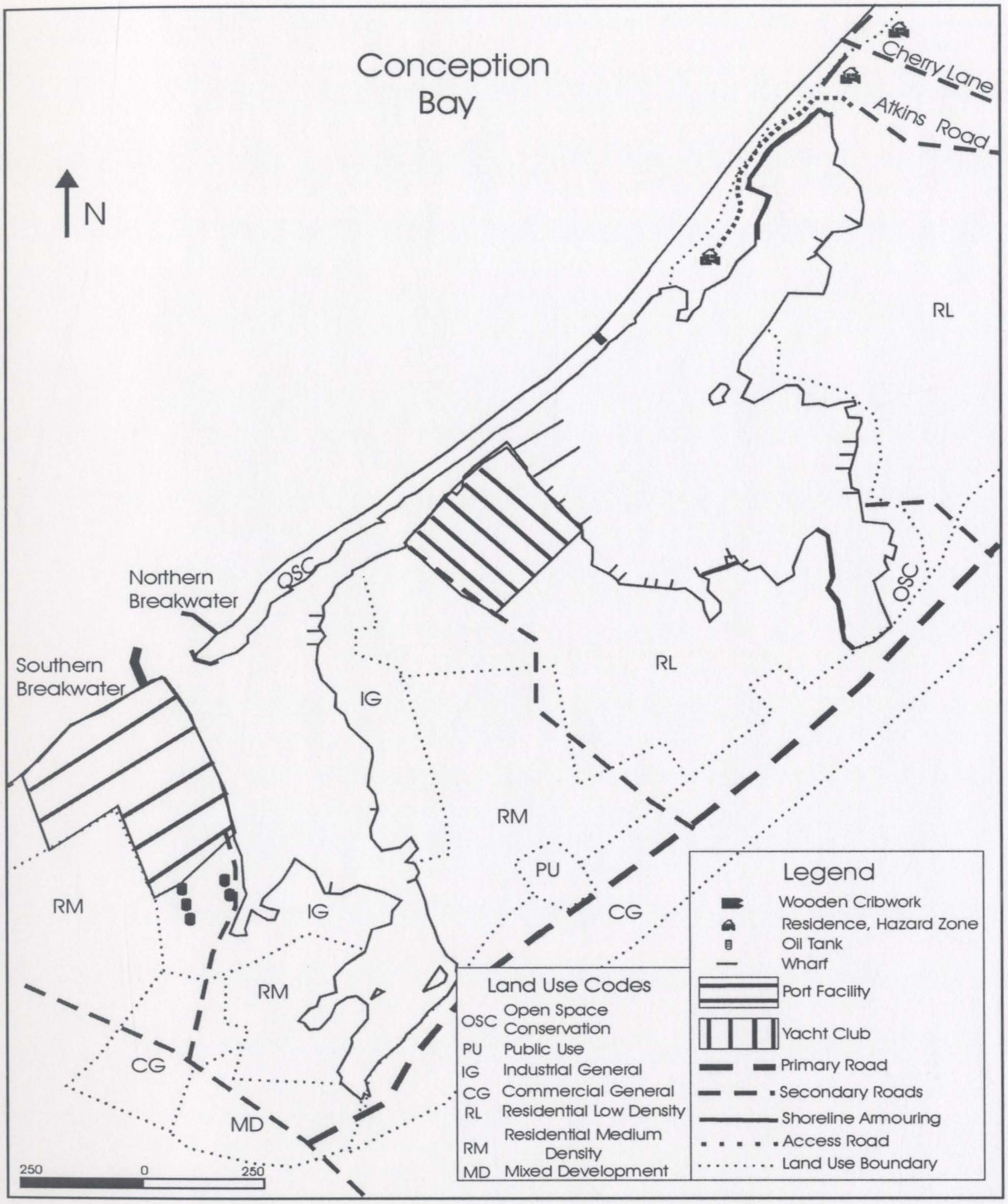


Figure 1.3. Long Pond: Infrastructure and land use. Land use zones adapted from D. W. Knight & Associated Ltd (1993).

until the orientation abruptly changed to 040° azimuth at an inflection point (concave landward). The barachois incorporated an island and locally displayed characteristics of a fringing barrier, as per Carter & Orford (1993). The barachois became a fringing barrier north of the lagoon but without any change in texture, sedimentary structure, or slope.

1.3 Climate

Climatic data were obtained from Holyrood (Fig. 1.1), approximately 12 km southeast of Long Pond at 6 m asl (Environment Canada, 2003) and have been summarized in Table 1.1. The northeastern Avalon can be characterized as a Maritime Boreal climate (Catto & St. Croix, 1998). Wind data were not collected at Holyrood and were instead obtained from MacLaren Plansearch Ltd (1991) and St. John's Airport (Environment Canada, 1993). Prevailing winds were dominantly westerly but switched to southwesterly between June and August (Fig. 1.4 a), during which wind direction was most consistent. Winds were most variable in April and May. Storms occurred most frequently during Autumn and Winter but could occur year-round. Maximum sustained wind speeds rarely exceeded 80 km/h, but could exceed 100 km/h during fall and winter storms and gusts up to 193 km/h have been recorded at St. John's Airport.

1.4 Oceanography

1.4.1 Wave Climate

There was no continuous monitoring of the Conception Bay wave climate. The nearest

Table 1.1: Climatic Data, Conception Bay and area (1971 - 2001).

Mean Annual Temperature	6.1° C
Mean February Temperature	-3.9° C
Mean August Temperature	16.8° C
Mean Annual Precipitation	1127.2 mm
Mean Annual Rainfall	982.3 mm
Mean Annual Snowfall	144.9 cm
Prevailing Winds	Westerly (Southwesterly in summer)
Maximum Gusts	193 km/h

monitoring station was located at Torbay, (Fig 1.1) in the open Atlantic. Fetch limitations from the eastern and southern quadrants meant that the Conception Bay wave climate could differ substantially from the open ocean. Swells recorded at Torbay that originated from the southern quadrant, for example, were not manifested in Conception Bay. As mathematical modelling based upon the Torbay data may have been at best inaccurate and at worst misleading, Torbay wave data have not been used.

The wave climate at Long Pond was dominated by local wind waves and extra-local wind waves and swells. Locally-generated wave incidence varied from near-normal to strongly oblique. Incident waves propagated primarily from the west and southwest during much of the year (Fig. 1.4 b) but were most variable in April and September to December. Bell Island, Little Bell Island, and Kelly's Island exerted strong refractory and diffractory controls on extra-local waves (Fig. 1.5), which could approach Long Pond at

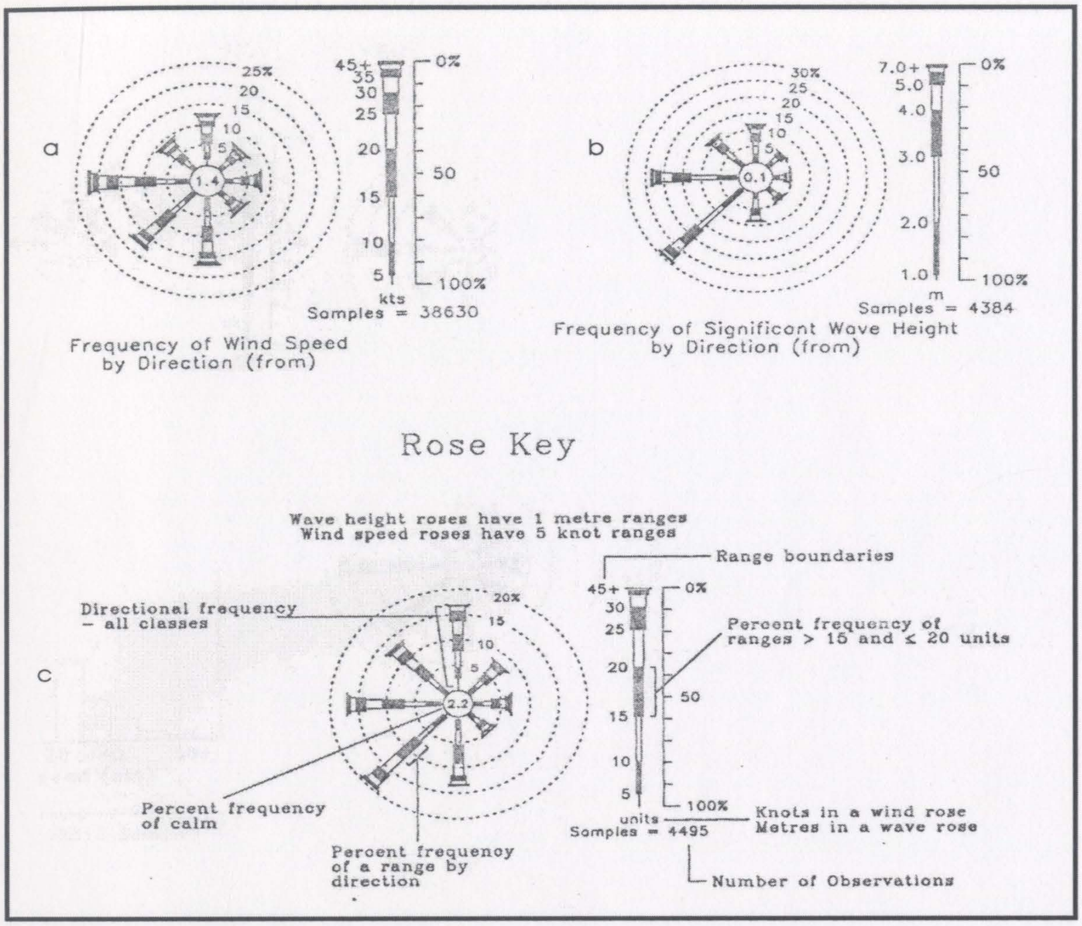


Figure 1.4 a. Frequency of wind speed by direction, Northeast Avalon.

b. Frequency of significant wave height by direction (from), Torbay monitoring station.

c. Rose Key (MacLaren Plansearch Ltd, 1991).

near-normal angles of incidence. Shore-normal incident waves may also have been refracted by the bottom topography. Westerly winds were fetch-restricted, and could stimulate small shore-normal waves. The steep shoreface facilitated onshore wave breakage, and Long Pond was highly reflective, as defined by Wright *et al.* (1979) and Wright & Short (1984).

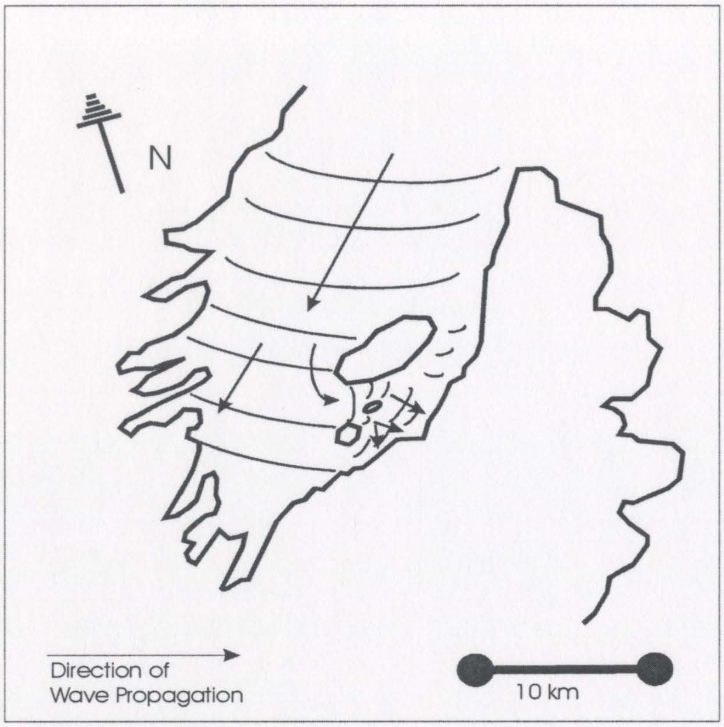


Figure 1.5. Refractory and diffractory influence of islands on wave propagation patterns in Conception Bay.

The barrier sheltered the lagoon from the Conception Bay wave climate, although the tidal inlet could transmit a subdued wave field into the southern basin, as evidenced by the recent development of a recurved spit (Plates 1.1 a, b, c). Wave size was limited by the breakwaters, which physically blocked incident waves (Plate 1.1 d, e) and induced physical drag on incident waves. Ebb tides generated currents that debouched through the tidal inlet and destructively interfered with incident waves. Fetch limitations restricted wave size within the lagoon, and locally generated waves had little transport potential. Shore-normal wave contact was not coincident alongshore. Depending upon the relative angle of wave incidence, the curved planform could accentuate or inhibit cross-shore and alongshore swash extension.

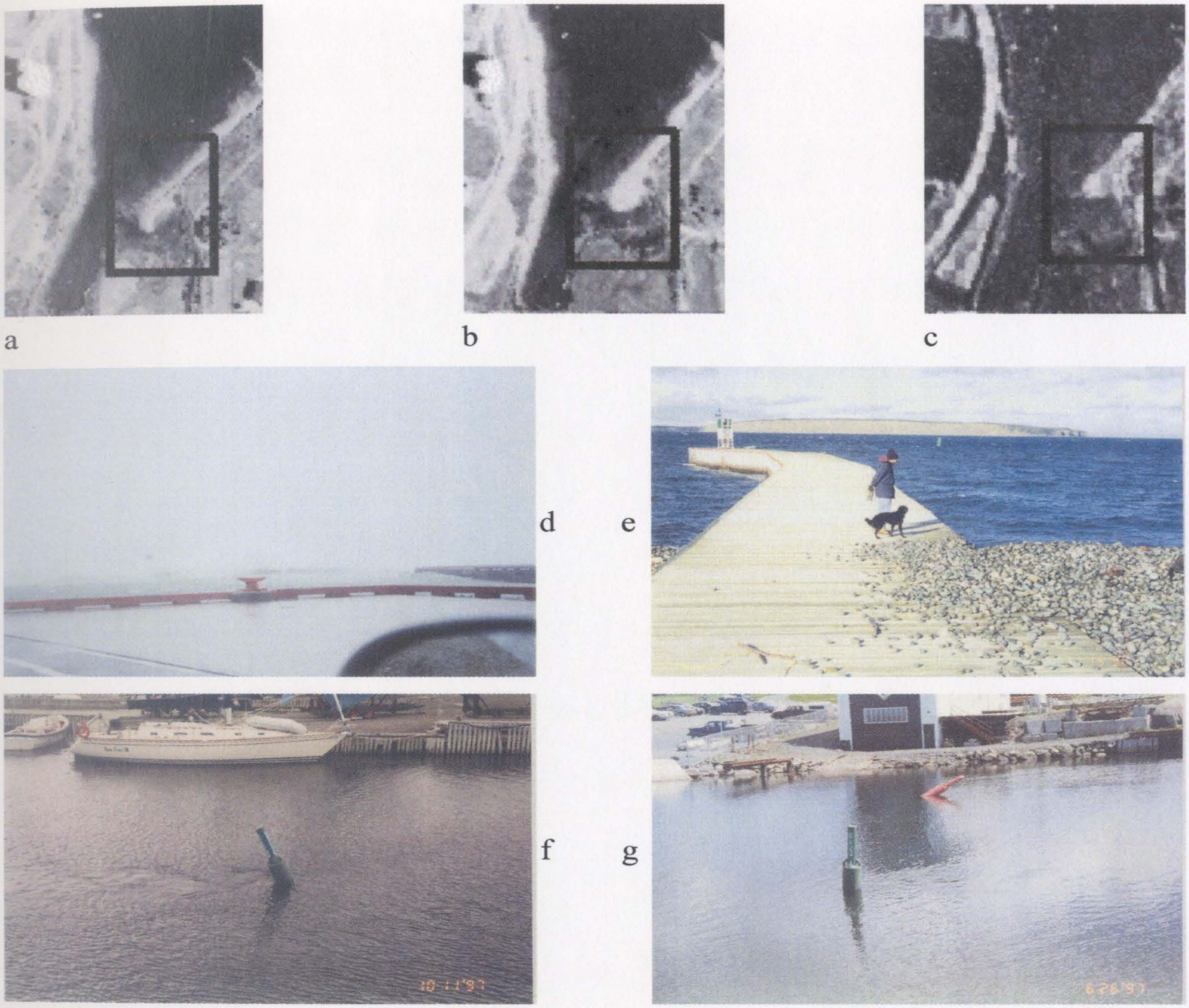


Plate 1.1 a. Recurved spit in southern basin, 2001. Spit is approximately 30 m in length.

b. Poorly developed spit, 1995.

c. Incipient spit, 1978.

d. Waves breaking against breakwater, Hurricane Gabrielle (20/09/01).

e. Overwash on breakwater (19/11/98).

f. Flood tide current in channel (11/10/97).

g. Ebb tide current in channel (26/06/97).

1.4.2 Tides

Long Pond was microtidal with a mean tidal range of 0.9 m (Canadian Hydrographic Service, 1997). Tides were mixed semidiurnal, with peaks and nadirs spaced 6 to 6.5 hours apart. Ocean tides controlled the wave elevation but did not directly transport gravel. The small tidal range and steep beach slope inhibited cross-shore swash extension during fairweather conditions. Tidal exchange facilitated regular flushing of the lagoon. Flow constriction through the tidal channel generated strong currents (Plates 1.1 f, g).

1.4.3 Currents

Conception Bay currents were generally weak and variable but current flow could be dictated by the coastal and subsea topography (DeYoung & Sanderson, 1995). Prevailing winds were aligned parallel to the coastline and generated consistent longshore currents that propagated from southwest to northeast (Fig. 1.6 a). Shoreline current reversals occurred when winds and/or waves originated from the northern quadrant (Fig. 1.6 b). Strongly oblique waves generated strong longshore currents, whereas near normal winds/waves stimulated shore-normal transport.

1.4.4 Ice

Sea ice has been recorded in Conception Bay as early as late January and as late as the end of May (Cote, 1989), but commonly occurred between early March and late April (DeYoung *et al.*, 1993). Pre-April ice cover, 30 cm thick on average, was usually

Table 1.2: Ice cover in Conception Bay, 1961 - 1998 (Hill & Clarke, 1999).

Sea Ice Cover	Frequency (Years)	Percentage
Heavy	17*	45
Light	14	37
Moderate	6	18

* 11 of the 17 heavy ice years occurred after 1983.

locally by subfreezing temperatures (Hill & Clarke, 1999) and retreated by late March or early April. The occurrence of arctic sea ice in Conception Bay was dependent ice cover on the adjacent continental shelf and coincident onshore winds (DeYoung & Sanderson, 1995). During heavy ice years, arctic pack ice, averaging 50 -120 cm thick, entered the bay in late April and early May and persisted until mid-May.

The occurrence and density of sea ice were variable (Table1.2). A period of light ice cover coincided with a regional warming trend during the 1960's (Hill & Clarke, 1999). Heavy ice cover was typical during the late 1980's and early 1990's, during a regional cooling period. Between 1984 and 1998, the Bell Island Ferries were impeded by pack ice 11 of 15 years. Conception Bay hosted little sea ice in 1997 and practically none in 1998, precluding the opportunity to measure the impact of pack ice on boreal gravel barrier morphology. Light ice years may be anomalous, and the heavier ice cover during the late 1980's and early 1990's may be typical within a long-term context.

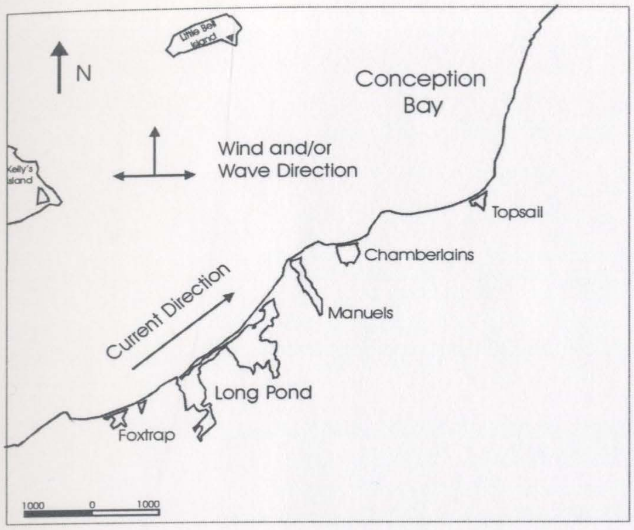
Icebergs, growlers, and bergy bits have been observed from late December to early August but were most common after late March, often coinciding with the initial retreat of sea ice (Hill & Clarke, 1999). The number of icebergs was variable and like arctic pack ice, depended on the abundance of icebergs on the adjacent shelf and coincident onshore winds. Iceberg trajectories were essentially random, dependent upon ambient winds and currents. Icebergs could pose a shipping hazard, particularly during storms and fog, but icebergs were commonly surrounded by recreational watercraft during fair weather.

Long Pond Lagoon did not freeze uniformly during the winter. The northern basin was usually ice-covered for a period but the tidal channel did not freeze. The port basin was usually ice-free, but ice has occasionally extended to the end of the breakwaters (Delcan, 1995). During heavy ice years, pack ice may be driven into the port basin by waves and tides. The sheltered inner reaches of the southern basin could freeze, although the ice seemed thinner than in the northern basin.

Spring breakup of Long Pond ice has caused structural damage to the northern breakwater (Delcan, 1995). Ice removed from the basin during ebb tides could be driven into the breakwaters or transported onshore by waves and tides. Pack ice could also conceivably damage the inlet stabilization infrastructure during heavy ice years.

1.4.5 Bathymetry

The shoreface at Long Pond steepened from south to north (Canadian Hydrographic Service, 1987). The 2 m depth contour was within 12.5 m of the shoreline along most of the barrier but shifted approximately 125 m offshore near the inflection point (Fig. 1.2). The 5 m depth contour, located between 200 and 250 m offshore, was approximately



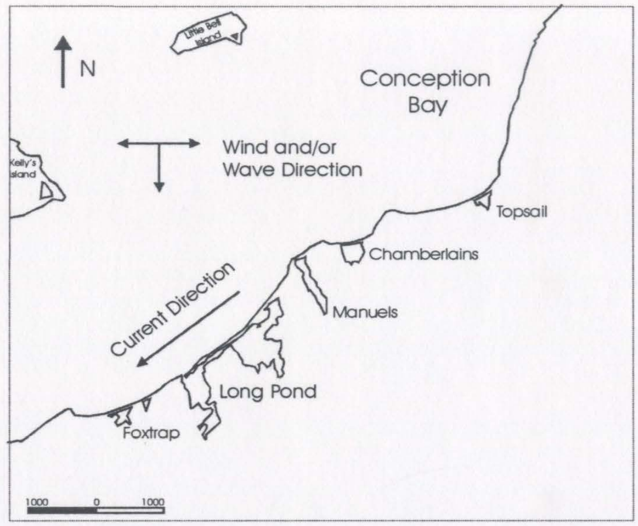


Figure 1.6 a. Longshore current generation, southeastern Conception Bay.

b. Current reversal generation, southeastern Conception Bay.

parallel to the coastline and parallel to the 10 m depth contour, located approximately 450 m offshore. The non-parallel orientation of the 2 m contour depth suggested that variations in shoreface slope were attributable to local processes.

Undredged lagoon reaches were less than 3 m deep at low tide and much of the lagoon was less than 1 m deep (Canadian Hydrographic Service, 1987). The port basin and inlet had been dredged to a depth of over 8 m and the yacht club basin was dredged up to 4 m in depth. The channel thalweg was 3 to 4 m deep.

1.5 Biota

Burnt Island was forested with balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), black spruce (*Picea Mariana*) and associated boreal understorey. The beach-adjacent trees adapted a krummholz morphology due to wind exposure. There were several trees and stumps that appeared to have grown out of the beach gravel but were actually rooted in underlying soil (Plate 1.2 a). Freestanding forest occurred within 3 to 5 m of the tree line. There were broad swaths of gravel within the krummholz and some gravel reached the freestanding forest. A subsistence timber harvest was conducted on Burnt Island prior to residential development (Plate 1.2 b). The island was not clearcut and the shoreline trees were not harvested. A fire during the mid 1990's killed a number of trees over an area of approximately 100 m^2 on the northwestern corner of the island (Plate 1.2 c). These trees were removed during the study period (Plate 1.2 d).

The barachois was sparsely vegetated except for the dredge spoil and crest segment between the inflection point and tidal inlet (Fig. 1.2). The dredge spoil hosted silts and sands, which may have been conducive to vegetative colonization (Plate 1.2 e). The inflection point crest was colonized by grasses and smooth hawksbeard (*Crepis capillaris*) despite the open-work gravel substrate (Plate 1.2 f). Several species of gull (*Larus* spp.) often congregated on this barrier segment, which also hosted a common tern (*Sterna hirundo*) nesting site. Several species of shorebirds were observed as well.

Beach users suggested that capelin (*Mollutus villosus*) spawned on the beach although this was not observed directly. Long Pond Lagoon hosted marine invertebrates (Christie, 1966), flounder (*Pseudopleuronectes americanus* (Walboum)) (Wells, 1974), cod (*Gadus morhua*) (A. Fairgreive, *pers. comm.* 2003), and other marine species.

Plate 1.2 a. Stump protruding through beach gravels, western Burnt Island.

b. Exposed tree roots, Burnt Island. Note harvested timber, top left.

c. Fire-killed trees, northwestern Burnt Island.

d. Trees removed due to residential development.

e. Silt lens on dredge spoil. Note colonization by grasses.

f. Vegetative colonization on crest. Note inflection point, top center.

1.6 Geology

1.6.1 Bedrock

Long Pond was perched atop two distinct geological units (Fig. 1.2). The Manuels River Formation underlaid the western lagoon segment. This member of the Harcourt Group consisted of Upper Cambrian black shales with limestone lenses and some volcanics (King, 1988). The shales were soft and thinly bedded (Geotechnical Associates Ltd, 1984). The Harcourt Group dipped 10 - 20° to the north-northwest and conformably overlaid Middle Cambrian green and red shales and slates and thin limestone beds of the Adeytown Group (Newfoundland Geosciences Ltd, 1991), known as the Chamberlains Brook Formation (King, 1988), which underlaid the remainder of Long Pond. The Manuels River and Chamberlains Brook Formations unconformably overlaid Hadrynian granites of the Holyrood Intrusive Suite (Newfoundland Geosciences Ltd, 1991). The hills were volcanic but hosted siliceous siltstone and sandstone outcrops (King, 1988).

1.6.2 Glacial Sediments

Subaerial sediments near Long Pond consisted of glaciofluvial outwash deposits that originated from an ice mass on the spine of the St. John's Peninsula (Henderson, 1972). The units consisted of poorly structured sand and gravel (Catto & St. Croix, 1998). Coastal erosion truncated these units, manifesting steep, unconsolidated bluffs (Plate 1.3 a) which have eroded at an average rate of 0.5 m/yr (Catto *et al.*, 1999; Liverman & Boger, 1994; Paone, 2003), although the bluffs adjacent to Long Pond eroded less than

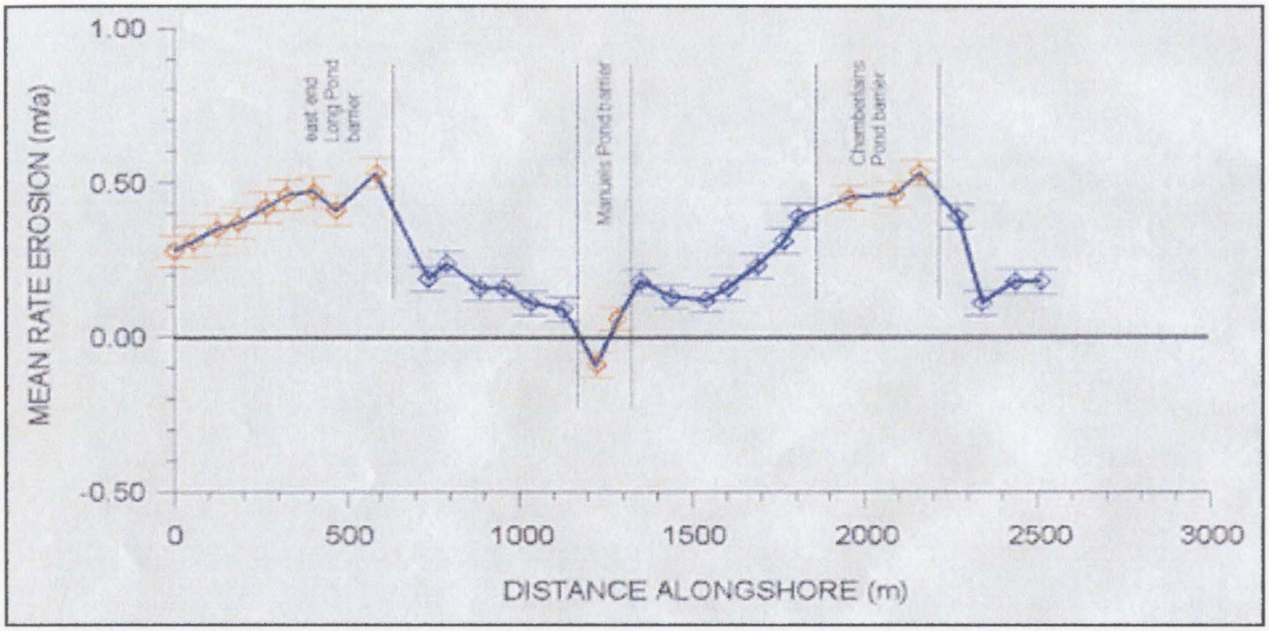


Figure 1.7. Mean estimated erosion rate (m/year) 1951-1995 for southern Long Pond to Chamberlains. Barrier retreat rates are in orange, cliff erosion rates are in blue. Low retreat rates at 1100 and 2400 m alongshore correspond to emerging headlands (unpublished data courtesy of Dr. Don Forbes, Geological Survey of Canada, Bedford Institute of Oceanography).

0.3 m/yr on average (Fig. 1.7). Burnt Island was also a glaciofluvial unit and prior to armouring, the lagoon shoreline was characterized by near-vertical scarps (Plate 1.2 b).

Deglaciation began circa 10,000 BP and proceeded by downwasting (Macpherson, 1995). Isostatic adjustment has been continuous and the rate of RSLR may be between 3 and 4 mm/yr (Catto *et al.*, 2000). Due to the continued influence of glaciation, Long Pond can be considered a paraglacial system, as described by Church & Ryder (1972).

1.6.3 Marine Sedimentology

The substrate in southeastern Conception Bay was gravel-dominated, but the nearshore

Plate 1.3 a. Bluff face, Conception Bay. Field assistant is 1.65 m in height.

b. Scarping, Burnt Island.

c. Glaciofluvial exposure in cusp, 25/01/97. Glove is 20 cm in length.

d. Glaciofluvial exposure, 04/11/00. Field assistant is 1.62 m in height.

e. Residential development, tidal channel (note the generous setback).

f. Residential development, northern basin.

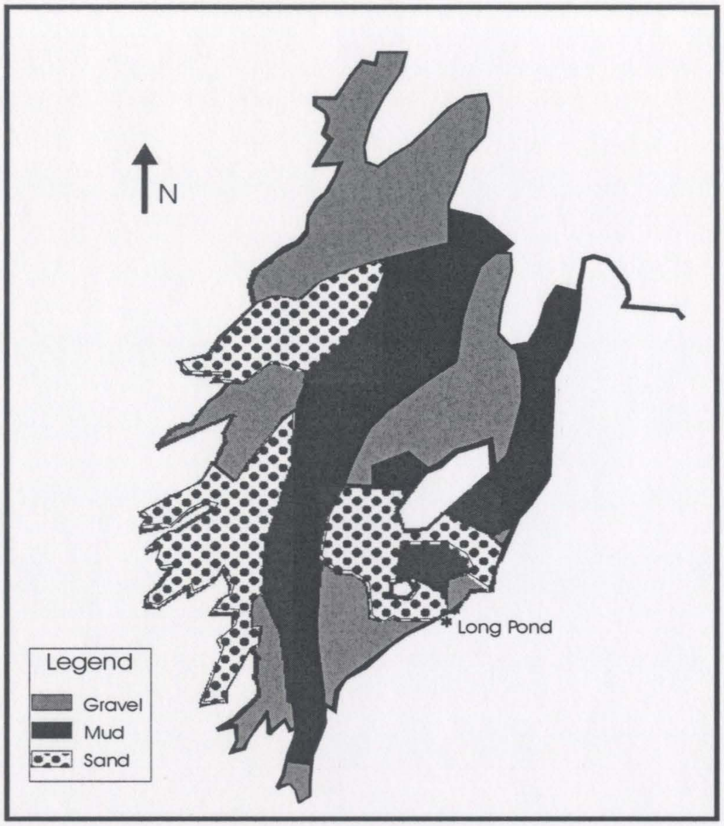


Figure 1.8. Marine substrate texture, Conception Bay (adapted from Wells, 1966).

substrate adjacent to Long Pond was sand-dominated (Fig. 1.8). The lagoon substrate consisted primarily of silty mudflats (Canadian Hydrographic Service, 1987; Christie, 1966; Wells, 1974), 0.61 m to 6.34 m in thickness (Geotechnical Associates Ltd, 1984) which generally thickened from west to east. Topographic controls imposed by the bedrock substrate influenced sediment depth. Interspersed boulders attested to the glacial history. Most lagoon gravels were associated with the barachois, but gravel also occurred along shoreline segments in the southern basin (Canadian Hydrographic Service, 1987; Canadian Hydrographic Service (prepared by E. J. Cooper), 1960). Sand was abundant near the lagoon shoreline, particularly in sheltered coves where it was mixed with silts.

1.6.4 Barrier Sedimentology

Siliceous siltstones comprised the most abundant sedimentary fraction, while siliceous sandstones, unmetamorphosed sandstones, shales and Holyrood granites constituted lesser fractions. Gravels were primarily derived from bluff erosion in southeastern Conception Bay, although marine gravels (Fig. 1.8) may have also been incorporated. Sand was abundant in the adjacent bluffs and nearshore but was rare on the barrier.

The barrier consisted almost exclusively of well mixed open-work gravels, primarily medium to coarse pebbles and small cobbles, with lesser fractions of fine pebbles and small boulders. Angular and subangular clasts were rare. Most gravel was well rounded, and there were also isolated well-rounded asphalt clasts, most commonly on the berm. Asphalt also occurred at the base of Cherry Lane (Fig. 1.3). There were several large, partially buried granitic boulders lodged into the barrier crest opposite the yacht club (Fig. 1.2). Directly south of the boulders, the berm was unsorted, consisting of gravel, sand, silt and debris. Sand was also evident in the berm midway between the tidal channel and Burnt Island. North of the lagoon, a glaciofluvial diamict structure incorporated into the bermface has become more exposed over time (Plates 1.3 c, d).

1.7 Historical Context

1.7.1 Settlement History and Land Use

The cod fishery attracted settlers to the Northeast Avalon during the 1600's (Brown, 1988), but southeastern Conception Bay was sparsely settled as of 1828 (Anspach, 1828) due to the absence of suitable harbours. The depletion of timber resources in established communities sparked interest in the southeastern Conception Bay forests during the 1830's (Brown, 1988). Timber harvesting revealed arable soil and agriculture spurred rapid land clearance. Road and rail links to St. John's constructed during the late 19th century provided further impetus for settlement and economic diversification.

Population growth in southeastern Conception Bay accelerated in the 1950's. Long Pond and surrounding communities were amalgamated into the town of Conception Bay South (CBS) in 1973. CBS was the fourth largest community in Newfoundland and Labrador by 2001, with a population of 19,772 (Statistics Canada, 2002), and has continued to experience rapid growth. The population distribution was irregular, as historic settlement patterns continued to influence residential expansion. Although population of Long Pond was not recorded since amalgamation, the community was historically one of the largest settlements in the CBS region (Hochwald & Smith, 1988).

The northern basin was zoned as a residential and recreational area (Fig. 1.3) and upscale residences were built along the shoreline (cf. Plate 1.3 f). The shoreline was not densely populated by urban standards due to large lot sizes. The minimum setback was 15 m (D. W. Knight & Associates Ltd, 1993) and while some landowners employed generous setbacks (Plate 1.3 e), others employed the minimum setback (Plate 1.3 f) and older dwellings were often within 15 m of the shoreline. Many of these properties were armoured. The southern basin was zoned primarily as an industrial area, dominated by the port facility, the pyrophyllite shipping facility and an oil tank farm, but also hosted residential zones. The Long Pond Peninsula was divided into recreational, residential and industrial zones, although industrial development has not been intensive. A major thoroughfare skirted the basin and was zoned as a commercial area.

In 1997, the barrier and Burnt Island sub-basin were zoned as Open Space Conservation (OSC) (D. W. Knight & Associates Ltd, 1993). The sub-basin was rezoned as Low Density Residential Development (RL) in 2000, after an access road was graded across the backbarrier. Rezoning facilitated access road improvement, development on Burnt Island and armouring of Burnt Island and the backbarrier (Plate 1.2 d). The access road has established a legal precedent for residential development in a coastal hazard zone.

1.7.2 Barrier Evolution

In 1868, the Long Pond barrier displayed a straight, continuous planform (Fig. 1.9 a). By 1941, a curved barrier planform with a stress point, inflection point, and a tidal inlet had developed (Plate 1.4). The air photo sequence at Long Pond did not contain sufficient control points to enable accurate photogrammetry (D. Forbes, *pers. comm.*, 2000), which is why Figure 1.7 did not extend the length of Long Pond. The air photo sequence did indicate that there was little change in barrier position since 1941 although morphological changes were evident, particularly south of the inflection point and north of Burnt Island (Plate 1.5). Barrier evolution has been driven in part by natural processes including RSLR and storms, and in part by anthropogenic modification of littoral processes.

Human modification of shoreline processes probably began with land clearance and the

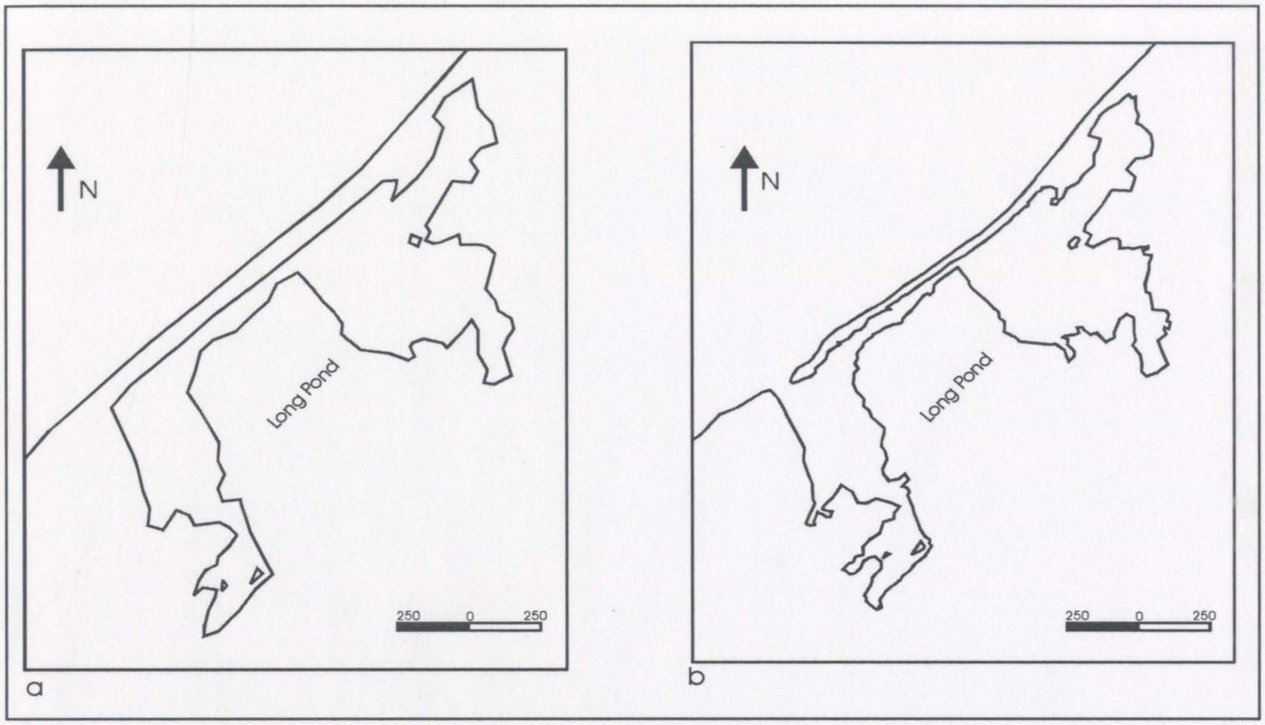


Figure 1.9 a. Approximation of barrier planform circa 1868. Adapted from Orlebar & Kerr (1868).

b. Barrier planform, 1995.

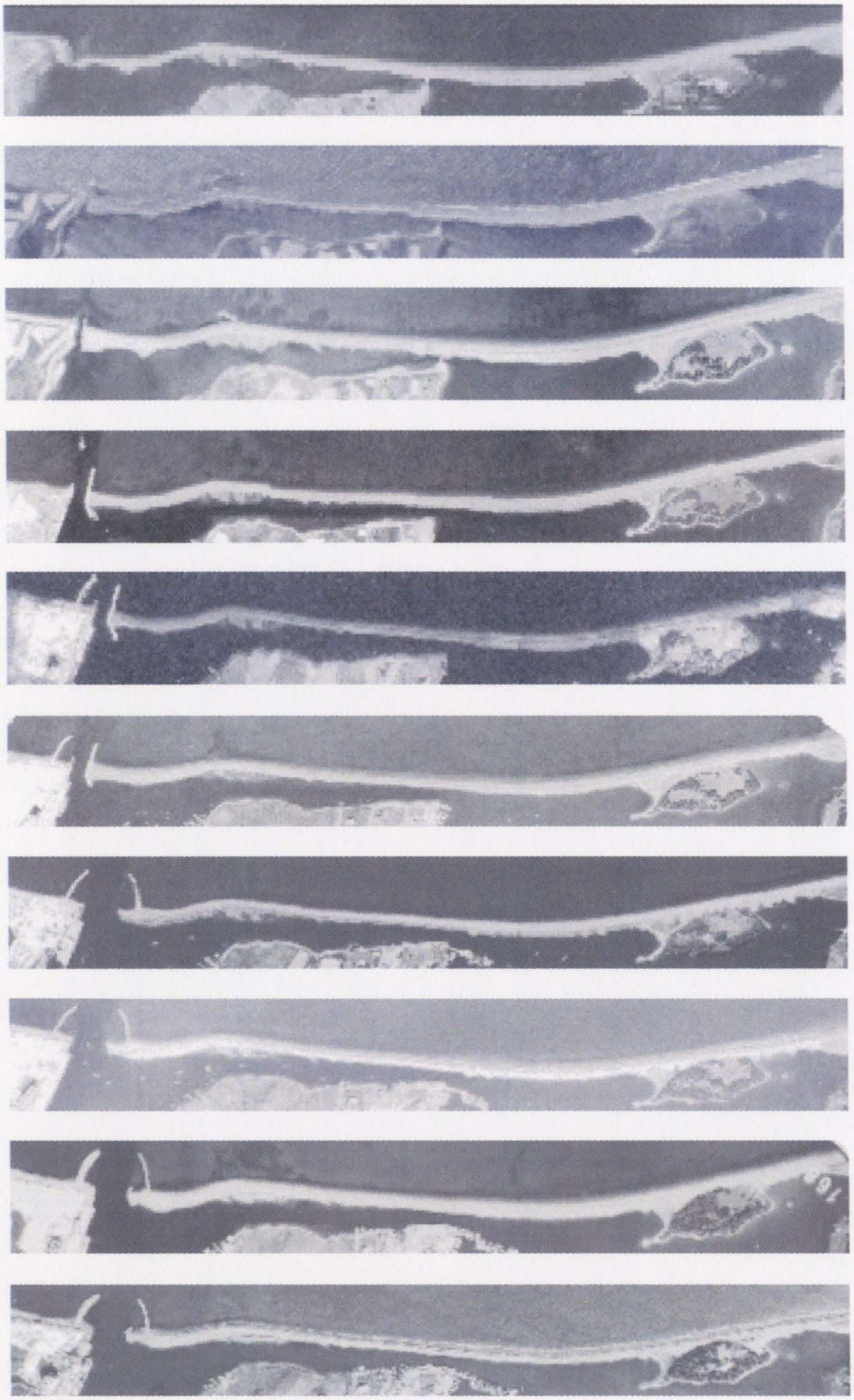
introduction of livestock. The loss of vegetation cover may have accelerated shoreline erosion, thus enhancing littoral flux. Coastal railway construction south of Foxtrap during the 1880's (Penny, 1988) negatively impacted the littoral sediment flux. The railbed was armoured to prevent erosional undercutting, slowing coastal erosion.

A trolley track was apparently built at Long Pond to transport gravel from the barrier prior to export. The track was not maintained after the project was abandoned. The beach segment adjacent to the Burnt Island sub-basin appeared to have been higher than at present, with a steeper backbeach (Plate 1.6 a). There was an attempt to dredge a channel at Long Pond (Public Works of Canada reprint, 1910), possibly to support the gravel

Plate 1.4. Long Pond, 1941 (NF14-612). Scale approximately 1:20,000, cut from original photo, scale 1:40,000.

mining operation. Apparently, the plans were never executed or, more likely, the channel filled in quickly and had to be abandoned.

There were no harbours between Portugal Cove and Holyrood in 1948 and "vessels wishing to anchor near the village (of Topsail) [were] recommended to do so between Kelly's Island and the coast, to avoid the heavy swell off Topsail Cove during north-easterly gales" (Canadian Hydrographic Service (prepared by C. J. Angus), 1952). The



1941 (NF14-612)

1948 (NFL 1-108)

1951 (A13527-145)

1960 (A17079-14)

1966 (A19584-19)

1973 (73379-38)

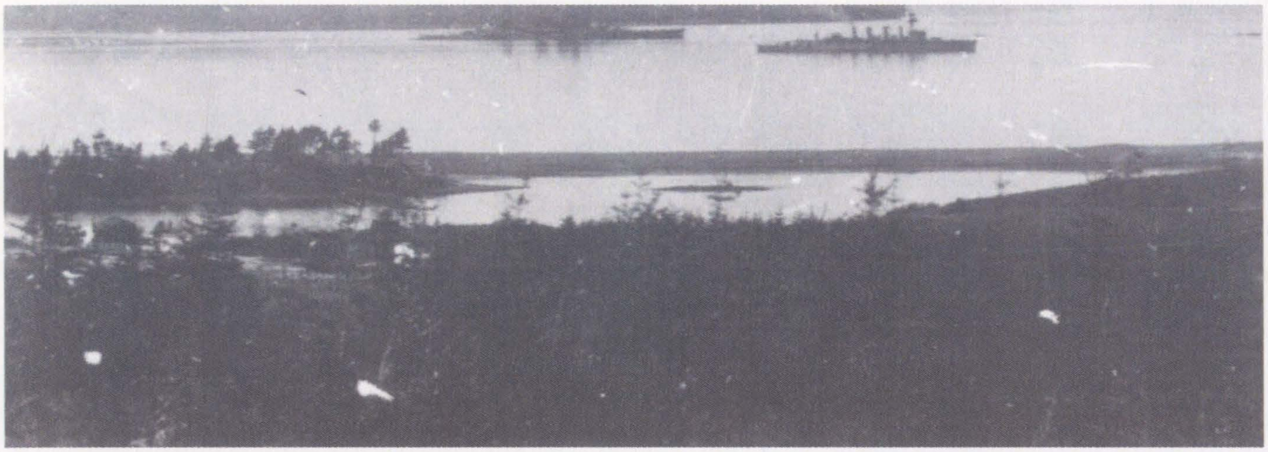
1978 (78005-62)

1981 (81003-46)

1995 (95033-168)

2001 (010102-85)

Plate 1.5. Time sequence of aerial photographs, Long Pond Barachois.



a

b

c

d

e

Plate 1.6 a. Burnt Island sub-basin, 1924.

b. Southern basin, Long Pond circa 1958. Note the absence of port facility.

c. Northern basin, Long Pond circa 1958. Note bridge on channel.

d. Southernmost Long Pond barachois circa 1964.

e. Long Pond port facility, 10/11/97.

yacht club was based at Topsail from 1936 to 1957 (http://www.rnyc.nf.ca, 2003). The tidal inlet was stabilized by 1951 (Plate 1.5), but a port facility was not developed until circa 1957 (Plates 1.6 b, c) , when stabilization infrastructure was improved, the inlet and adjacent basin were dredged, and a wharf was constructed (Public Works of Canada, 1957). The tidal channel was dredged to facilitate the relocation of the yacht club to the Long Pond Peninsula. The tidal inlet, basin, and tidal channel were periodically dredged, the inlet stabilization structures have been repaired and reconfigured and the wharf has been repaired on several occasions (Appendix 2). Long Pond has evolved into the main port facility in CBS. South of the inflection point, the barrier has widened and built vertically since the 1960's (Plates 1.5, 1.6 d).

Conception Bay hosted pleasure craft, fishing vessels, cargo ships, and oil tankers (Plate 1.6 e). While there have been no major accidents in Conception Bay, there have been a number of small oil spills at the Long Pond port facility and marina (Taylor, 1994), and presumably elsewhere in the bay that have degraded environmental quality.

Climate change adds an element of uncertainty to potential barrier evolutionary patterns. Some of the anticipated impacts of climate change include an increase in storm frequency and intensity, and accelerated RSLR (cf. Bacon & Carter, 1991; Catto *et al.*, 2003; Goldenberg *et al.*, 1996; Hanson *et al.*, 2004; Rodwell *et al.*, 1999). An increase in either of these factors could potentially trigger a significant threshold response, manifesting a rapid barrier adjustment. In this context, anthropogenic activity may influence (positively or negatively) barrier threshold responses and evolutionary behaviour.

2.0 Previous Work

2.1 Coarse Clastic Barriers

Coarse clastic beaches are characterized by: (i) steep, reflective beaches (often with low-angle platforms or aprons), (ii) high permeability, swash infiltration and seepage potential, (iii). high entrainment thresholds and hydrodynamic roughness (except where large clasts move across a finer substrate), (iv) particle shape and size interaction in sediment transport and sorting (effects can be reduced under rapid sediment supply or barrier breakdown), (v) restricted influence of wind and vegetation effects (Forbes *et al.*, 1995). Gravel beaches can be drift-aligned, where barrier morphology is controlled by longshore drift-induced sediment transport or swash-aligned, where sediment transport is predominantly cross-shore with a weak drift component (Orford *et al.*, 1991b). Different sediment sizes respond differently to a single hydrodynamic regime (Medina *et al.*, 1994). Sustained drift transport can induce lateral sediment grading (Bird, 1996b) and cross-shore sorting (McKay & Terich, 1992). The coarsest sediments therefore occur at the barrier crest. Well developed lateral clast grading indicates drift alignment whereas well developed cross-shore clast grading indicates swash alignment. Some beaches display aspects of drift and swash alignment (Orford *et al.*, 1991b).

Beach slope can be proportional to permeability and coarse beaches are therefore steeper than sandy beaches (Quick, 1991). Storms move sediment bedload offshore, generating net erosion (Dubois, 1989; Lee *et al.*, 1995). Berm and cliff-backed beaches are conducive to strong seaward-directed horizontal pressure gradients that drive offshore currents, possibly to depths where fairweather waves cannot induce onshore transport (Héquette *et al.*, 2001). Along low barriers, sediment transport can be directed obliquely due to a smaller storm surge as overwashing removes excess water from the nearshore, decreasing the offshore pressure gradient. Sediment moves onshore during fairweather conditions, manifesting net deposition (Dubois, 1989; Lee *et al.*, 1995). Berms indicate net sediment accretion while berm absence indicates net erosion (Thom & Hall, 1991).

Gravel barrier evolution is controlled by local basement expression during slow RSLR, and sediment supply fluctuations during fast RSLR (Carter *et al.*, 1989). RSL passively influences barrier form by raising the platform on which other processes operate (Orford *et al.*, 1995a). RSLR can trigger horizontal transgression and/or vertical crest building (Orford *et al.*, 1995b). Gravel barriers are often characterised by long periods of slow evolution, punctuated by periods of rapid reorganization (Forbes *et al.*, 1995). Gravel barriers migrate by overstepping when storms overwash the barrier, depositing fans of coarse sediment which act as basement structures on the backbarrier (Forbes *et al.*, 1991). There is little to no return sediment transfer seaward. During less extreme storms, barrier crests build up in response to overtopping (Orford *et al.*, 1991a), in which sediment is deposited at the barrier crest, increasing barrier resistance to overwash and breaching.

Four gravel barrier evolutionary domains have been identified (Orford *et al.*, 1996):

1. Growth, where an increasing sediment supply induces drift-aligned shoal construction in re-entrant traps. The shoals evolve into low-crested islands over time.
2. Consolidation, where shoreline realignment drastically reduces the effective sediment

supply, triggering a shift from drift to swash alignment. Crest elevation builds through overtopping, and the barrier can maintain positional stability.

3. Breakdown, in which overwashing drives transgression. There are 3 distinct phases: (i) slow rollover (~ 1 m/yr) characterized by orderly sediment assemblages; (ii) fast rollover (5-10 m/yr) characterized by chaotic assemblages (the switch from slow to fast rollover is triggered by greater wave exposure or a radical loss of sediment); (iii) dissolution, characterized by the evolution of littoral subcells due to differential longshore transgression rates which locally accelerate washover and breaching. The breaches feed transverse drift-aligned structures which over time completely rework the original barrier.

4. Reformation, where a new barrier evolves from recycled barrier sediments.

Human activities can generate significant morphodynamic shifts in gravel barrier systems. Commercial and subsistence gravel extraction can accelerate the rate of barrier transgression (Prentice, 1993) or even contribute to barrier breakdown (Forbes *et al.*, 1995). Land clearance on adjacent slopes and watersheds can accelerate backbarrier sedimentation rates (Jennings *et al.*, 1998). The forcing of cross-shore drainage via dredging can alter the morphodynamic regime and ultimately, the course of barrier evolution (Orford *et al.*, 1988).

2.2 Coastal Defence and Beach Nourishment

Shoreline armouring can reduce the available sediment supply (McFarland *et al.*, 1994; Kirk, 1992) or interfere with natural transport processes (Bray, 1997), causing downdrift erosion. Unmaintained coastal protective structures may fail catastrophically, generating coastal flooding and associated damage (Ciavola, 1997). Past activities can significantly constrain management options (Bray, 1997).

In order for a beach to provide an effective sea defence, an adequate volume of beach material is required to withstand both a typical storm and to supply sediment for continued littoral transport along the shoreline (Whitcombe, 1996). If sediment is not replaced over the long term, the beach as a unit will be depleted. Shoreline erosion is sometimes mitigated by beach nourishment, usually on sandy, tourism-oriented shorelines with high adjacent property values (Bird, 1996a; Charlier & De Meyer, 2000; Committee on Beach Nourishment and Protection, 1995). Beach nourishment projects often add excess sediment because of rapid initial losses due to natural processes (Cooper, 1998) and most nourishment projects require additional sediment inputs to compensate for long term losses (cf. Bird, 1996a; Charlier & De Meyer, 2000). Rapid initial losses occur because the new profile is not in equilibrium with the boundary conditions (Eitner, 1996) and a portion of the new sediment moves seaward as a response (Leatherman, 1996).

Beach nourishment durability is dependent upon sediment texture (the mean grain size, the percent mud, and the percent coarse material), placement techniques, environmental conditions, including background erosion rates, shoreline morphology, wave climate, currents, tides, and storm frequency (Kana & Mohan, 1998). Ideally, sediment texture should match the natural beach since finer sediments can winnow offshore while coarser sediments may form an excessively steep beach, promoting reflective scour (Bird, 1996a).

Gravel beach nourishment projects are less common than sandy nourishment projects. Some gravel nourishment has occurred in the British Isles and New Zealand (Bird, 1996a). Gravel beach nourishment may be effective when the elevation is raised above the pre-existing elevation and the fine fraction is very small (Jennings *et al.*, 1998; Kirk 1992). Fine-grained sediments interspersed with gravels can manifest a dense compact beach with low permeability (McFarland *et al.*, 1994), which impairs responsiveness to wave attack and form cliff-like scarps on the beach face.

2.3 Tidal Inlets and Barrier Breaching

Barrier breaches can be diagnostic of barrier retreat (Carter *et al.*, 1990) or breakdown (Carter *et al.*, 1989; Carter & Orford, 1993; Orford *et al.*, 1996). Breaching occurs opportunistically where barrier elevation is lowest (Carter *et al.*, 1987b) or the cross-section is thinnest (Fitzgerald, 1993; Friedrichs *et al.*, 1993; Sanchez-Arcilla & Jimenez, 1994) or where cusps locally weaken the cross-shore profile (Orford *et al.*, 1991b). On longer time scales, breaching can occur if RSLR outpaces barrier growth.

Breaches can be triggered by storm wave erosion, overwash, and storm surge flooding (Fitzgerald *et al.*, 1987) when the oceanic water level exceeds that of the backbarrier due to storm setup (Basco & Shin, 1999; Fitzgerald, 1988) or to a differential in the tidal range or a lag in the tidal phase (Fitzgerald, 1993), or when the backbarrier water level significantly exceeds that of the ocean during flood events (Elwany *et al.*, 1998). The water level differential generates a significant hydraulic head that stimulates cross-shore flow when the water level exceeds the barrier height.

Barrier breaches can also be triggered by a depleted sediment supply (Carter *et al.*, 1989) which can alter the cross-shore profile and/or induce barrier cannibalization to supplement some or even all deficiencies in the sediment budget. Adjacent sediment cells may generate opposing sediment transport pathways, the borders of which delineate potential cross-barrier breaching positions (Orford *et al.*, 1996). This relationship may be complex as breaches can alter the behaviour of existing sediment cells (Carter & Orford, 1993; Ciavola 1997), by forcing a new sediment cell boundary at the breach.

Breach vulnerability can be defined by a number of other factors, including the coastal aspect, shoreface bathymetry, mainland topography, planform geometry, and the location of existing inlets (Basco & Shin, 1999). Sediment texture variations can influence breach vulnerability (Johnston & Orford, 1984; Carter *et al.*, 1987b; Orford *et al.*, 1991b) as can saturation of the barrier base or impaired permeability due to the introduction of fine lacustrine or marine sediments (Carter, 1982). Wave refraction patterns may influence inlet position (Johnston & Orford, 1984) and by inference, breach vulnerability by introducing alongshore variations of incident wave power.

Tidal inlets form when barrier breaches lie beneath the mean lower low water elevation (Basco & Shin, 1999). Inlets are commonly narrow, shallow, and ephemeral at inception but a permanent inlet may form if the tidal prism is sufficient to generate scour (Hume & Herdendorf, 1992). Significant consistent fluvial discharge into the backbarrier can often maintain permanent tidal inlets (Soons *et al.*, 1997) but in the absence of significant terrestrial inputs, RSLR can also generate permanent tidal inlets (Boyd *et al.*, 1987).

Inlet-influenced shorelines transgress more rapidly that overwash-dominated shorelines because inlets transfer sediment to the backbarrier more efficiently (Armon & McCann, 1979). Flood tidal deltas can be constructed in lagoons behind wave- and storm-dominated inlets (Fitzgerald, 1988; Leatherman, 1979) due to net sediment transport from the ocean to the lagoon. These deltas become basement structures upon which subsequent deposition and barrier migration can occur (Duffy *et al.*, 1989; Orford *et al.*, 1991b).

Tidal inlets may stabilize near the inception point when protected by an updrift headland that deflects longshore currents offshore (Hume & Herdendorf, 1992; Johnston & Orford, 1984). Exposed tidal inlets may migrate, particularly if the inlet is shallow and narrow (Fenster & Dolan, 1996). On wave-dominated shorelines, migration may be triggered when flood tidal deltas reduce the hydraulic efficiency of the inlet (Dean, 1988). Barriers commonly migrate downdrift due to the preferential erosion of the downdrift inlet shoreline (Fitzgerald, 1988) while sedimentation on the updrift shoreline promotes spit extension (Fenster & Dolan, 1996).

Updrift tidal inlet migration is rare. Updrift migration has been attributed to (i) the attachment of swash bars to the downdrift inlet shoreline, (ii) breaching of the spit updrift of the inlet (most common), or (iii) cutbank erosion of the updrift inlet shoreline (Aubrey & Speer, 1984). Cutbank erosion occurs where obliquely approaching backbarrier ebb tidal currents are directed against updrift shoreline and pointbar accretion can occur on the downdrift shoreline (Fitzgerald *et al.*, 1987).

2.4 Beach Cusps

Cusps are crescentic features found on sandy (cf. Antia, 1989; Holland & Holman, 1996; Masselink & Pattiaratchi, 1998a), mixed sand and gravel (cf. Jennings & Shulmeister, 2002; Nolan *et al.*, 1999), and coarse clastic (cf. Carter & Orford, 1993; Kristensen *et al.*, 1993; Sherman *et al.*, 1993) beaches. There is no single set of conditions under which beach cusps develop, although approximately shore-normal incident waves are often cited (cf. Longuet-Higgins & Parkin, 1962; Rausch *et al.*, 1993; Sunamura & Aoki, 2000). Cusps formation may be inhibited beyond a threshold incident wave angle of 6° (Coco *et al.*, 2000) to 12° (Holland 1998) from shore-normal.

Cusp wavelengths can vary from centimetres to hundred metre megacusps. Cusp shape, volume, and horn morphology are also variable. Cusps are often rhythmic, displaying consistent dimensions alongshore. Cusps form through the interaction of incident waves with beach sediments, manifesting a distinct circulation pattern. Five basic circulation forms have been documented (Masselink & Pattiaratchi, 1998b):

i. Oscillatory Swash Motion, where swash and backwash move up and down the beach.

ii. Horn-Divergent Swash Motion, where swash is deflected from the horn to the centre of the embayment, concentrating into a massive energetic backwash.

iii. Horn-Convergent Swash Motion, where swash enters the embayment in a broad front aligned with the embayment contours and deflects towards the horns, concentrating backwash along the sides of the cusp.

iv. Sweeping Swash Motion, where obliquely incident waves force swash and backwash laterally across the beachface.

v. Swash Jet, where strong backwash interferes with incoming swash to generate a standing wave. When sufficient hydraulic head is built up, swash breaks through the diminishing backwash as a strong jet, subsequently spreading out in the embayment.

The first three circulation patterns are typical of fair weather conditions, while the last two develop under more energetic wave conditions.

Although the cusp structure is relatively simple, the mechanism that induces cusp formation remains unclear. The difficulty in formulating a comprehensive explanation stems from the fact that cusps form under a broad range of textures and energy conditions and exhibit a broad range of morphologies. Rhythmic cusp development has often been ascribed to shore-normal standing edge templates superimposed upon incident waves, which produce systematic variations in wave run-up height (Inman & Guza, 1982), manifesting periodic erosional disruptions on the beach face (Sallenger, 1979). Edge waves are discrete-mode waves trapped by reflection and refraction against a topographic obstacle (Bryan & Bowen, 1996) which can be generated by wind stress acting directly on the water surface (Blondeaux & Vittori, 1995) or by uneven pressure distributions, which may be related to coast-parallel storms. Edge waves are aligned perpendicular to the incident wave field and can develop along steep gravel shorelines (cf. Carter & Orford, 1993; Forbes *et al.*, 1995; Sherman *et al.*, 1993). Standing edge waves develop when pairs of equi-period edge waves propagate in opposite directions (Sherman *et al.*, 1993).

Irregular edge wave templates, which produce arrhythmic cusps, have been attributed to

a) changes in beach slope and/or texture, b) the interaction of incident waves, scattered waves, and currents near a boundary which reduces the incident wave spectrum and excites different edge wave frequencies, c) processes associated with combinations of standing and progressive edge waves, due to presence of shore-normal reflectors that perturb the regular pattern (Carter & Orford, 1993), or d) a series of overlapping stationary and progressive edge waves that are dependent on the rapid shift of incident wave periods which normally appear in a storm (Orford & Carter, 1984).

Where field data does not support edge wave stimulation, cusp formation is often ascribed to self-organization (Werner & Fink, 1993). Cusps form at random alongshore topographic depressions which attract and accelerate water flow, enhancing cusp development. Regular spacing occurs due to a vaguely defined communication of surface gradients by smoothing and by interactions between water particles. Cusp spacing is related to swash excursion length (Masselink, 1999).

Cusps sometimes evolve from backwash channels cut into pre-existing beach ridges (Antia, 1989; Sallenger, 1979; Seymour & Aubrey, 1985). Intertidal beach cusps were not associated with beach ridges at Long Pond, however and supratidal cusps were etched into the storm berm and were not the product of ridge breaching by backwash sediments. Intersecting wave trains may be capable of generating cusps (Darlymple & Lanan, 1976; Monfort *et al.*, 2000), although incident angles are not clearly defined.

Field data do not always provide a definitive formative mechanism since the theoretical results of both models are similar (Allen *et al.*, 1996; Coco *et al.*, 1999; Werner & Fink, 1993). The cusp form seems to be a classic case of equifinality (Antia, 1987), as indicated by the variation in beach texture, cusp dimensions, and circulation patterns.

2.5 Ice Processes

Sea ice can protect coastlines by dampening and deflecting incident wave energy while an icefoot locks sediments in place (Forbes & Taylor, 1994). Icefoot development can also displace incident wave energy offshore, enhancing scour and shoreface adjustment (Barnes *et al.*, 1993; 1994; Forbes & Taylor, 1994).

Dynamic ice can influence coastline morphology. Ice-push occurs when winds and currents push ice onshore (Gilbert, 1990) manifesting boulder ramparts, poorly sorted ridges, cobble pavements, and ice keel and boulder grooves. Storms can move pack ice onshore, building pile up structures that induce ice processes above the mean high water mark (Christensen, 1994; Gilbert, 1990). Ice-push on small lakes can deposit pebbles and cobbles on lakeshore vegetation without incurring damage (Anthony & Blivi, 1999). Ice-lift occurs when tidal fluctuations entrain frozen sediments which may be transported by ice rafting (Gilbert, 1990). Ice rafting can transport silts to boulders (Dionne, 1993). Coarser sediments, including pebbles and cobbles, are transported by basal adfreezing. The sediment volume to ice ratio can exceed 1/10 because nearshore ice is often agglomerated from different sources as well as snow with densities commonly between 0.4 and 0.6 g/cm^3, as opposed to the common value of 0.9 g/cm^3 for non-shoreline ice (Dionne, 1993). Sediment is released upon melting. Ice-lift can be morphologically expressed as boulder-strewn tidal flats and platforms, boulder barricades and garlands, perched stones, and ice keel depressions. Shore and pack ice does not exert a significant morphological control on the southeastern Conception Bay shoreline (Catto, 1994).

Studies of coastal ground ice have focussed on bluffs (cf. Kobayashi *et al.*, 1999) and soft sediments (cf. Allard *et al.*, 1998), but Kobayashi & Aktan (1986) examined ground ice in a gravel causeway. They found that thermal erosion can occur rapidly if the meltout gravels are removed by sediment drawdown during storms. Kobayashi *et al.* (1999) concluded that frozen beach gravel meltout due to heat conduction through unfrozen beach sediment was negligible in comparison to the meltout that occurred when frozen gravels were directly exposed to wave and current action during storms.

2.6 Bluffs

Erosional fronts control shoreline position (cf. Carter *et al.*, 1989) and the redistribution of sediments across or alongshore (Orford *et al.*, 1991b) on large coastal segments. This is a manifestation of the interdependence of adjacent shoreline segments. Erosional fronts are driven by macroscale RSLR (Orford & Carter, 1995), but can be influenced in the short term by rapid localized shoreline adjustments which manifest a disequilibrium that can trigger accelerated transgression of adjacent units. Barrier transgression can be triggered by a loss of headland control (Jennings *et al.*, 1998) as a headland or bluff erodes. Alternately, periods of accelerated transgression during barrier evolutionary cycles (Orford *et al.*, 1991a; 1995a), may exert a control on adjacent bluff recession rates.

Shoreline bluffs in southeastern Conception Bay consist of glaciofluvial sand and gravel, display weak stratification (Catto & St. Croix, 1998) and retreat an average of 0.5 m/yr (Paone, 2003). Bluff erosion and transgression may be triggered by freeze-thaw action, wave undercutting (Wilcock *et al.*, 1998), and wet-dry cycles (Jibson & Odum, 1994). Overland runoff channelization is often considered background erosion but can contribute to bluff erosion by moving sediment downslope.

Wave undercutting can generate rapid bluff retreat rates (Amin & Davidson-Arnott, 1995; Carter & Guy, 1988; Jibson & Odum, 1994; Robinson, 1977; Wilcock *et al.*, 1998). Waves that break directly on slope face exert the largest forces on slope material, while the erosive potential decreases as the breakpoint distance from the bluff increases (Kirkgoz, 1995). Since these conditions are associated with storm activity, bluff retreat is episodic (Amin & Davidson-Arnott, 1995). While extreme storms may generate the largest bluff retreat episodes, on longer timescales moderate storms may generate greater net bluff retreat because they occur more frequently than larger storms (Wolam & Miller, 1960). On this timescale, RSLR raises the platform upon which these storms operate, increasing the erosive potential. Smaller waves do not break on or near the bluffs and lack the power to induce erosion. Consequently, undercutting does not occur during fairweather conditions as bluff retreat opens accommodation space, facilitating the approximate maintenance of cross-shore beach dimensions under the influence of RSLR.

The texture and cross-sectional volume of the beach fronting the bluffs can also influence undercutting potential. Sediment-rich beaches are more effective at dissipating incident wave energy than sediment-poor beaches (Bray & Hooke, 1997; Jibson & Odum, 1994; Marine Institute, 1999; Sunamura, 1977). Swash percolation potential also increases as beach slope and volume increase. In addition to influencing beach slope and permeability, coarser sediments are rougher and induce frictional energy dissipation.

Sediment mobility can influence erosional vulnerability in two ways: (i) mobile sediments are more easily drawn down during a storm, decreasing the beach slope and volume and increasing erosional vulnerability (Davidson-Arnott & Ollerhead, 1995); and (ii) mobile sediments can be incorporated into the wave column, effectively sand (or gravel) blasting the bluff toe (Carter & Guy, 1988; Kamphuis, 1987; Robinson, 1977; Sunamura, 1977). Coarser sediment loads are less mobile and may therefore armour the base of bluff, decreasing the potential for undercutting (Bray & Hooke, 1997).

Sediment saturation increases bluffs are more erosion-prone while saturated. Erosional peaks correspond to winds coincident with increased wave heights, water levels and precipitation (Manson, 2002). Pore space increases during saturation and decreases during dessication. Soil saturation induced by heavy precipitation, snowmelt, and spray can reduce the shear strength of the bluff sediments, rendering them vulnerable to accelerated erosion during storms.

3.0 Methodology

3.1 Beach Profiles

In 1996, the Newfoundland and Labrador Geological Survey (NLGS) installed three rebar benchmarks on Long Pond Barachois (Transects 11, 13, and 15). For this study, an additional twelve rebar benchmarks were installed in January 1997. These benchmarks were 1.8 m in length and were planted 1.2 m deep. The subaerial benchmark height was recorded for each. With the exceptions of Transects 12, 13 and 14, the survey markers were planted on the upper lagoonal apron (Fig. 3.1). Survey marker 13 was established on Burnt Island, while ice cover forced the placement of markers 12 and 14 above the breakpoint. Transect 15, located in the sub-basin, was uprooted by tidal ice-lift before it could be surveyed. Fourteen transects (Fig. 3.2) were monitored between 02/02/97 and 23/02/98, after which Transect 12 was lost. The remaining transects were monitored until 10/07/99. Transect 14 was disturbed by access road construction between 13/05/98 and 14/07/98 and subsequent profiles were analysed separately.

Surveys were conducted opportunistically when transportation and volunteer field assistants were available. The tide level did not influence survey scheduling since (i) the lack of flexibility in obtaining the necessary support and (ii) it seemed useful to survey the site through a variety of incident environmental parameters, provided there was no hazard involved. The value of surveying through a variety of tide levels instead of surveying exclusively at ebb tide proved its worth on 15/03/97 when 1.5 - 2 m swells were recorded during peak tide, providing the most dynamic and informative survey results of the study.

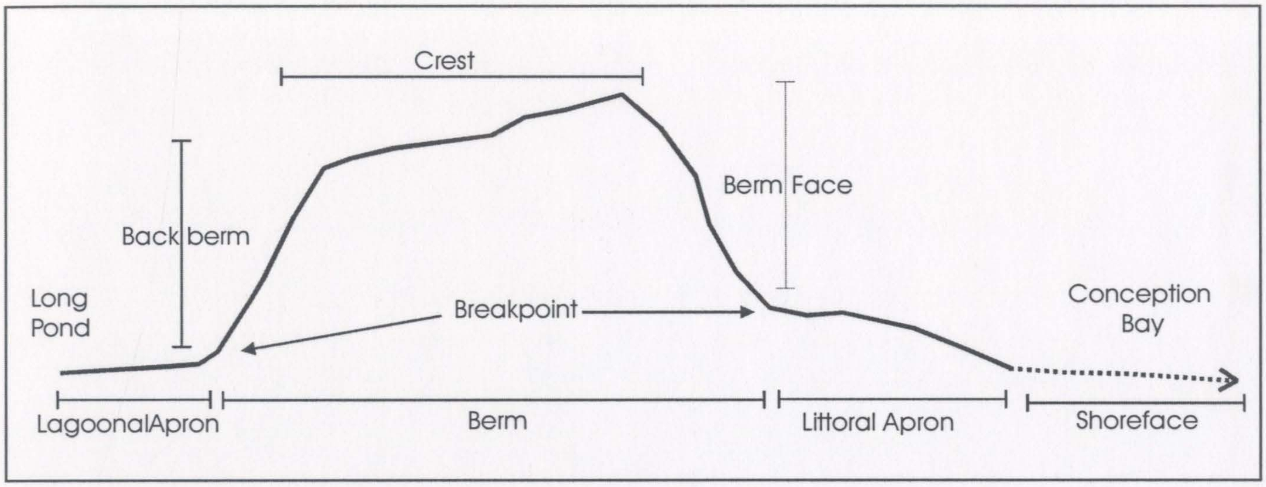


Figure 3.1. Profile terminology employed in this study.

Beach profile surveys were measured along shore-normal transects that intersected the benchmark as described by Emery (1961). Horizontal measurements were read directly from the measuring tape. Segments between the benchmark and Conception Bay were assigned positive values and those between the benchmark and Long Pond were assigned negative values. Vertical measurements were obtained by recording elevational differences with the Emery poles. The surveyor held the landward rod and aligned the eye with the top of the seaward rod and the horizon and read the elevational change off the landward rod. The landward rod was moved to the seaward rod position and the seaward rod was moved to the next break in slope, textural change, or 3 m distant. Rises in elevation were assigned positive values while decreases in elevation were assigned negative values. When the horizon was not in view, an Abney hand level was used to approximate the horizon. The Abney hand level initially did not function properly and

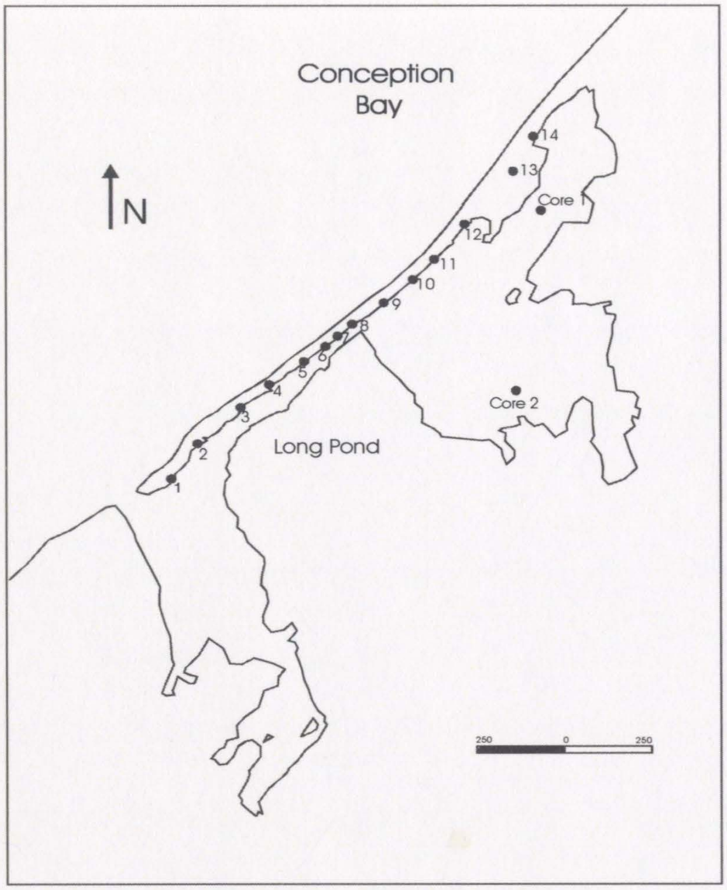


Figure 3.2. Transect and core locations, Long Pond.

a

b

Plate 3.1 a. Establishment of RTK-DGPS base station.

b. Recording benchmark position, Transect 11.

the problem was not detected until later. Some of the profile surveys therefore required calibration. The profile measurements were entered into a Microsoft Excel™ database, and graphed as two-dimensional profiles on scatter plots.

The sample size required to obtain a statistically valid quantitative assessment of a heterogeneous gravel body is prohibitive (cf. Church *et al*., 1987; Ferguson & Paola, 1997; Gale & Hoare, 1992). The sediment texture was therefore assessed qualitatively while the profiles were recorded.

The beach profile surveys were complemented by a crest profile survey, using a Real Time Kinematic Digital Global Positioning System (RTK-DGPS) provided courtesy of Dr. Donald Forbes of the Geological Survey of Canada (GSC) on 19/11/98. The positions of the remaining thirteen benchmarks were also surveyed. These measurements were recorded as part of a larger coastal monitoring program on the Avalon Peninsula. The crest survey was subsequently used to calibrate the beach profile survey.

Profile surveys were complemented by non-systematic inspection of Burnt Island and the adjacent bluffs and beaches north and south of Long Pond and a photographic record was obtained. Local infrastructure around Long Pond was also recorded.

3.2 Cusp Measurements

Cusps were classed on the basis of their location. Apron (intertidal) cusps formed on the littoral apron. Berm (supratidal) cusps formed on the berm, above the high water mark. Cusp position was recorded on the basis of proximity to the nearest transect. Cusp

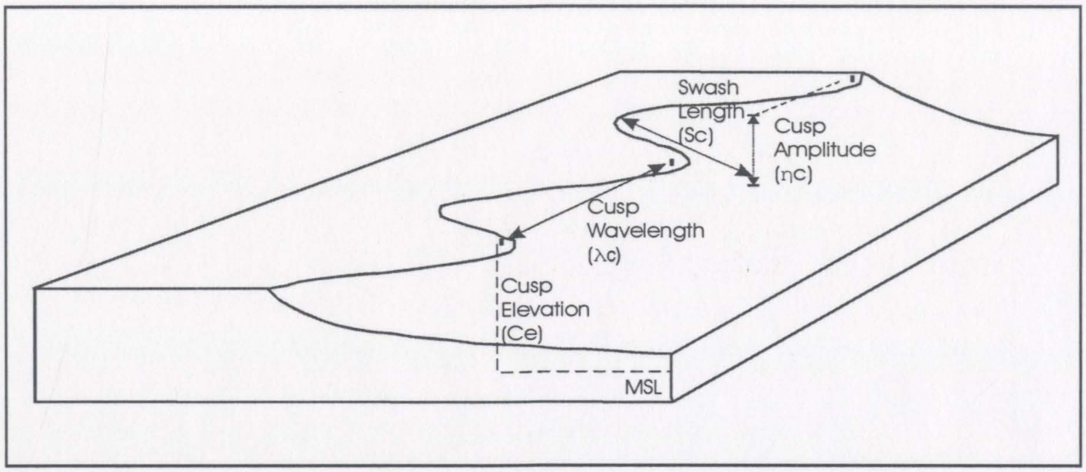


Figure 3.3. Cusp dimensions (adapted from Nolan *et al.*, 1999).

wavelength (or spacing), λ_c, and swash length (or cusp depth), S_c, were measured with a standard 50m measuring tape. Wavelengths were measured from cusp horn tip across the cusp bay to the adjacent cusp horn tip (Fig. 3.3). Swash lengths were measured from the approximate midpoint of the wavelength axis to the backwall. Beach profile methodology was employed to measure cusp amplitudes, η_c, on the littoral apron and cusp depths, D_c, on the berm. Cusp amplitudes (high point of the horn to the nadir of the cusp bay) were well defined on the apron cusps but poorly defined on the berm cusps. Berm cusp horns often resembled the antecedent berm structure and it was uncertain where the high point occurred. Cusp depth extended from the rim of the cusp backwall to the cusp bay nadir.

The average slope angle, β, was calculated from the profile data. Cusp texture was assessed by qualitative comparison between the cusp horn, bay and the antecedent texture. Cusp skew was assessed relative to a hypothetical shore-normal axis.

Cusp wavelength may be related to the frequency of standing subharmonic or synchronous edge waves (Inman & Guza, 1982; Seymour & Aubrey, 1985). Direct hydrodynamic testing was not possible due to the unpredictability of cusp building events. Edge wave occurrence was therefore tested mathematically, using methodology described by Inman & Guza (1982). Subharmonic edge waves have a period twice the incident wave period. The cusp wavelength is determined by the equation

$$\lambda_c = (g/\pi)\ T^2{}_i \tan\beta \quad (1)$$

where g is the acceleration due to gravity and T_i is the period of the incident wave. Synchronous edge waves have a period equal to the incident wave period. The cusp wavelength is determined by the equation

$$\lambda_c = (g/2\pi)\ T^2{}_i \tan\beta \quad (2)$$

Apron cusp wave periods were approximated and used to derive cusp spacing, which was then compared to the measured spacing. Berm cusps were measured after formation and no reliable estimate of the incident wave period was available, except during the 21/03/97 survey when the cusps were related to the 14 s swells of 15/03/97. Potential wave periods were calculated (Equations 1 and 2) to indirectly test whether synchronous or subharmonic edge waves were capable of inducing apron cusp development.

Edge wave theory holds that the cusp spacing is positively related to the beach slope (Masselink, 1999). The Pearson Correlation Coefficient, which can identify positive and negative correlations, was used to correlate cusp spacing with slope. Apron and berm cusps were tested separately. Berm cusps were tested collectively, by horn morphology (since different morphologies may indicate different cusp-inducing mechanisms), slope complexity (since slope type may influence swash excursion behaviour), and the 21/03/97 survey. The swash length and wavelength/swash length ratio were also correlated to beach slope to assess whether slope influenced swash excursion and cusp dimensions.

Self organization was tested by conducting a regression analysis of swash length and spacing. Spacing should be proportional to the swash length, graphically expressed by a straight line through the zero intercept and a slope between 1 and 3, with a statistically significant R^2 value. Whereas Coco *et al.* (1999) utilized a log-log graph due to the wide range of cusp dimensions incorporated in their analysis, Long Pond cusps were not as variable and a standard integer graph was employed. Berm cusps were tested along the same parameters as the edge wave testing. Apron cusps were tested separately.

3.3 Tracer Experiment

To assess the sediment transport potential of tidal currents in the channel, four groups of 25 gravel tracers were placed on the lagoonal apron on 11/05/97. Gravel tracers obtained from Long Pond barachois were treated with Matchless™ Ocean Marine Alkyd Marine Paint and were differentiated by colour scheme. Tracer groups consisted of 20 pebbles and 5 cobbles. Experiment parameters are summarized in Table 3.1.

3.4 Core Sample Logs

Two sediment cores were extracted from the northern basin (Fig. 3.2) on 21/03/97 when

Table 3.1: Gravel tracer experiment parameters.

	Location	Colour	Blades	Discs	Spheres	Rollers
Group 1	Transect 3	orange/yellow, split perpendicular to a-axis	10	4	8	3
Group 2	Transect 6	orange	12	8	3	2
Group 3	Transect 8	yellow	8	7	4	6
Group 4	Transect 9	orange/yellow, split parallel to a-axis	10	3	7	5

ice facilitated a stable base. The southern basin did not completely freeze during the survey period and no cores could be obtained. A piston corer was used to extract the samples. Three core segments were extracted from each coring site.

Six samples were obtained per core at 25 cm intervals from top to bottom. Macrofossils were removed and identified by type. The residual was pulverized with mortar and pestle. The samples were treated and analysed for texture according to the hydrometer analysis methodology described in Appendix 1 of Catto & Quaternary Research Group (1989). The dry sample weights were less than 50 g, so the analysis was adjusted accordingly.

4.0 Profile Results

4.1 Overview

Long Pond Barachois did not transgress during the study period and there was no barrier overtopping or overwashing. The littoral apron and bermface were active during the study period while the crest, backbarrier slope, and lagoonal apron were comparatively inert. A great deal of anthropogenic disturbance occurred during the study period. Pedestrian and ATV traffic were common. The breach site was reinforced with gravel borrowed from the adjacent berm and littoral apron in response to erosional weakening. The Burnt Island sub-basin was rezoned, permitting residential construction on the island, access road construction on the backbarrier, and armouring of the sub-basin.

4.2 Profiles

The complete set of profile surveys is presented in Appendix 3. Eight profiles were selected and are depicted in Figures 4.1 through 4.14 a and b. Transect 12 (Fig. 4.12) is represented by 6 profiles because the benchmark was lost during the study period and Transect 14 is represented by 2 profile diagrams (Fig. 4.14 a, b) due to beach disturbance by access road construction. A crest profile survey, courtesy of Dr. Donald Forbes of the Geological Survey of Canada, is depicted in Figure 4.15.

There were two basic profile types: simple and compound. Simple slopes were characterized by an oblique breakpoint between the berm and littoral apron. Simple slopes were recorded on Transects 13 and 14 (Figs. 4.13 and 4.14 a, b). Compound

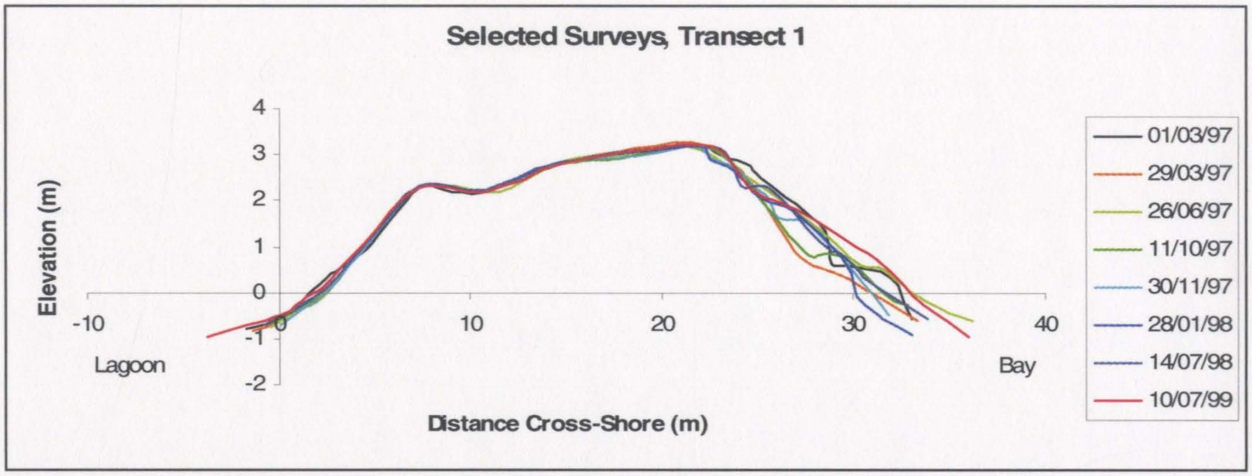


Figure 4.1. Selected surveys, Transect 1 (Vertical Exaggeration x2.5).

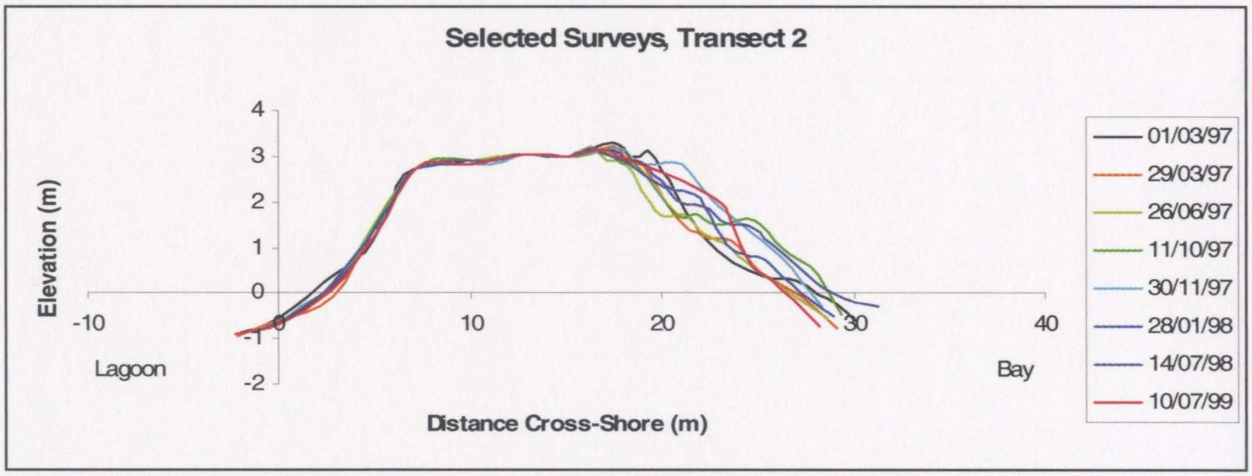


Figure 4.2. Selected surveys, Transect 2 (Vertical Exaggeration x2.5).

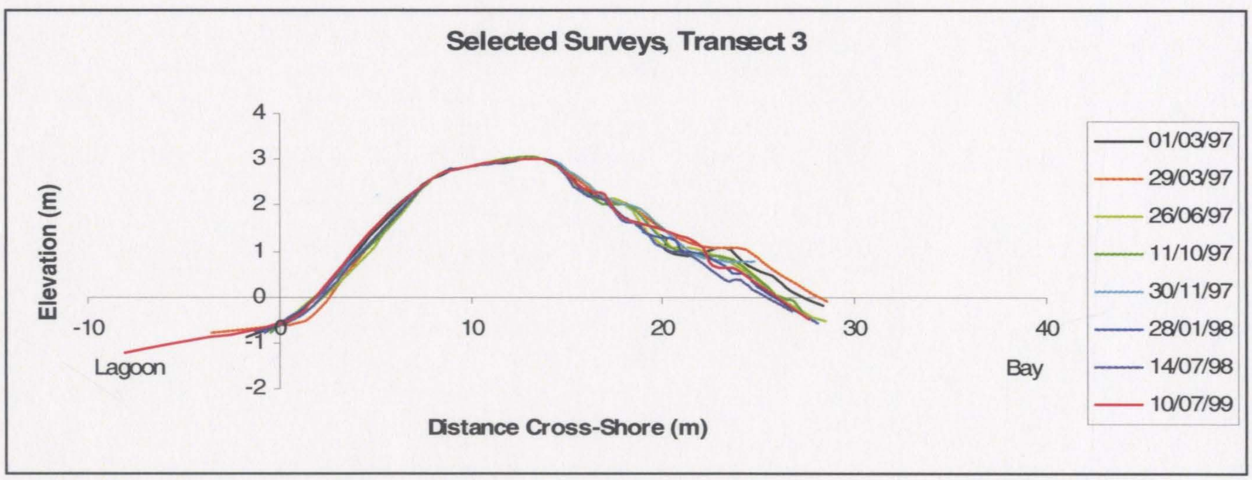


Figure 4.3. Selected surveys, Transect 3 (Vertical Exaggeration x2.5).

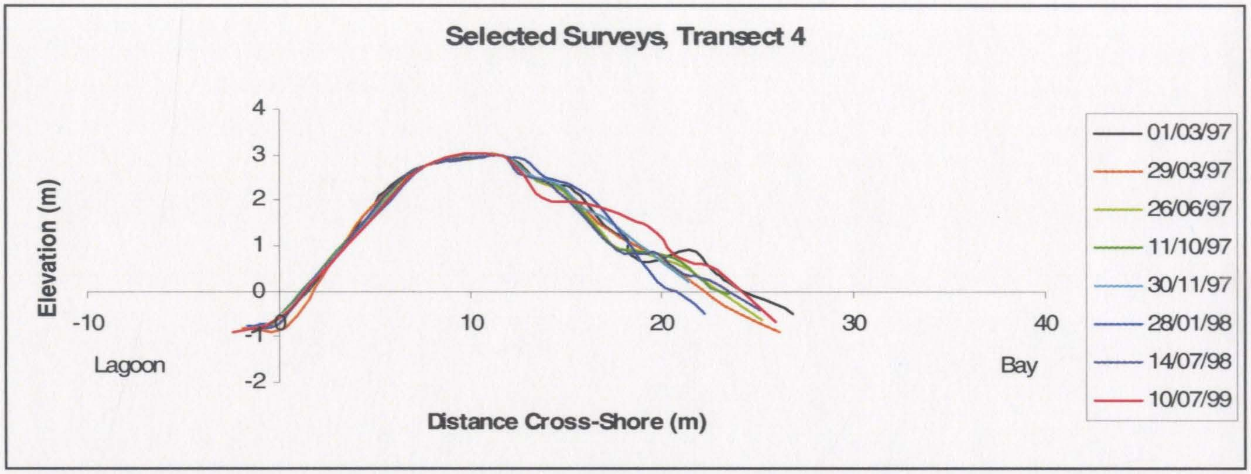


Figure 4.4. Selected surveys, Transect 4 (Vertical Exaggeration x2.5).

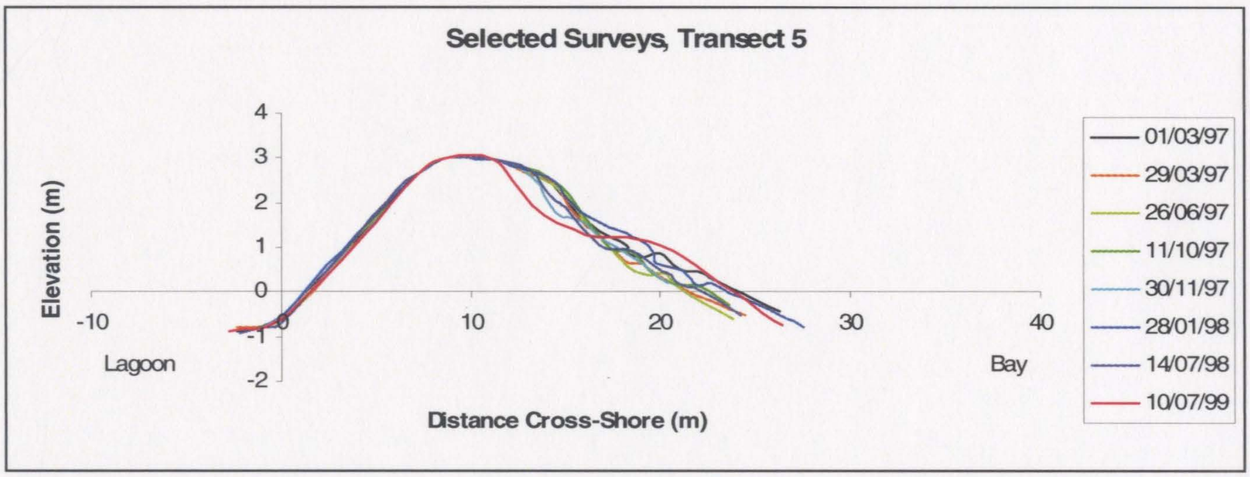


Figure 4.5. Selected surveys, Transect 5 (Vertical Exaggeration x2.5).

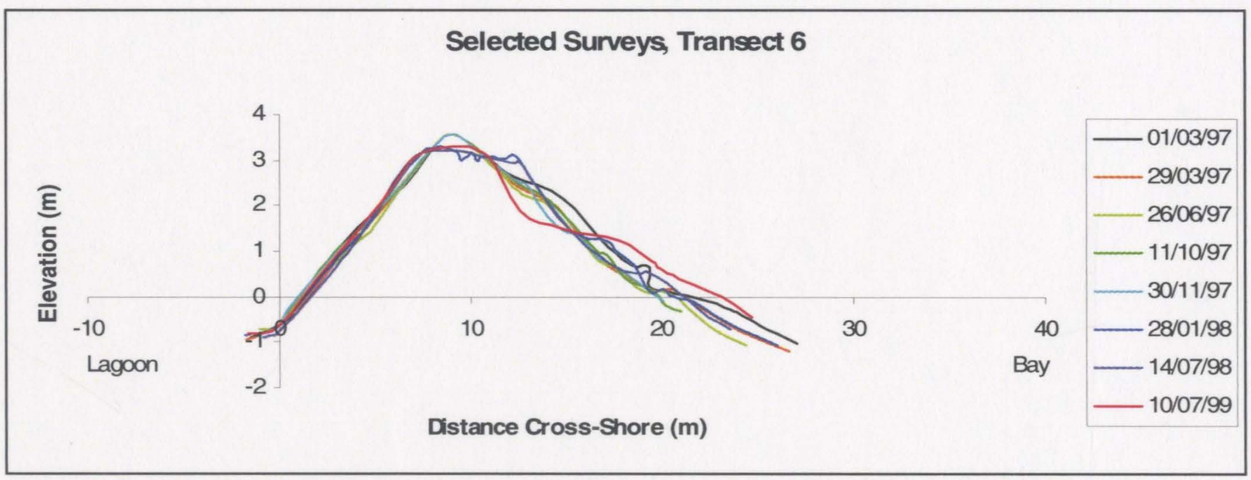


Figure 4.6. Selected surveys, Transect 6 (Vertical Exaggeration x2.5).

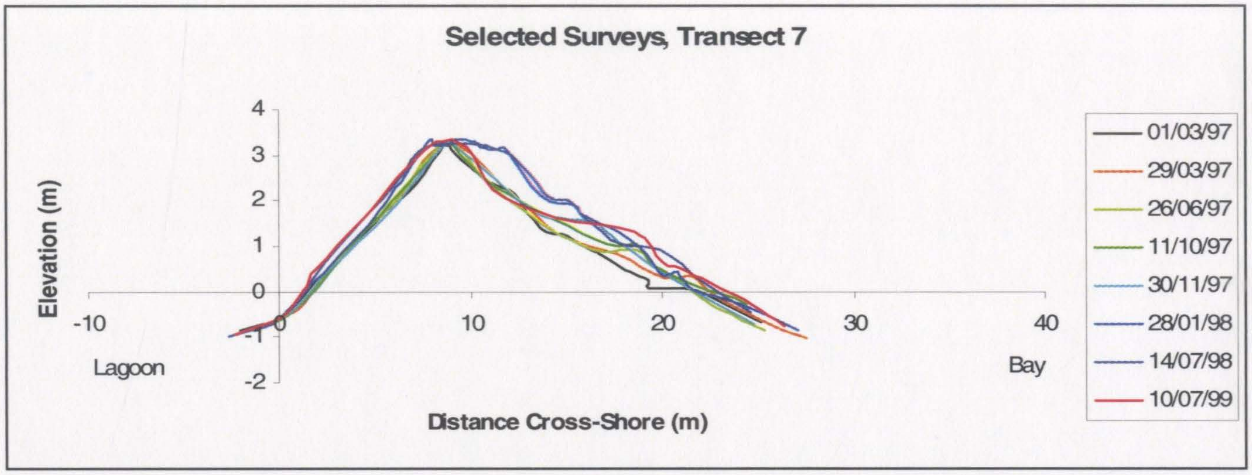


Figure 4.7. Selected surveys, Transect 7 (Vertical Exaggeration x2.5).

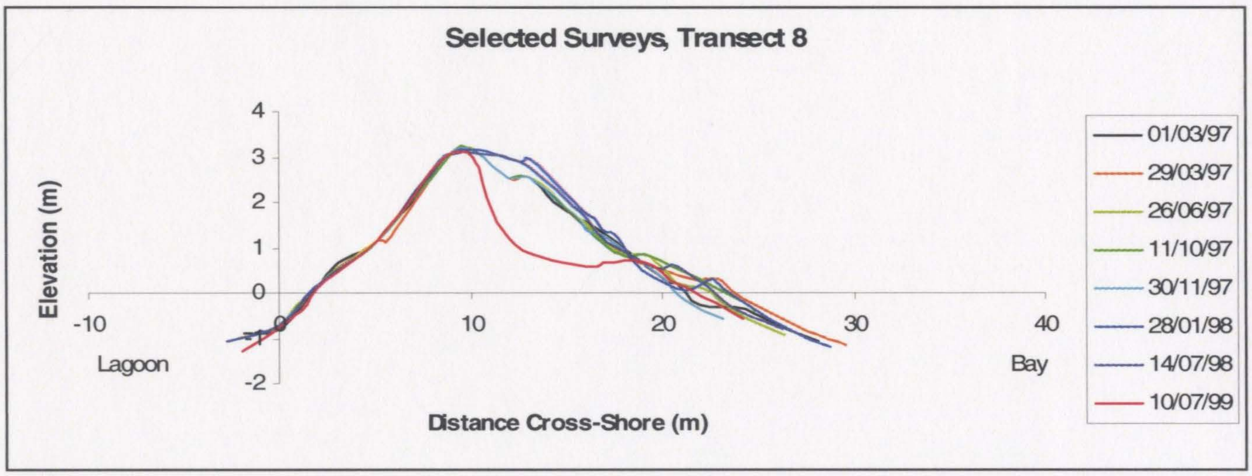


Figure 4.8. Selected surveys, Transect 8 (Vertical Exaggeration x2.5).

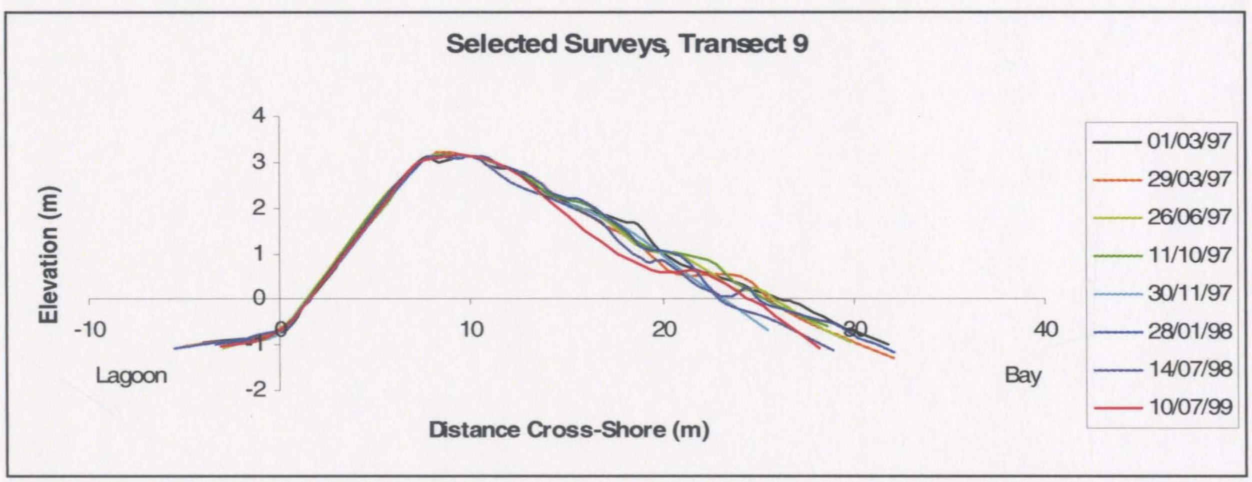


Figure 4.9. Selected surveys, Transect 9 (Vertical Exaggeration x2.5).

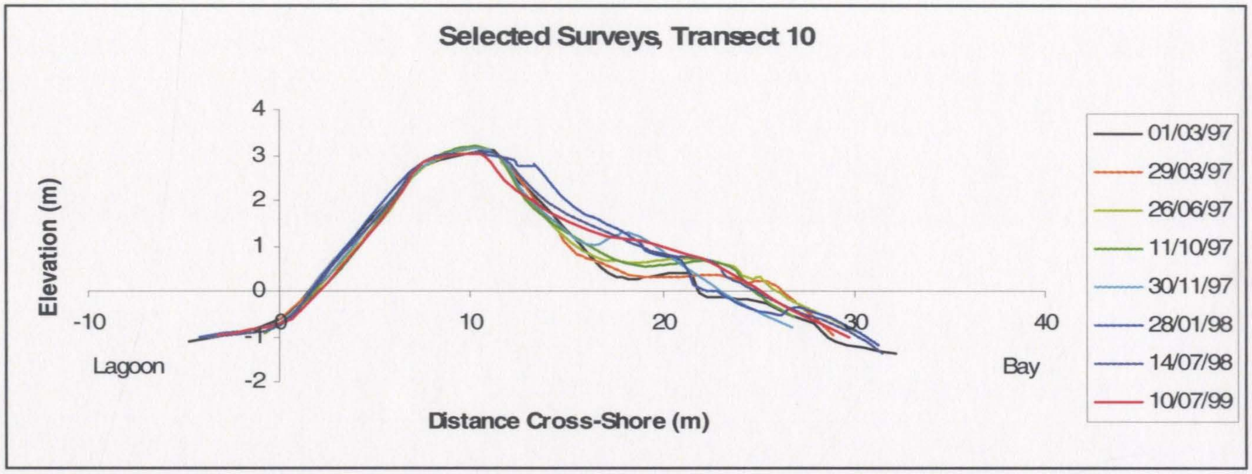


Figure 4.10. Selected surveys, Transect 10 (Vertical Exaggeration x2.5).

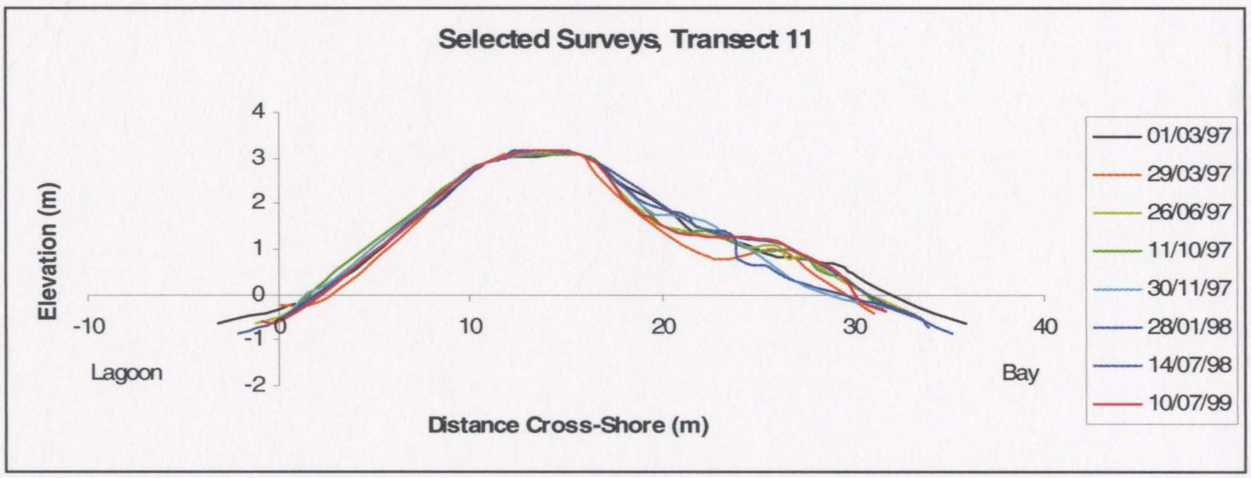


Figure 4.11. Selected surveys, Transect 11 (Vertical Exaggeration x2.5).

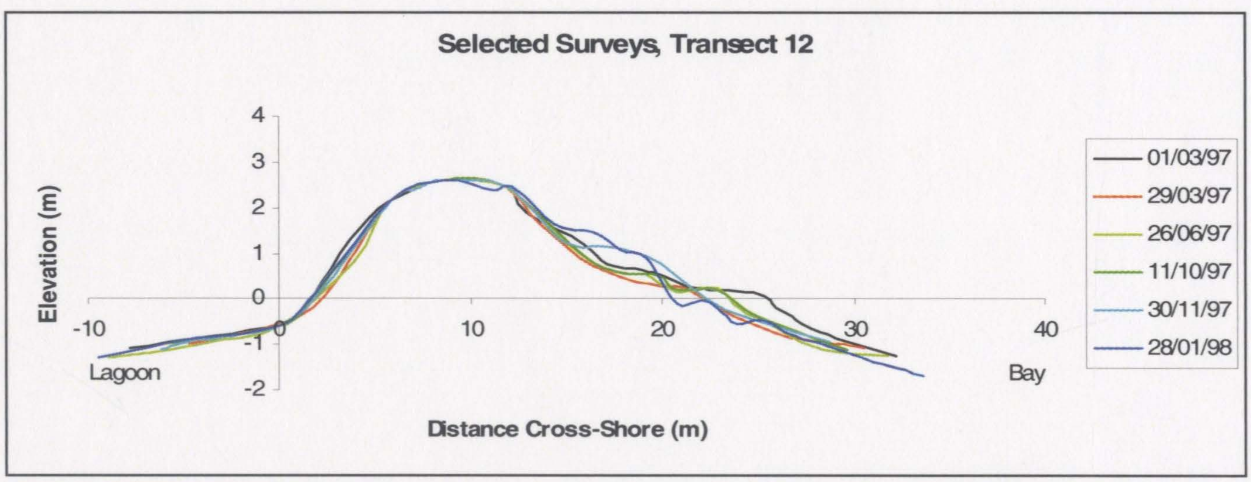


Figure 4.12. Selected surveys, Transect 12 (Vertical Exaggeration x2.5).

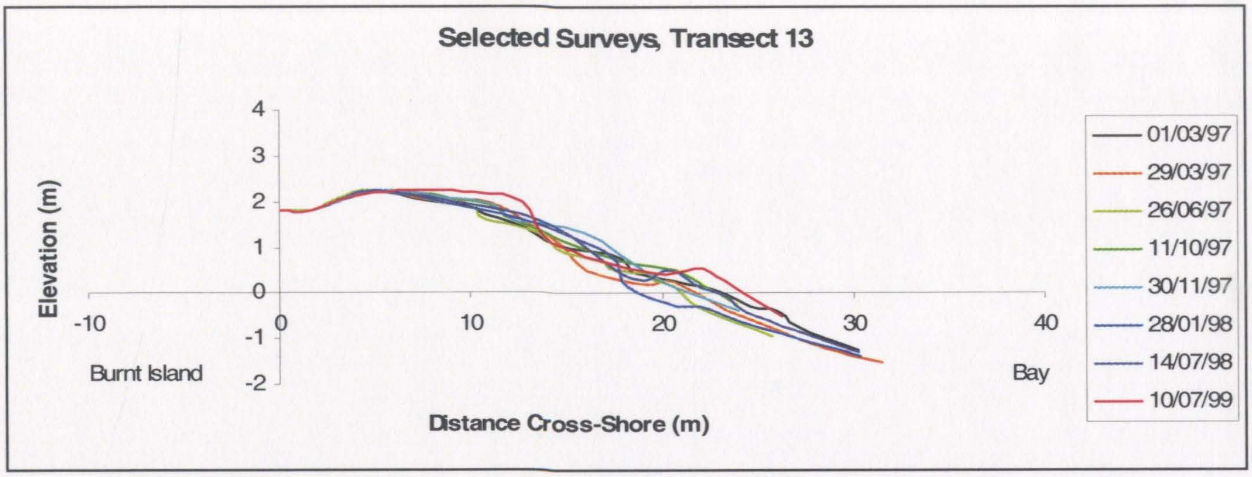


Figure 4.13. Selected surveys, Transect 13 (Vertical Exaggeration x2.5).

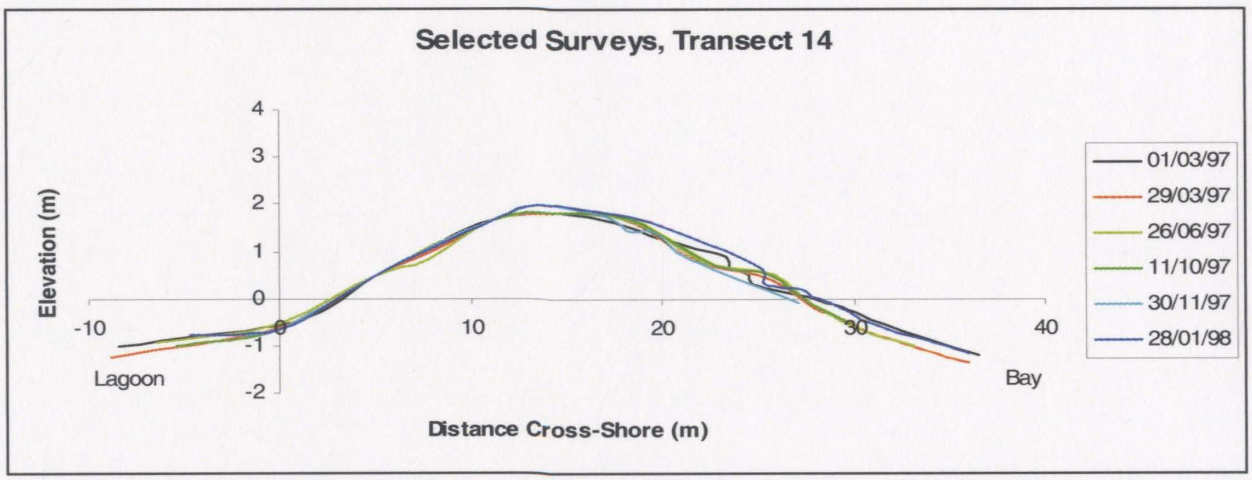


Figure 4.14a. Selected surveys, pre-road Trans. 14 (Vertical Exaggeration x2.5).

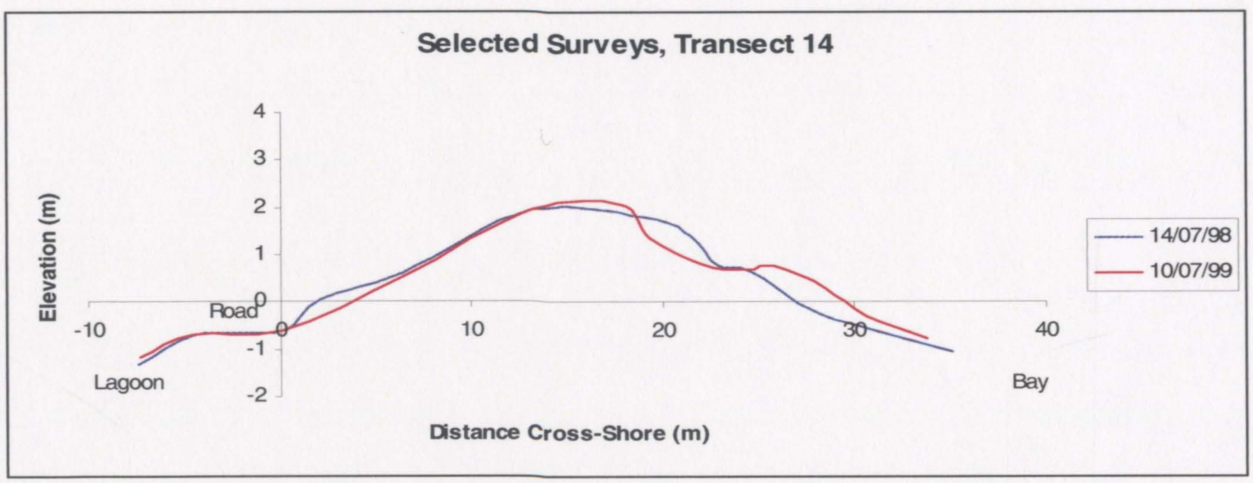


Figure 4.14b. Selected surveys, post-road, Trans. 14 (Vertical Exaggeration x2.5).

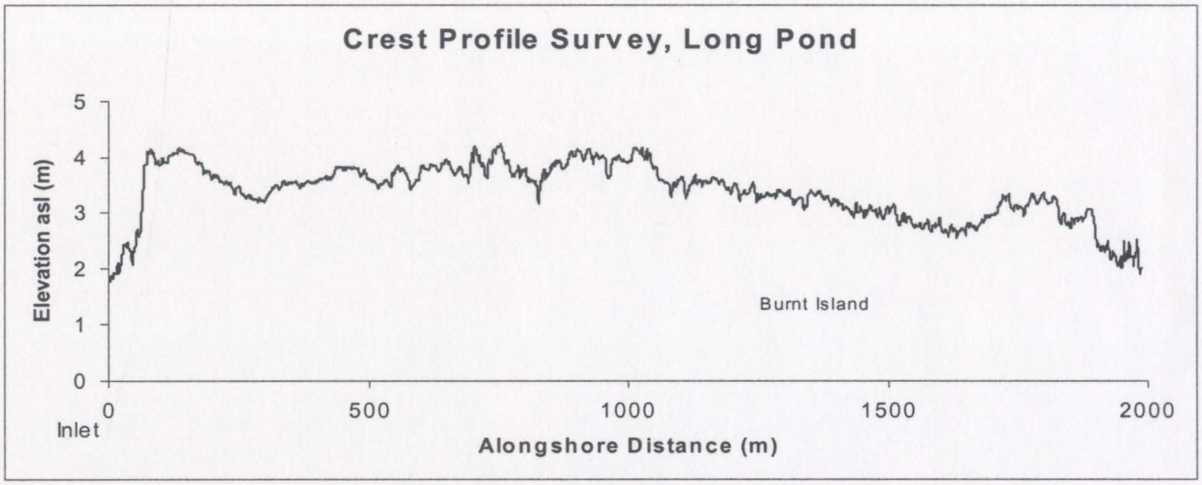


Figure 4.15. Crest Profile Survey, Long Pond, 11/18/97. Vertical Exaggeration x100. (Courtesy Dr. Donald Forbes, Geological Survey of Canada).

slopes were characterized by acute breakpoints between the berm and littoral apron. There were three distinct sets of compound slopes. Transects 1 and 2 hosted the sharpest breakpoints and the most massive crests (Figs. 4.1 and 4.2). Transects 3 through 12 exhibited similar profile shapes (Figs. 4.3 - 4.12), but large cusps were etched into the berm between Transects 8 and 12.

Bermface fluctuations did not occur seasonally or consistently alongshore. On 19/04/97 for example, Transect 8 lost volume, Transect 9 maintained roughly the same volume but did not maintain profile shape, and Transect 10 gained sediment volume as compared to the previous survey (Table 4.1). There was no obvious pattern to this behaviour and it seems unlikely that gravel eroded from one segment was simply deposited on another. It should be noted that, although not directly surveyed, the bermface of the fringing barrier directly north of Long Pond displayed evidence of sustained (if slow) retreat during the study period reflected by the increase in the exposure and the vegetative colonization of a buried glaciofluvial structure (Plate 1.3 c, d).

There were no consistent textural trends observed at Long Pond (Table 4.2). Berm texture was dominated by coarse pebbles and cobbles at non-disturbed sites but small to medium sized pebbles were abundant. The littoral apron texture was variable, but there were no apparent seasonal patterns. There were no consistent alongshore or cross-shore sorting trends observed during the study period. The lagoonal apron was texturally sorted: fine to medium pebbles dominated south of the tidal channel, coarse pebbles and cobbles dominated north of the channel. Sorting was generally poor adjacent to the breach site (Transects 6 - 8) although silt lenses were evident and a line of coarse clasts occurred at the breakpoint. Barachois gravels were generally well rounded, although some subrounded to subangular clasts were observed, particularly north of Transect 12. Well-rounded asphalt clasts were rare but could be observed on the littoral apron, the berm, and the backbarrier, most commonly north of Transect 12.

Table 4.1: Changes in profile volume by survey date (+: Volume Increase, −: Volume Decrease, N/C: No Change, N/A: No Available Data, c: Cusp, *: Anthropogenic Disturbance, ‡: Minor Change, †: Decreased Crest Width, ▲: Changed Profile Shape).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
01/03 /97	N/A	N/A	N/A	N/A	N/A	−	−	−	$+_{c}$	$-_{c}$	−	−	N/C$_{\blacktriangle}$	$-_{c}$
29/03 /97	−	−	+	−	−	−	$+_{\ddagger}$	+	−	$+_{c}$	$-_{c}$	$-_{c}$	$-_{c}$	−
19/04 /97	$+_{\ddagger}$	+	−	+	N/C	+	$+_{\ddagger}$	−	N/C$_{\blacktriangle}$	$+_{c}$	+	+	+	N/C$_{\blacktriangle c}$
11/05 /97	$+_{\ddagger}$	$+_{\ddagger}$	$+_{\ddagger}$	−	$+_{\ddagger}$	−	+	$+_{\ddagger}$	+	$-_{c}$	$+_{\ddagger}$	N/C$_{\blacktriangle}$	N/C$_{\blacktriangle}$	N/C$_{\blacktriangle}$
09/06 /97	+	−	+	$+_{\ddagger}$	N/C$_{\blacktriangle}$	$-_{\ddagger}$	+	−	−	$+_{c}$	+	+	$+_{\ddagger}$	+
26/06 /97	$-_{\ddagger}$	N/C	−	$-_{\ddagger}$	$-_{\ddagger}$	−	−	N/C	N/C	$-_{c}$	N/C	$-_{\ddagger c}$		$+_{\ddagger c}$
20/09 /97	−	+	$-_{\ddagger}$	N/C	$+_{\ddagger}$	$-_{\ddagger}$	−	$-_{\ddagger}$	$-_{\ddagger}$	N/C$_{c}$	N/C	+	+	$-_{\ddagger c}$
11/10 /97	N/C$_{\blacktriangle}$	$+_{\ddagger}$	$-_{\ddagger}$	N/C	$+_{\ddagger}$	$+_{\ddagger}$	+	+	$+_{\ddagger}$	$-_{c}$	$-_{\ddagger}$	$-_{\ddagger c}$	−	N/C$_{c}$
11/11 /97	+	+	$+_{\ddagger}$	$+_{\ddagger}$	−	$+_{\ddagger}$	$-_{\ddagger}$	−	−	$+_{c}$	−	$+_{\ddagger}$	−	N/C$_{\blacktriangle}$
30/11 /97	−	−	N/C	N/C$_{\blacktriangle}$	N/C$_{\blacktriangle}$	$-_{\ddagger}$	N/C$_{\blacktriangle}$	N/C$_{\blacktriangle}$	$+_{\ddagger}$	$-_{c}$	$+_{\ddagger}$	+	+	−
29/01 /98	N/C$_{\blacktriangle}$	−	−	$-_{\ddagger}$	+	$+_{*}$	$+_{*}$	$+_{*}$	+	+	−	N/C$_{\blacktriangle}$	−	+
23/02 /98	+	−	$+_{\ddagger}$	−	−	N/C$_{\blacktriangle}$	$-_{\ddagger}$	+	+	$+_{\ddagger}$	+	$+_{\ddagger}$	+	+
13/05 /98	−	+	$-_{\ddagger}$	+	N/C$_{\blacktriangle}$	$+_{\ddagger}$	+	−	−	$+_{c}$	$-_{c}$	N/A	$-_{\ddagger}$	+
14/07 /98	N/C	+	−	−	−	−	N/C$_{\blacktriangle}$	$+_{\ddagger}$	N/C$_{\blacktriangle}$	−	+	N/A	+	N/A
12/09 /98	N/A	N/A	N/A	N/A	−	+	−	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10/07 /99	+	−	$+_{\ddagger}$	+	$+_{\dagger}$	$+_{\dagger}$	$-_{\dagger}$	$-_{c}$	N/C$_{\blacktriangle}$	$-_{\ddagger}$	−	N/A	$+_{c}$	$+_{c}$

Table 4.2: Sedimentary assemblages on the littoral apron by survey date (p: Pebble, c: Cobble, b: Boulder, s: Sand, f: Fine, m: Medium, r: Coarse, n: No Dominant Size, u: Unsorted, *: Sorted Component, i: Icefoot, †: Fining Seaward, ‡: Coarsening Seaward, N/A: No Available Data).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
08/02 /97	$p_n$ciu	$p_r$ciu	p_fi*	$p_n$ciu †	$p_n$ciu	$p_n$ciu	cp_rb u	$p_n$cs u	$p_n$ci*	$p_n$cu ‡	$p_n$cu ‡	$p_f$cs*	$p_n$cs u	$p_n$csu
01/03 /97	$p_r$ciu	$p_n$ciu	$p_n$iu	$p_n$iu	$p_f$iu†	$p_n$iu	p_fi*	$p_r$ciu †	$p_f$ci*	$p_f$ci*	$p_n$iu	$p_f$csi *	p_ni*	$p_n$csi u
15/03 /97	cp_nu	cp_nu	$p_n$cu	c$p_n$iu	$p_n$cu	$p_n$cu	$p_n$cu	$p_f$cb *	cp_fu	$p_r$cu	N/A	$p_r$cu	$p_n$cu	cp_nu
29/03 /97	$p_n$cu	cp_nu	p_nc* ‡	$p_m$ci *	p_fc*	p_nc*	$p_f$cu ‡	$p_f$cb *	p_nc*	p_nc*	p_mc*	$p_n$cu	$p_n$cs u	$p_f$csu
19/04 /97	$p_n$cu	$p_r$cu	p_m*†	p_fc*	p_fc*	p_fc*	$p_n$cb u	$p_f$cb u	$p_n$cu	p_mc*	$p_n$cs u	$p_n$cs u	$p_n$cs u	$p_n$cb u
11/05 /97	cp_nu	$p_n$cu ‡	p_f*†	p_nc* ‡	$p_f$csb *	p_fc* †	$p_n$cs u	p_fc*	$p_n$cs bu	p_nc*	$p_n$cs u	p_fc*	$p_n$cu	$p_n$cs*
09/06 /97	$p_n$cu ‡	cp_nu	p_nc* †	p_rc* †	$p_m$cs *	$p_f$cs*	$p_n$cs *†	$p_f$cs*	p_nc*	p_nc* †	$p_n$cs *	$p_m$cs *	$p_n$cs u†	$p_n$cs*
26/06 /97	$p_r$cu	cp_nu	$p_n$cu ‡	p_nc*	$p_m$cu	p_mc*	p_nc*	p_mc*	$p_n$cu	p_nc*	$p_f$cu	$p_n$cs u	$p_n$cs *	$p_n$csu
20/09 /97	$p_r$cu	$p_n$cu	p_mc* †	p_fc* ‡	$p_n$cb u‡	cp_nu	$p_n$cu	$p_n$cu	p_fc*	$p_m$cu	$p_n$cu	$p_f$cs*	$p_m$cs u	$p_n$csu
11/10 /97	cp_nu	p_mc*	p_mc* †	p_fc* †	p_mu	$p_n$cu ‡	p_nc* †	$p_n$cu †	$p_n$cu	$p_n$cu	$p_n$cu †	$p_n$cu †	$p_n$cu †	$p_n$cu ‡
11/11 /97	$p_r$cu †	$p_n$cu ‡	$p_n$cu	$p_n$cu	cp_nu	cp_nu	cp_nu	$p_n$cu	$p_n$cu	$p_f$csb u	$p_n$cs u	$p_n$cs bu	$p_n$cs u	$p_n$csu
30/11 /97	p_rc*	$p_n$cu	cp_nu	$p_n$cu	$p_n$cu	$p_r$cu	$p_r$cu	$p_n$cu	cp_nu	$p_n$cs u	$p_m$cs u	$p_m$cu	$p_n$cu	cp_nu
29/01 /98	$p_m$ci *	$p_m$ci *†	$p_m$ci *	$p_n$ciu	$p_n$ciu	$p_f$cbi *	$p_n$ci*	$p_m$ci *	$p_n$ciu	$p_n$csi *	$p_f$csi *	$p_f$ci* ‡	$p_n$csi u	$p_n$ciu
23/02 /98	$p_n$cu	cp_nu	$p_n$cu	$p_n$cu	$p_n$cu	$p_n$cb u†	cp_nb u	$p_n$cu	$p_m$cs *	$p_n$cs u	$p_m$cs u†	$p_n$cu	$p_n$cu	$p_n$csu ‡
13/05 /98	$p_n$cu	cp_nu	$p_n$cu	p_mc*	$p_n$cu	$p_n$cb u	$p_n$cb u	p_fc*	$p_n$cu †	$p_n$cu	p_nc*	N/A	$p_n$cu	$p_n$csu
14/07 /98	cp_nu	cp_nu	$p_m$cu	$p_n$cu ‡	p_fc*	$p_m$cu †	$p_n$cb u†	$p_n$cs u	p_fc*	$p_n$cu	$p_n$cu	N/A	$p_n$cs u†	$p_f$csu
12/09 /98	N/A	N/A	N/A	N/A	$p_n$cu	$p_n$cu	$p_n$cb u	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10/07 /99	cp_nu	$p_n$cu	cp_nu †	p_mc* †	$p_n$cu	$p_n$cu †	cp_nu	$p_n$cu	p_nc* †	$p_n$cu	p_fc*	N/A	cp_nu	cp_nu

5.0 Cusp Results

5.1 Context

Large cusps were etched into the berm north of Transect 8 when the study commenced (Fig. 5.1). The extent to which cusps dominated the beach profile and the discrete zones of cusp occurrence and absence dictated that the cusps be analysed. Field surveys detected berm cusp reworking, destruction, and reformation, and cusp formation on the littoral apron. Cusp survey summaries have been presented in Appendix 4.

Beach cusp formation is often ascribed to edge wave stimulation or to self-organization. Due to the unpredictability of cusp development, hydrodynamic testing for edge wave occurrence was not possible. Edge wave stimulation was tested through comparison of recorded wavelengths or periods with derivations based upon Equations 1 and 2 (Section 3. 2) based upon Inman & Guza (1982). Edge wave theory holds that cusp spacing is positively related to beach slope (Masselink, 1999). The relationship between spacing and beach slope were tested by the derivation of Pearson Correlation Coefficients, which can determine positive and negative correlations. Pearson Correlation Coefficients were also derived between beach slope and swash length and cusp size (wavelength/swash length) because the slope varied alongshore (cf. Figs. 4.1- 4.14).

Cusp self-organization theory holds that cusp spacing is related to swash length. Self-organization was tested by conducting regressions of these variables with the regression line was forced through the origin, as per Coco *et al.* (1999). Ideally, the regression slope should measure between 1 and 3, with a statistically significant R^2 value.

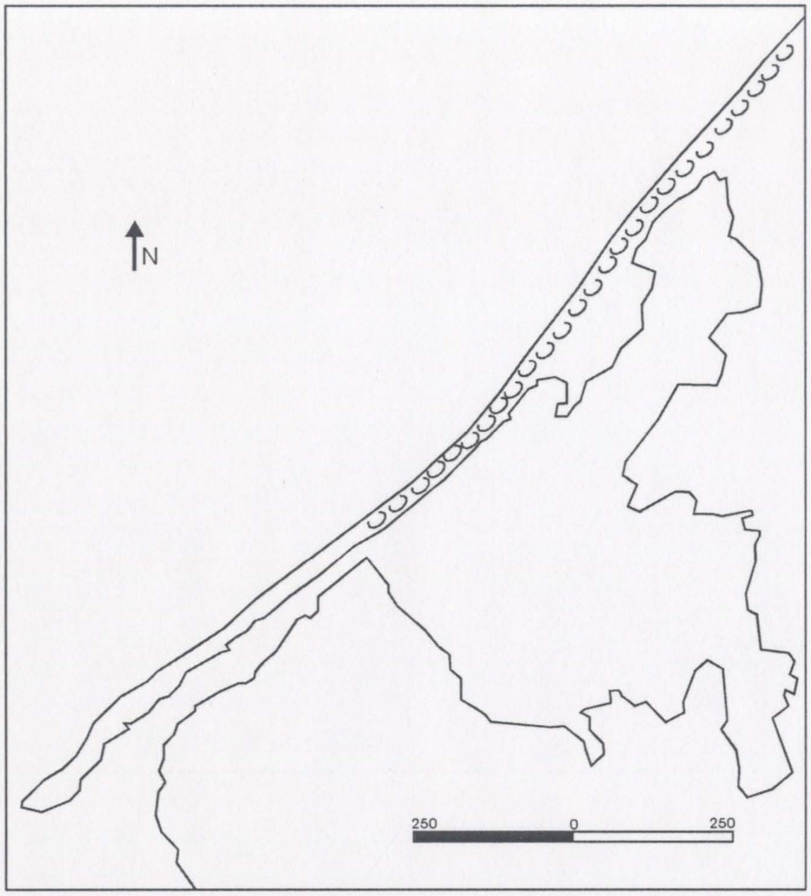


Figure 5.1. Schematic diagram of berm cusp occurrence at Long Pond.

5.2 Apron Cusps

5.2.1 Overview

Rhythmic apron cusps formed on the littoral apron. They exhibited a low preservation potential. Apron cusps were observed during three surveys (11/11/97, 15/12/97, and 23/02/98), during which 8 cusps were measured. Cusp wavelengths measured 4.6 to 15.2 m, swash lengths measured 3.3 to 9 m, and amplitudes measured 0.2 to 0.5 m. Cusp form and environmental parameters have been summarized in Table 5.1.

Table 5.1 Summary of apron cusps: a. 11/11/97, b. 15/12/97, c. 23/02/97.

Occurrence	a. South of Transect 2. b. Ubiquitous (apparently). c. Ubiquitous.
Wave Climate	a. Long crested shore-normal swells, 30 - 50 cm high, period 6 - 8 s; smaller short crested southwesterly waves interfered with swells north of Transect 2; plunging breakers; no standing waves. b. Long crested shore-normal swells, 40 - 60 cm high, period 8 - 10 s; superimposed local wind waves; surging breakers; standing waves. c. Short crested shore-normal waves, 30 - 50 cm high, period 6 - 8 s; plunging breakers; no standing waves.
Tide	a. Near ebb. b. Near ebb. c. Near ebb.
Winds	a. Light southwesterlies. b. Light west-northwesterlies. c. Moderate west-northwesterlies
Horns	a. Erosional: texture and slope similar to adjacent beach; skew: near normal to 5° Southeast, increased from south to north, function of horn size and orientation. b. Depositional: reverse graded; perched atop littoral apron; skewed towards stress point between Transects 2 and 13, skew magnitude appeared to increase with distance from stress point, function of horn orientation. c. Erosional: texture and slope similar to adjacent substrate; skewed towards stress point between Transects 2 and 13, skew magnitude increased with distance from stress point: near normal to over 15°; south of Transect 2: 15° Southeast; north of Transect 13: 5 - 10° Northeast; function of horn size and orientation.
Bays	a. Etched into substrate; texture similar to horn; nadir closer to southern horn. b. Slope similar to littoral apron; texture finer than cusp horns but occasional coarse deposit near centre, cusp floor wide and flat. c. Etched into substrate; texturally similar to adjacent substrate but sand-dominated between Transects 10 and 13, although often overlain with scattered coarser clasts; nadir positioned closer to horn in direction of skew.
Comments	a. Two cusps measured; oscillatory circulation, swash did not fill cusp bay. b. One cusp measured; standing wave due to interference between breakers and backwash; oscillatory circulation with weak horn-divergent component; swash to end of cusp, but not sufficient to rework or undermine the berm structure. c. Five cusps measured; oscillatory circulation, swash did not fill cusp bay.

The 15/12/97 survey was geared towards a qualitative inspection of Burnt Island, which did not require Emery Poles. The wavelength and swash length of one cusp were recorded and the amplitude and beach slope were estimated from Plate 5.1 a. Apron cusp formation south of Burnt Island was inferred by regular swash excursion and the manifestation of arcuate shore-parallel standing waves. At a distance, standing waves appeared as short, temporarily stationary, arcuate white lines. Cusp dimensions appeared to have been consistent alongshore. Cusps may have developed south of the inflection point, which was not visible from Burnt Island.

Apron cusps were usually skewed in the direction of the beach alignment. This was most noticeable when cusps developed along the entire barrier. Between Transects 2 and 13, cusps were skewed towards the stress point (Plate 5.1 a, b, c). North of Transect 13, the beach was aligned along a southwest to northeast axis and cusps exhibited slight northeasterly skews (Plate 5.1 d). South of Transect 2, the beach was aligned along a northwest to southeast axis and cusps exhibited a slight southeast skew.

5.2.2 Potential Formative Mechanisms

Derived subharmonic (Equation 1) and synchronous (Equation 2) wavelengths compared poorly with recorded wavelengths (Table 5.2). Apron cusp spacing was not significantly correlated to beach slope (Table 5.3). In the absence of direct hydrodynamic testing, edge waves cannot be conclusively discounted as a formative mechanism, but edge wave - induced cusp formation was not statistically supported by the data.

Plate 5.1 a. Apron cusps looking south from Burnt Island 15/12/97. Field assistant approximately 150 cm in height.

b. Apron cusps skewed north, 23/02/98, looking north from Transect 14.

c. Apron cusps skewed north, 23/02/98, looking north from Transect 6. Field assistant approximately 185 cm in height.

d. Apron cusps skewed south, 23/02/98, looking south from Transect 12. Field assistant approximately 185 cm in height.

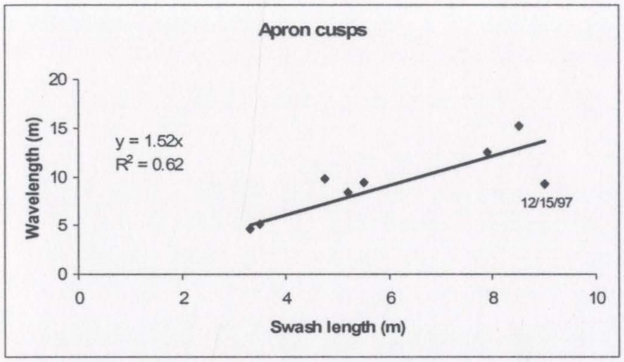
Apron cusps displayed strong support for self-organization (Fig. 5.2 a). The 15/12/97 cusp, which was morphologically distinct, was positioned further from the regression line than the other cusps. The removal of this cusp generated an extremely strong self-organizational relationship (Fig. 5.2 b) despite displaying self-organization signatures, including standing waves (observed) and horn-divergent flow (inferred).

Table 5.2: Assessment of edge waves as potential apron cusp stimulators based upon comparison of measured cusp wavelengths with derived synchronous (Equation 1) and subharmonic (Equation 2) cusp wavelengths.

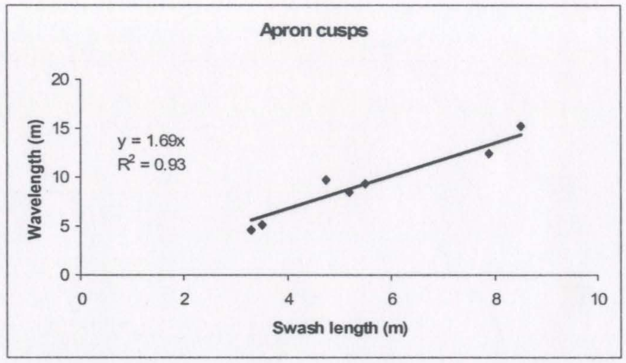
			Wavelength (m)		
Date	**Location**	**Period (s)**	**Measured**	**Subharmonic**	**Synchronous**
11/11/97	1	6 - 8	5.1	33.7 - 60.0	16.9 - 30.0
	adjacent		4.6	33.7 - 60.0	16.9 - 30.0
15/12/97	13	8 - 10	9.3	30.0 - 46.8	15.0 - 23.4
23/02/98	2	6 - 8	9.8	29.2 - 52.0	14.6 - 26.0
	4		12.5	28.1 - 50.0	14.1 - 25.0
	5		8.4	27.0 - 48.0	13.5 - 24.0
	7		9.4	20.2 - 36.0	10.1 - 18.0
	10		15.2	31.5 - 56.0	15.7 - 28.0

Table 5.3: Pearson Correlation Coefficients of cusp wavelength, wavelength/swash length, and swash length to beach slope (S: Significant Coefficient).

		Wavelength	Swash	Wavelength/Swash
All Cusps		0.12	-0.19	0.28
Apron		-0.19	-0.54 (S)	0.36 (S)
Berm	*Collective*	0.12	-0.18	0.27
	Simple Slope	0.14	0.14	0.15
	Complex Slope	0.17	-0.10	0.32 (S)
	Distinct Horns	0.03	0.09	-0.06
	Indistinct Horns	0.40 (S)	0.11	0.27
	21/03/97	0.22	0.10	0.16



a



b

Figure 5.2 a. Regression analysis, apron cusps.

b. Adapted regression analysis, apron cusps.

Swash length should be negatively correlated with beach slope since steeper beaches incur more percolation and gravitational resistance. Apron cusps exhibited a statistically significant negative correlation with the beach slope (Table 5.3). The statistically significant positive correlation between beach slope and wavelength/swash length may indicate that cusp evolution is influenced by other forcing mechanisms, in light of the lack of a statistically significant relationship between beach slope and wavelength.

5.3 Berm Cusps

5.3.1 Overview

Arrhythmic berm cusps formed north of the tidal channel (Fig. 5.1) on the berm face and were observed throughout the survey period, exhibiting good preservation potential. Forty-five berm cusps were selected and measured during eight surveys. Cusp wavelengths measured 8.5 to 23.2 m, swash lengths measured 1.0 to 15.0 m, and cusp depths measured 0.7 to 3.14 m. Berm cusp parameters are summarised in Table 5.4.

Berm cusp size could vary significantly by location (Fig. 5.3 a - d). Cusps were usually spatially grouped (Plate 5.2 a), although rhythmic cusps were observed during the crest survey on 18/11/99 (Plate 5.2 b). Cusp bay texture was often similar to the adjacent substrate except for the common occurrence of coarse deposits at the nadir.

Berm cusp circulation was observed on15/03/97, when the seastate was dominated by shore-normal, long crested, extra-local swells, 1.5 - 2 m in height, with an average period of 14 s. Cusp backwash interfered with incident waves, generating a convex standing wave at the bay mouth (Plate 5.2 c). The incident wave initially overwhelmed the backwash at the cusp horns which were junctures between adjacent standing waves. The swash advanced quickly over the horns as a jet (Plate 5.2 d), following the cusp wall to the rear of the cusp. The remainder of the swash overwhelmed the backwash more slowly and flooded the cusp bay, often intersecting at the swash excursion peak (Plate 5.2 e), at which point the combined flows began to move energetically seaward as backwash. Reverse graded cusp horns were commonly observed during the next site visit.

5.3.2 Potential Formative Mechanisms

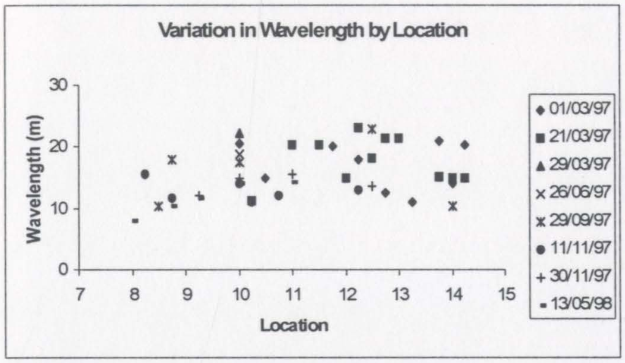
As cusp cell circulation was observed on only one occasion, subharmonic and synchronous wave periods were derived based on recorded wavelengths. There was no opportunity to measure the minimum incident wave period capable of reworking the berm, but given the wave periods associated with apron cusp formation, the value

Table 5.4: Summary of berm cusp parameters, Long Pond.

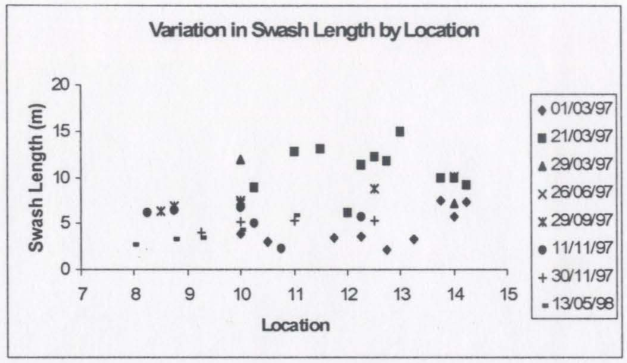
Spacing	Spatially grouped instead of rhythmic; groups of 5 - 8 cusps; cusp size within group decreased from north to south; no apparent seasonal pattern of occurrence; dimensions were variable at a given location
Elevation	Consistent alongshore, perched above littoral apron
Stacking	Rare, extended 1 or 2 wavelengths when occurred; lower cusps truncated upper cusps
Skew	Variable, but within 5° north or south of symmetrical; cusp skew function of horn size differential and/or orientation
Horn Morphology	18 cusps characterized by horns distinct in slope and texture from adjacent berm: cusps on 21/03/97 and 30/11/97 with reverse graded horns; 27 cusps characterized by horns that resembled slope and texture of adjacent berm; occasionally truncated, sometimes in association with beach ridges
Bay Morphology	Texture often similar to horn and berm, some bays texturally finer than horns, some coarser; often very coarse near nadir regardless of average texture; sand occasionally observed; no evidence of impermeable layer
Associated Structures	Triangular structure in cusp at Transect 10 persisted from 19/04/97 until after 20/09/97; elongated beach ridges occasionally manifested near cusp bay mouths, often fronting two or more cusps, usually developed outside the cusp bay mouth, and when they developed at the bay mouth

probably exceeded 10 s. Derived subharmonic wave periods were less than 10 s and 2 of 45 derived synchronous edge wave periods were between 10 and 11 s while the remainder were lower (Table 5.5). These cusps hosted swash lengths of 7.4 and 7.55 m and probably required longer wave periods given the erosional requirements.

Collectively, berm cusp spacing was not significantly correlated with the beach slope



a



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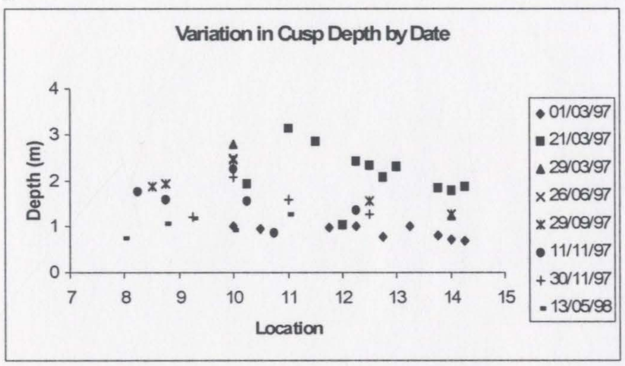

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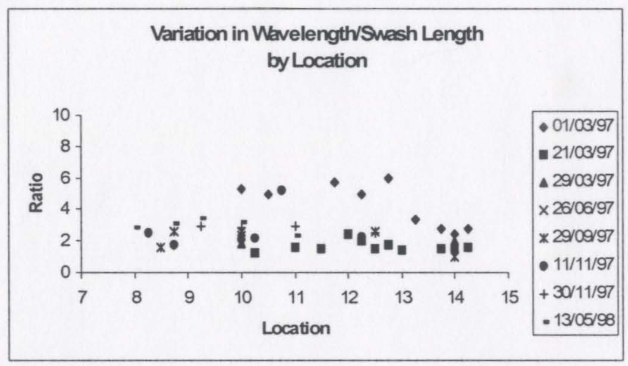


d

Figure 5.3 a. Variation in berm cusp wavelength by date and location.

b. Variation in berm cusp swash length by date and location.

c. Variation in berm cusp depth by date and location.

d. Variation in berm cusp spacing/swash length ratio by date and location.

(Table 5.3). When subdivided by slope type, neither simple nor composite slopes were significantly correlated with cusp spacing. When subdivided by horn texture, texturally distinct cusps did not generate a significant correlation to beach slope, but a statistically significant positive correlation occurred when the horns were similar in texture to the adjacent berm. This does not confirm edge wave occurrence, however due to the poor comparison between measured and derived spacing.


a


b


c


d


e


f


g

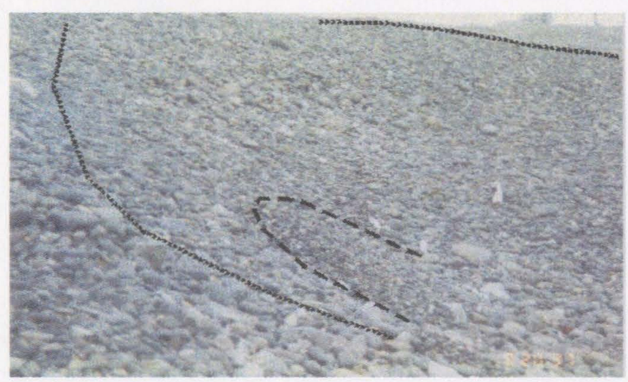

h

Plate 5.2 a. Arrhythmic berm cusps, north from Transect11 (bays snow-filled).

b. Rhythmic berm cusps south from Transect 12 (courtesy D. Forbes).

c. Arcuate standing waves generated by differential interference between backwash and incident breakers at horns and bays.

d. Incipient swash jet at horn.

e. Intersection of adjacent cusp cells at horn near swash excursion peak.

f. Limit of swash excursion near Burnt Island. Photo taken within 20 minutes of Plate 5.2 a.

g. Triangular structure on cusp wall, 19/04/97.

h. Same triangular structure on cusp wall, 20/09/97.

Subharmonic edge wave periods derived from the 21/03/97 cusps ranged from 3.2 - 6.35 s, while derived synchronous edge wave periods ranged from 4.53 to 8.98 s (Table 5.5). Cusp spacing derived from a 14 s period displayed poor agreement with recorded cusp wavelengths and was not significantly correlated with beach slope (Table 5.3).

If cusp spacing is related to beach slope, as postulated by edge wave theory, cusp dimensions should have been consistent at a given position, allowing for minor slope variations. Cusp dimensions were not consistent by location (Fig. 5.3 a). Swash lengths (Fig. 5.3 b) and cusp depths (Fig. 5.3 c) were also not consistent by location. This implies that the seastate was the primary determinant of cusp size. In the absence of direct hydrodynamic measurements, edge waves cannot be conclusively discounted as a formative mechanism, but edge wave - induced cusp formation did not seem to be statistically supported by the data. However, the positive correlation between cusp spacing and slope when horn texture resembled the antecedent substrate support the

Table 5.5: Summary assessment of edge wave mechanism based upon the range of derived subharmonic (2x incident wave period) and synchronous (= incident wave period) wave periods and number of wave periods measuring greater than 10 s per survey.

	Subharmonic		**Synchronous**	
Date	**Period (s)**	**Edge Wave Fit**	**Period (s)**	**Edge Wave Fit**
01/03/97	3.65 - 7.48	0/9	5.16 - 10.58	2/9
21/03/97	3.20 - 6.35	0/11	4.53 - 8.98	0/11
29/03/97	4.51 - 4.98	0/2	6.37 - 7.04	0/2
26/06/97	4.20	0/1	5.93	0/1
29/09/97	3.57 - 5.40	0/5	5.05 - 7.64	0/5
11/11/97	3.00 - 4.92	0/6	4.25 - 5.97	0/6
30/11/97	3.49 - 4.09	0/4	4.93 - 5.78	0/4
13/05/98	3.43 - 3.45	0/5	4.85 - 6.15	0/5

possibility of edge wave occurrence at some point of cusp formation at Long Pond.

Regression analysis of berm cusps generated negative R^2 values in five of the six tests when the regression line was forced through the origin (Fig. 5.4 a - f). The five negative results do not support self-organization. Regression analysis was then conducted without forcing the regression line through the origin. Comparison of the forced (a) and unforced (b) regression lines revealed that negative R^2 values were generated when points were positioned between the two regression lines. R^2 values are calculated by the equation

$$R^2 = 1 - SSE/SST \quad (3)$$

Table 5.6: Comparison of measured and derived cusp spacing, 21/03/97.

Location	**Wavelength (m)**		
	Measured	*Derived Subharmonic*	*Derived Synchronous*
10 (North)	11.2	214.2	107.1
11	20.2	195.9	97.9
11 (North)	20.4	189.7	94.9
12	15.0	177.5	88.7
12 (North)	23.1	177.5	88.7
12 - 13	18.2	153.0	76.5
13 (South)	21.3	153.0	76.5
13	21.4	128.5	64.3
13 (North)	15.1	73.4	36.7
14	15.0	73.4	36.7
14 (North)	15.0	73.4	36.7

where $SSE = \sum(\mathbf{Y}_j - \hat{\mathbf{Y}}_j)^2$ and $SST = (\sum\mathbf{Y}_j^2) - (\sum\mathbf{Y}_j^2/n)$.

Normally, the sum of squares is weighted equally on either side of a best fit regression line. When the regression line was forced through the origin, some data points were placed on the opposite side of the line from where they would normally be, which weighted one side of the regression at the expense of the other. This manifested an SSE/SST ratio greater than 1, which generated negative R^2 values. Self-organization testing works if the slope of the forced regression line is significantly different from the natural regression line. The 21/03/97 dataset statistically supported self-organization.

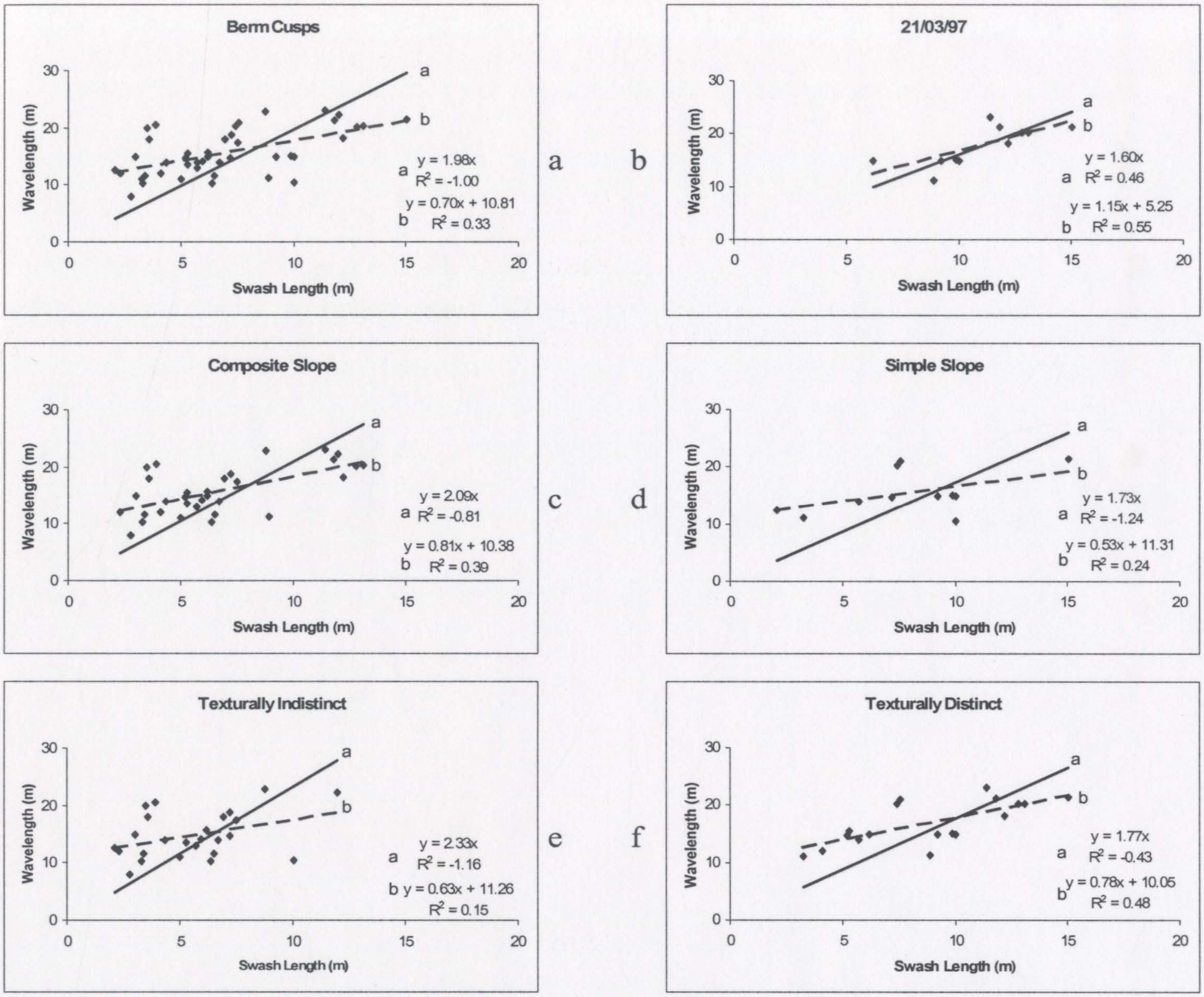


Figure 5.4 a. Regression analysis, berm cusp spacing and swash length, full data set (a: regression forced through origin, b: regression not forced).

b. Regression, berm cusp spacing and swash length, 21/03/97.

c. Regression, berm cusp spacing and swash length, composite slopes.

d. Regression, berm cusp spacing and swash length, simple slopes.

e. Regression, berm cusp spacing and swash length, indistinct horns.

f. Regression, berm cusp spacing and swash length, distinct horns.

Berm cusp swash length was not significantly correlated to beach slope (Table 5.3), in contrast to the strong negative correlation that would be expected. Berm cusp swash lengths varied alongshore per survey, and by position over time (Fig. 5.3 b). The poor statistical correlation may indicate that swash excursion was influenced by mechanisms other than the incident wave parameters that may have masked not only a self-organization signature, but possibly an edge wave signature as well. This may also be supported by the statistically insignificant correlation of beach slope to the wavelength/swash length ratio (Table 5.3) and the variability of the wavelength/swash length ratio observed during the survey period (Fig. 5.3 d).

6.0 Tracer, Core, Geological Inheritance and Seasonal Ice Results

6.1 Tracer Experiment

Tracer results are summarized in Figure 6.1 and Table 6.1. Tracer movement between 11/05/97 and 08/09/97 is depicted in Plate 6.1 (a - d). Transect 3 tracers were quickly transported southeast to an intertidal swale in the spit complex and remained inert. Transect 6 tracers were inert until 26/06/97 when there was a net southeast shift towards the thalweg. Upon moving, tracers were quickly entrained by the channel due to the proximity of the low water line to the thalweg and all but two subsequently disappeared. Transect 8 tracers were inert until 09/08/97 when they were transported northeast towards the thalweg. The distance from the low water line to the thalweg was greater than at Transect 6, which may have accounted for the longevity of the tracers as a unit. Transect 9 tracers were inert until 20/09/97. The net transport direction was northeast towards the thalweg, but there was also a southern component as the clasts began to scatter.

6.2 Core Samples

Core 1 was 2.1 m in length (Fig. 6.2) and consisted primarily of texturally homogeneous structureless brown silts (Plate 6.2 a), with a thin layer of grey sand 20 cm from the bottom. Core 2 was 3.1 m in length (Fig. 6.2) and consisted of texturally homogeneous structureless brown silts (Plate 6.2 b). There was little to no vertical gradation evident, suggesting sediment mixing. This precluded the dating of insect carapaces and twigs.

Four cores (three 2 m in length, one 1 m in length) were extracted from the channel and

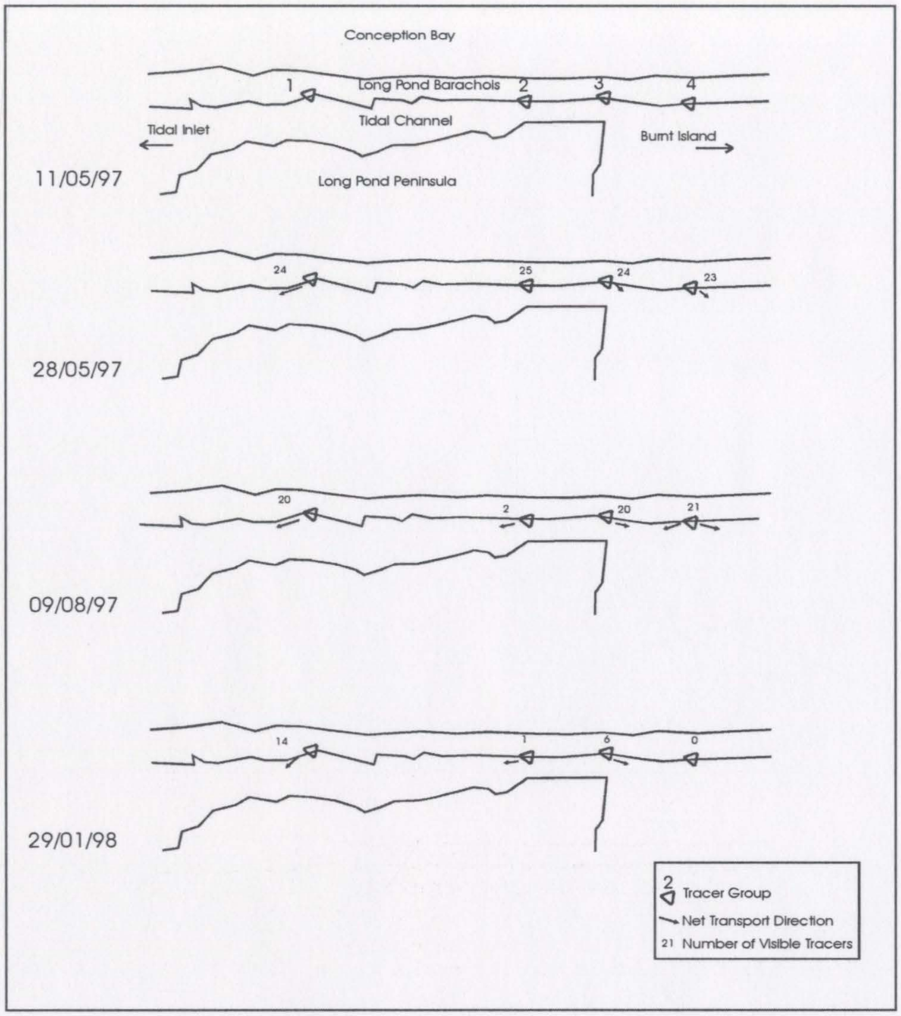


Figure 6.1. Tracer movement in the tidal channel, 11/05/97 - 29/01/98.

southern basin prior to dredging in 1989 (Public Works of Canada, 1989). The cores consisted of grey sands with some pebbles and cobbles that terminated in glaciofluvial deposits. There had apparently been little sedimentation in the thalweg. Cores extracted adjacent to the government wharf (Public Works of Canada, 1988) ranged from 1 to 7 m in length, although 2 to 4 m cores were most common. The longest cores were extracted from undredged basin reaches while shorter cores were obtained from the dredged sites.

a i

a ii

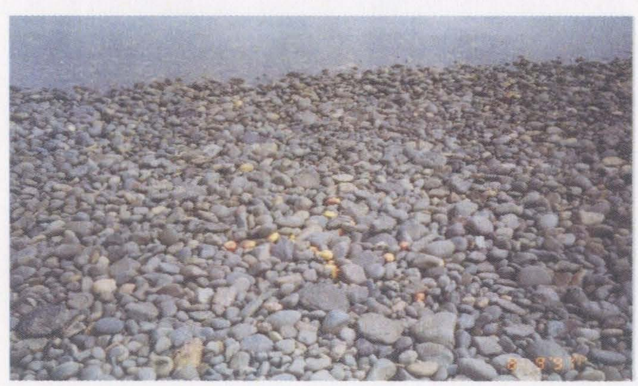
b i

b ii

c i

c ii

d i



d ii

Plate 6.1 a. Tracer group 1, Transect 3 (i 11/05/97, ii 09/08/97).

b. Tracer group 2, Transect 6 (i 11/05/97, ii 09/08/97).

c. Tracer group 3, Transect 8 (i 11/05/97, ii 09/08/97).

d. Tracer group 4, Transect 9 (i 11/05/97, ii 09/08/97).

Table 6.1: Summary of tracer experiment. *Remaining*: number of clasts recorded, *Direction*: predominant direction of transport, *: little movement.

	Transect 3		**Transect 6**		**Transect 8**		**Transect 9**	
Date	*Remaining*	*Direction*	*Remaining*	*Direction*	*Remaining*	*Direction*	*Remaining*	*Direction*
28/05/97	24	SE	25	N/A	24	NE	23	NE*
09/06/97	24	SE*	25	SE*	24	NE*	23	SW*
26/06/97	24	SE*	24	N/A	22	NE*	21	SW
09/08/97	20	SE	2	SE	20	NE*	21	N&S (E)
20/09/97	22	SE*	0	N/A	20	NE*	16	N&S (E)
11/11/97	19	SE*	2	SE	14	NE	14	N & S
29/01/98	14	SE	1	SE	6	NE	0	N/A
23/02/98	13	SE	0	N/A	6	NE*	0	N/A
13/05/98	10	SE	1	SE	2	NE	5	NE
14/07/98	13	SE	0	N/A	0	N/A	2	NE

The cores terminated in bedrock at depths of 8.1 to 9.5 m. A typical core consisted of organic silty sands with woody macrofossils in the upper segment, grading into glaciofluvial deposits and terminating in weathered shales. Sand and gravel dominated the cores that were obtained adjacent to the government wharf.

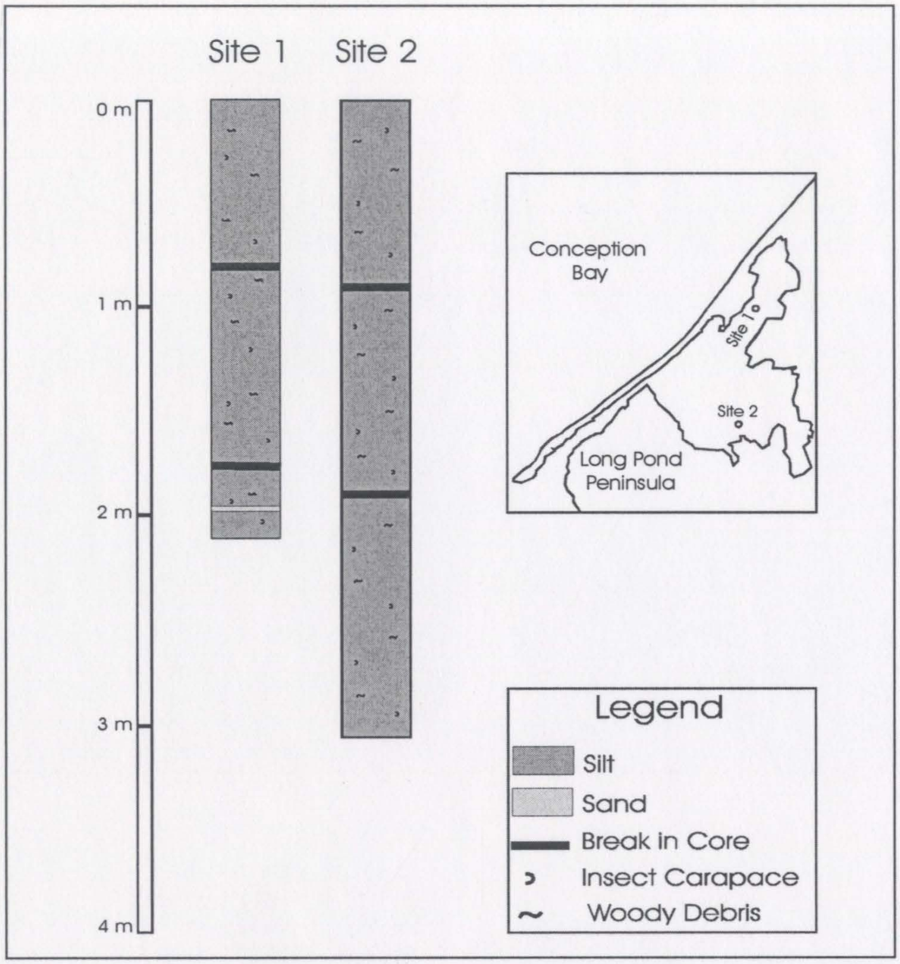


Figure 6.2. Core samples obtained from northern basin, Long Pond.

6.3 Geological Inheritance

6.3.1 Bluffs

The bluffs between Long Pond and Manuels (Plates 1.3 a, 6.2 c) were not systematically monitored but periodic site inspections, air photo interpretation and photogrammetry (courtesy of Dr. Donald Forbes, G.S.C.) were conducted. The unvegetated bluff face was steep (60° - 70°) and consisted of silt and sand, with minor fractions of angular to subangular pebbles, cobbles, and boulders which did not exhibit a predominant shape.

a

b

c

d

e

f

Plate 6.2 a. Core sample, Site1.

b. Core sample, Site 2.

c. Bluffs directly north of Long Pond (Field assistant 1.85 m in height).

d. Channel erosion from overland runoff.

e. Seawall, north of Cherry Lane.

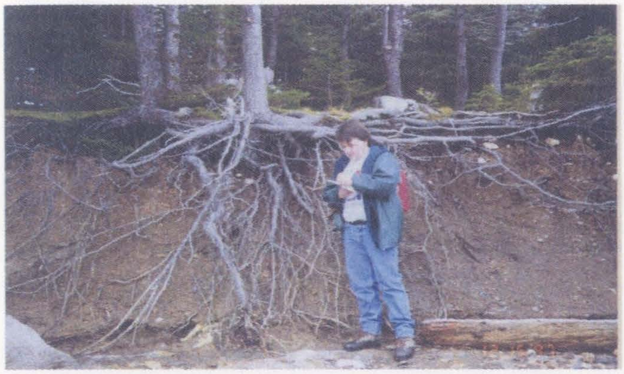
f. Flanking scour, north of seawall (Field assistant 1.65 m in height).

The bluffs consisted of two units (northern unit up to 15 m, southern unit up to 5 m) separated by a 60 m interbuff area. Glaciofluvial sediment extended south to barachois and was initially exposed by a cusp bay (Plates 1.3 c, d). The exposure hosted preserved grasses and unidentified herbaceous vegetation, but tripled in size, was permanently exposed and hosted a dense grass cover by the end of the study period.

Bluff erosion has averaged 0.2 - 0.3 m/yr (Fig. 1.7) and manifested sod overhangs up to 0.5 m wide (Plate 6.2 c, d) with tension cracks. There were no large debris flows or slides during the study period. Fallen sods, and small alluvial and talus fans accumulated over beach gravels during quiescent periods, but were removed during high energy wave events. Bluff face rivulets were common (Plate 6.2 d) but not ubiquitous.

Adjacent gravel beaches were flat and sediment-poor but the interbluff area hosted a well-developed beach segment. Silts and sands were rarely incorporated into the beach matrix. Large boulders eroded from the bluffs were not transported, remaining approximately *in situ*. Boulders occurred more than 20 m offshore elsewhere in CBS.

Property erosion north of Cherry Lane prompted seawall construction, consisting of boulders reinforced with railway ties (Plate 6.2 e). The construction date was unclear but probably dates from late 1988 or 1989 when the railway was decommissioned. The seawall maintained the property line while the adjacent bluffs eroded. The wall oversteepened and boulders were dumped on the beach to protect the protective structure. A 10 m long flanking scour zone extended at a 45° angle from the northern end of the seawall (Plate 6.2 f). Boulders were dumped as a protective response.


a


b


c


d


e


f

Plate 6.3 a. Scarping, eastern Burnt Island. Note exposed tree roots and abrasion zone at the base. Researcher is 1.62 m in height.

b. Scarping, eastern Burnt Island. Note exposed tree roots, abrasion zone at the base and subangular clast deposit below tree roots, adjacent to log.

c. Well-rounded clast interspersed among angular clasts on platform.

d. Well-rounded clast interspersed amongst vegetation.

e. Shoreline armouring and access road, Burnt Island and adjacent beach.

f. Elevated water level, southern Burnt Island. This is the only instance where flooding was observed.

The bluff-adjacent beach maintained shape and volume but the seawall-adjacent beach narrowed and lost sediment, rendering the wall impassible during high tides. The wall was rebuilt in 2001 and was extended to cover the edge of the flanking scour zone.

6.3.2 Burnt Island

Aside from Transect 13, Burnt Island was not systematically monitored but periodic site inspections and air photo analysis were conducted. The island consisted of glaciofluvial sediments, up to 5 m asl. The seaward margin was approximately 2.5 m above high water (Fig 4.13). During high tides and storm surges however, the water line could be 1.5 m below the tree line (Plate 6.3 f). Stumps protruding through beach gravel (Plate 1.2 a) indicated that the barrier was rolling over onto the island.

Prior to boulder armouring, the eastern shore of Burnt Island was dominated by vertical scarps 0.2 - 2 m high (Plate 6.3 a, b). Exposed tree roots were common and several trees had fallen. The lowermost 15 - 30 cm were abraded. A gravelly shore platform, up to 25 m in width bounded the lagoon shoreline. The platform was sediment-poor and lacked sedimentary structures except where gravels were pushed to the base of the scarp at discrete intervals (Plate 6.3 b). Platform gravels were unsorted subangular pebbles and cobbles, but isolated well-rounded clasts were interspersed (Plate 6.3 c). Well-rounded clasts also occurred amongst the vegetation on the eastern island fringe (Plate 6.3 d). Backbarrier and island morphology was masked when the island and the sub-basin barrier shoreline were armoured (Plate 6.3 e).

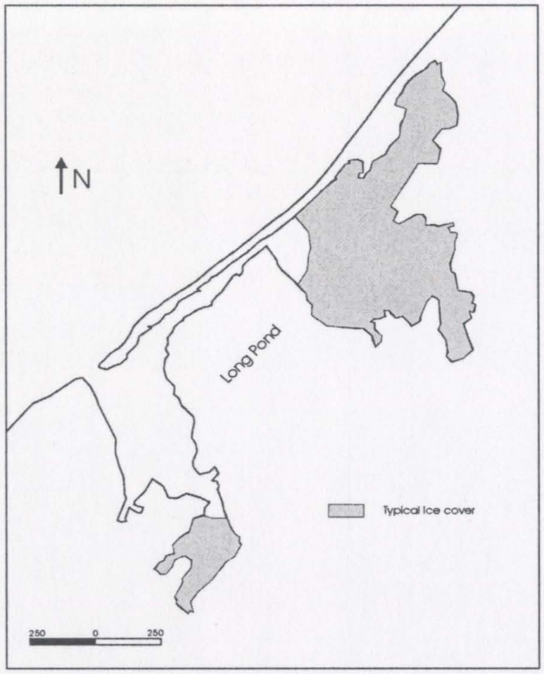


Figure 6.3. Typical winter ice cover at Long Pond, December - mid March.

6.4 Impact of Seasonal Ice

Light sea ice cover occurred in1997 and 1998, precluding the opportunity to observe the impact of sea ice. There were no apparent ice-lift or -push structures on the barrier. The northern basin froze during the winter (Fig. 6.3, Plate 6.4 a). Pressure ridging was observed (Plate 6.4 c) and Transect 15 could not be surveyed after ice removed the benchmark. The tidal channel and most of the southern basin did not freeze (Plate 6.4 b).

An icefoot formed on littoral apron in 1997 (Plate 6.4 d) but did not occur in 1998. A thin icefoot (Plate 6.4 a) formed along the entire backbarrier during both seasons. Interstitial ice developed south of the inflection point, acting as a matrix that manifested vertical scarps (Plates 6.4 e, f).

Plate 6.4 a. Icefoot development on the lagoonal apron (1997). Note the extent of ice cover in the northern basin at the top of the photo.

b. Lack of ice cover, southern basin (1997).

c. Pressure ridging in the northern basin (1997).

d. Icefoot development on the littoral apron(1997).

e. Interstitial ice and associated scarping (1997). Note the icefoot.

f. Interstitial ice and associated scarping (1998). Note the lack of icefoot.

7.0 Barrier Morphology

7.1 Barrier Inception

Sea level in Conception Bay was 10 - 25 m below present circa 6,000 BP during the postglacial lowstand (Shaw & Forbes, 1995). Submerged shoreline features had not been discovered in southeastern Conception Bay (Catto *et al.*, 2003) and hindcasting former shoreline positions was problematic.

The largest stream in the Long Pond watershed, Conways Brook, debouched into the southern basin. The basin substrate was 9 to 10 m below water (Public Works of Canada, 1988). The southern basin was narrow in relation to its length which, along with the basin depth, suggested that stream discharge may have been relatively consistent, allowing for seasonal and longer term climatic variations. The northern basin was wide in relation to its depth. Core samples extracted at depths of 1 - 1.5 m in the northern basin were 2 - 3 m in length, and the basin substrate was 4.5 - 5 m below water. The basin width and shallow depth suggested variable stream discharge, probably characterized by repeated stream avulsions. These streams probably discharged into Conception Bay through what is now the Burnt Island sub-basin. At some point, the streams avulsed to a more direct seaward route (Fig. 7.1). Burnt Island was therefore a remnant of the original topography.

The Long Pond Peninsula was recessed from the adjacent mainland despite having been protected by the barrier. Plate 1.6 a depicted Burnt Island as having been recessed from the barrier as well. These shoreline positions suggest that Long Pond originated as a cove bounded by Manuels and Foxtrap. Barrier inception may have occurred between the

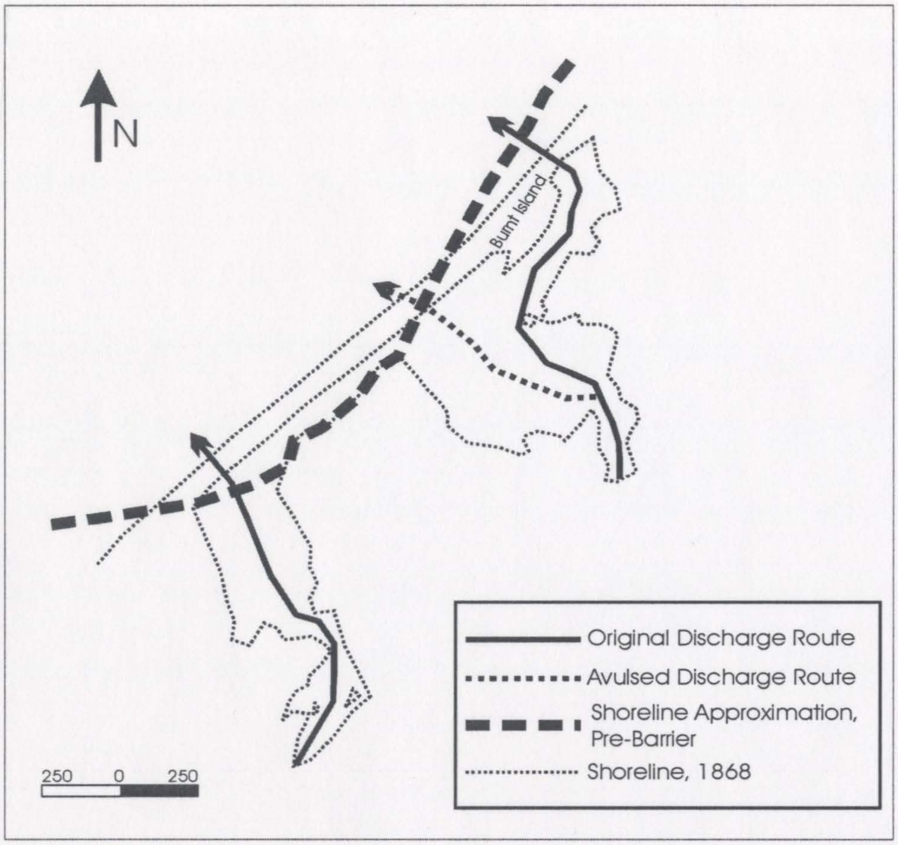


Figure 7.1. Discharge from what is now the northern basin was originally directed north of Burnt Island. The stream avulsed at some point, taking a more direct approach south of the island and separating the island from the mainland. Stream avulsion eroded a broad valley. Discharge from the southern basin was more consistent, eroding a long narrow valley.

headlands, transgressing to the modern position in response to RSLR. Most of the Long Pond basin was subaerial at barrier inception, and was gradually inundated as sea level rose. Accretion and water levels in lagoons can be controlled by barrier dynamics rather than RSL forcing (Jennings *et al.*, 1997). In the absence of reliable dates, inundation timing was uncertain because the barrier probably elevated the basin water level.

RSLR after the postglacial lowstand triggered coastal erosion, introducing a mobile littoral sediment supply. The Foxtrap and Manuels headlands acted as a re-entrant trap and facilitated drift-aligned shoal accumulation, similar to the barrier inception process described by Orford *et al.* (1996). The shoals coalesced into islands and consolidated into a barrier which built vertically as the sediment supply decreased and the barrier moved from drift to mixed drift and swash alignment. Sediment was never abundant and the barrier probably evolved as a single-ridged structure. The barrier transgressed by periodic overstepping in response to RSLR, forming fringing barriers when it encountered bluffs and baymouth barriers at inundated basins at Long Pond and Foxtrap. The pattern was disrupted in the 1880's when updrift shoreline armouring depleting the sediment supply.

7.2 Barrier Context

Single ridged gravel barriers are diagnostic of a low sediment supply (Johnston & Orford, 1984). This form seems to have typified the Long Pond barrier since at least 1868 (Orlebar & Kerr, 1868) and there were no apparent drowned ridges in the nearshore or lagoon (Canadian Hydrographic Service, 1987) that suggested that any other barrier form occurred. The scarcity of sand (Table 4.2) also suggested a continuously low sediment supply. Sediment depletion may trigger a curved planform as the barrier moves into equilibrium with the new flux regime (Carter *et al.*, 1987b). The barrier stretches due to differential rollover rates that increase with distance from a headland. Sediment depletion can also manifest a composite beach profile (Orford *et al.*, 1988) and increase cross-shore drainage requirements (Carter *et al.*, 1989).

Gravel barriers often exhibit long periods of slow evolution punctuated by periods of rapid reorganization (Forbes *et al.*, 1995). A barrier adjustment, which included stretching and the formation of a tidal inlet, probably occurred between 1910 (Public Works of Canada reprint, 1910) and 1941 (Plate 1.4). There was no apparent increase in storm frequency during this period (B. Whiffen, *pers. comm.* 2002) that might have triggered this response. Terrestrial water flux did not change quickly or substantially. Inlet formation suggested that barrier volume decreased dramatically.

Gravel beaches can transgress by overstepping (Forbes *et al.*, 1991), flood tidal delta construction (Orford *et al.*, 1991b), rollover onto a terrestrial substrate (McKay & Terich, 1992), or backbarrier infilling (Shaw *et al.*, 1993). Rapid transgression may occur when barrier volume is reduced and/or crest elevation is low (Forbes *et al.*, 1991) and may occur without major changes in barrier form (Forbes & Taylor, 1987). Overstepping occurs when barrier overwashing deposits gravel fans on the backbarrier which act as basements that extend a short distance into the backbarrier. Sediment is transferred inland with little to no return sediment transfer seaward. Flood tidal deltas, which are associated with tidal inlet processes, may also act as basements as may terrestrially-derived backbarrier sedimentation. While photogrammetric analysis was not feasible on much of Long Pond (D. Forbes, *pers. comm.* 2000), the barrier seemed positionally stable between 1941 and 1976 except for localized changes near the inlet and Burnt Island (Plate 1.5).

A hypothetical straight line extended from the southwestern inlet corner through the inflection point to the stress point in 1941 (Fig. 7.2). Burnt Island was aligned parallel to the Long Pond to Manuels shoreline. Plate 1.6 a depicted the barrier as spatially removed from Burnt Island but connected by a tombolo. This suggested that the parallel alignment occurred when the erosional front pushed the barrier and adjacent bluffs back to the island's position. Burnt Island exerted a significant control over barrier morphology and stability. During the early 20th century barrier adjustment, rollover onto the elevated, forested island occurred more slowly than overstepping on the lagoon-backed barrier. Differential rollover rates can induce barrier stretching, manifesting an arcuate planform (Carter *et al.*, 1987b). The stress point was located less than 100 m south of the island. The slower rate of rollover helped stall transgression, and in doing so, slowed the rate of beach narrowing and bluff erosion north of Long Pond. Burnt Island was therefore an important stabilizing anchor for Long Pond Barachois, and was critical in establishing an extended period of positional stability along the entire barrier. The rate of transgression was slower than the erosional front, which cyclically rendered the sub-basin barrier prone to large adjustments, such as occurred in 1976.

In the absence of significant fluvial inputs, the availability of source materials in gravel-dominated coastal systems is limited to an erosional front within a narrow band of the shoreline (Forbes *et al.*, 1995; Orford *et al.*, 1991b). Most Long Pond gravel was initially derived from longshore currents and the modern littoral apron was drift-aligned, although swash and current reversal transport were evident. Railbed armouring south of Foxtrap probably depleted sediment flux, triggering barrier retreat as the barrier cannibalized itself to accommodate the alongshore transport requirement, as per Carter *et al.* (1989). Updrift

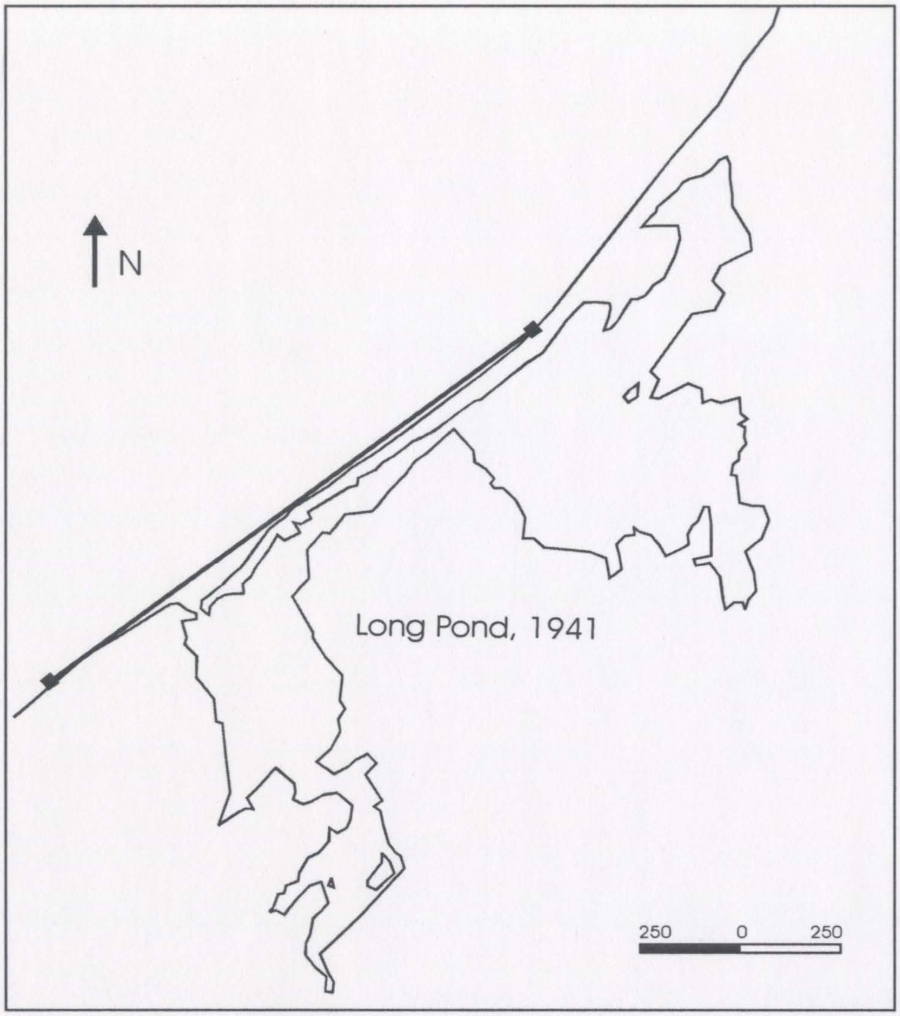


Figure 7.2. Hypothetical straight line between southern shoreline, inflection point, and stress point.

armouring did not modify littoral cell dimensions. South of Kelligrews, the shoreline lithology was dominated by Holyrood granites while siliceous siltstones were dominant from Kelligrews to Topsail (Paone, 2003). The change in lithology suggested a littoral cell border. Holyrood granites occurred at Long Pond, suggesting that the littoral cells were not closed, although the pattern of glacial flow may have incorporated some granites into the outwash deposits (Catto, 1998), essentially bypassing the littoral system.

The littoral cell may have extended to Topsail, given the consistency of the lithology. Shoreline orientation changed obliquely at Manuels Head which, given the comparatively slow rate of erosion (Fig. 1.7), appears to have been an emerging headland. It seems likely that Long Pond was either influenced by a discrete littoral cell that extended to Manuels Head, or that this unit was a subcell of a larger Long Pond to Topsail cell.

Dredging and breakwater construction, beginning in the 1950's, effectively modified the littoral cell by isolating either side of the inlet. A sediment catchment developed adjacent to Segment 1 during current reversals (Section 8.2), which may have served as a sediment source during longshore drift conditions. Finer gravels were preferentially transported due to fetch limitations induced by the breakwaters and coarse textured gravels observed at Transects 1 and 2 (Table 4.2) were probably lag deposits.

Small storms facilitate overtopping rather than overwashing, which stimulates vertical crest construction (Orford *et al.*, 1991a; Orford & Carter, 1995). A higher crest is more resistant to overwash and breaching until the berm oversteepens and becomes vulnerable to sudden reorganization. Barrier narrowing associated with progressing erosional fronts can enhance vulnerability. A large storm can short-circuit vulnerability cycles but the storm intensity required to trigger a barrier response decreases as vulnerability increases.

The berm was not overtopped or overwashed during the study period, but was modified by access road construction and breach site reinforcement (Sections 8.6, 10.5). The berm was swash-aligned, constructed by large extra-local incident waves. The open work gravel enhanced percolation and swash was more energetic than backwash in the absence of cusps. This asymmetry promoted deposition, vertically building the berm and reducing barrier vulnerability to overtopping and overwashing. The berm therefore reflected the maximum significant wave height along most of the barrier. There was no evident barrier narrowing (Figs. 4.1 - 4.14), although crestal narrowing was evident directly north of the lagoon (Plates 1.3 c, d). Frequent and/or intense storms can trigger erosion and transgression (Forbes *et al.*, 1991). Long Pond Barachois was stable because storms were not sufficiently frequent and/or intense to generate a response. The quiescent period dates from 1976 when the barrier was breached (Fig. 1.2) and overwashed north of the tidal channel. The barrier was breached in 1992 but the absence of overwash fans suggests that breaching was due to local processes rather than a storm-induced adjustment.

Fetch limitations precluded local waves from reworking the berm. The limited size and wavelength facilitated onshore wave breaking, which reduced bottom-induced refraction and facilitated oblique approach angles which diffused wave energy.

7.3 Process Controls

First order processes included sediment supply, sea level change, terrestrial basement geometry, and wave climate (Orford *et al.*, 1996) which provided the context in which smaller scale processes operated (Table 7.1). RSLR controlled the elevation upon which other processes operated over the long term. Over shorter intervals, RSLR may control the rate of barrier breakdown. Rapid RSLR drives erosional fronts which control the rate transgression, generating cycles of sediment over- and undersupply (Carter *et al.*, 1989).

Table 7.1: Process controls, Long Pond.

First Order Processes	Relative Sea Level Rise
	Climate
	Wave Climate
	Geological Inheritance
	Sediment Supply
Second Order Processes	Storm Frequency and Intensity
	Sea Ice and Icefoot
	Extra-Local Storm Waves and Swells
	Tidal Range
Third Order Processes	Barrier Breaching and Tidal Inlet Migration
	Barrier Planform
	Backbarrier Tidal Currents
	Anthropogenic Activity
	Geologic Inheritance (local)
	Sluicing Overwash
	Sediment Sink and Localized Impacts
	Berm Cusps
	Lagoon Ice
	Interstitial Ice

The climate controlled the storm frequency, which also could influence the transgression rate (Forbes *et al.*, 1991). The sediment supply was of critical importance, controlling barrier formation, texture and cross-shore morphology. Long Pond Barachois was fed by poorly sorted glaciofluvial bluffs which included a broad range of gravel size and shapes

(Section 13. 1). Geological inheritance at Long Pond referred to the inherited surficial geology, particularly the inundated river valleys and the nature of the adjacent shoreline.

Second order processes, such as tidal range, storm frequency and intensity, and sea ice processes, influenced the entire barrier. Storm frequency and intensity controlled barrier reworking and ultimately, barrier position at short (10 - 100 yrs) time scales in association with RSLR and the inherited geology (Orford & Carter, 1995). Ice could protect the barrier by physically dampening incident waves or by locking gravel in place (Forbes & Taylor, 1994). Ice could also act as an erosive agent, scouring the barrier in conjunction with wind and/or tidal activity (Barnes *et al.*, 1994).

Third order processes were localized to specific barrier segments and generated alongshore variations in barrier morphology. Third order processes included barrier breaching and tidal inlet behaviour, the barrier planform, backbarrier tidal currents, anthropogenic activity (on a variety of levels), localized impacts of geological inheritance, sluicing overwash, sediment sink formation (with attendant impacts on sediment transport patterns), berm cusp formation, lagoon ice, interstitial ice, and anthropogenic activity.

7.4 Profile Classification

Rapid changes in alongshore slope and morphology are usually generated by textural gradation or variations in wave exposure. The alongshore morphological variation exhibited by Long Pond Barachois was remarkable in that it occurred within a relatively short alongshore distance (< 2 km) without significant changes in sediment shape, texture

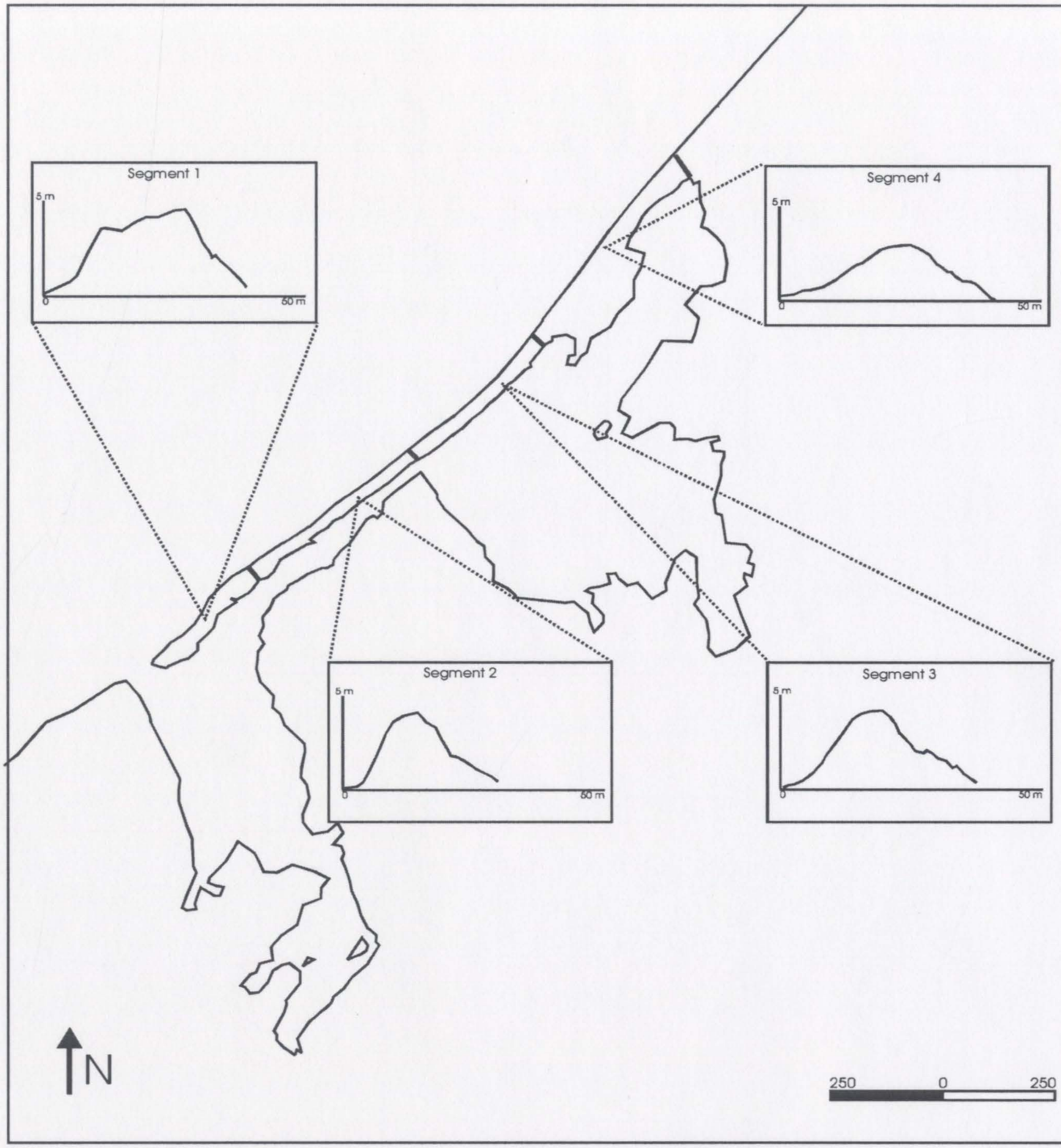


Figure 7.3. Beach segments at Long Pond, based on process and profile variations.

or mineralogical composition and without significant changes in wave exposure. Long Pond Barachois can be classed into four distinct segments (Fig. 7.3), defined by the site-specific interaction of coastal processes and their resultant morphology.

7.4.1 Segment 1

Segment 1 was located between the tidal inlet and the inflection point (Fig. 7.3), incorporating Transects 1 and 2. Segment 1 reflected the tidal inlet migration path (Section 10.2), which generated the abrupt change in planform configuration south of the inflection point. The segment was over 35 m in width, circa 4 m asl and hosted a massive berm with a wide, flat crest and steep bermface and backberm slopes (Figs. 4.1, 4.2). The breakwaters and tidal inlet deflected longshore currents offshore. Segment 1 was therefore the most strongly swash-aligned barachois segment.

The crest prograded and built vertically after 1974, which steepened backbarrier and berm slopes. Breakwater construction transformed Segment 1 into a sediment sink. Segment 1 had previously been low, narrow and easily overwashed (Plate 7.1, 1.6 d). Swash processes induced onshore transport of trapped gravel, triggering progradation. Interstitial ice induced vertical berm scarping during winter (Plates 6.4 e, f, Section 12.3). Smooth hawksbeard (*Crepis capillarus*) colonization (Plate 1.2 f) and the tern (*Sterna hirundo*) nesting colony each suggest prolonged barrier stability although the isolation from the mainland probably influenced nesting behaviour (Bull & Farrand, 1994).

7.4.2 Segment 2

Segment 2 was adjacent to the tidal channel, extending 550 m north of the inflection

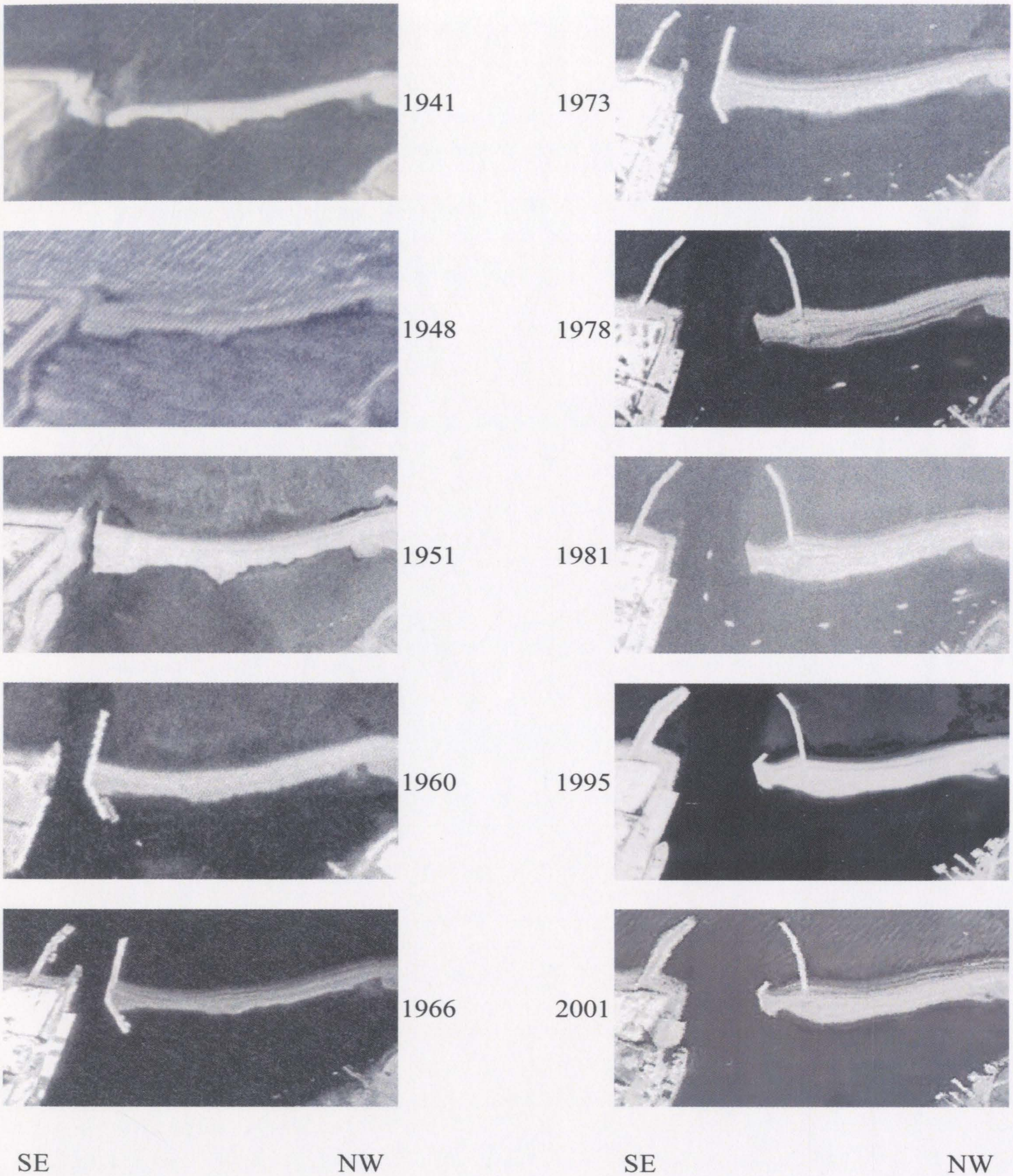

1941
1948
1951
1960
1966
1973
1978
1981
1995
2001
SE
NW
SE
NW

Plate 7.1. Time sequence of aerial photographs, Segment 1, 1941 - 2001 (Scale approximately 1:7000). Note: (i) inlet stabilization, 1948 and reconfiguration in 1960, 1966, 1978, and 1995; (ii) rapid progradation associated with inlet stabilization, 1948, 1960 and 1978; (iii) vertical crest building, 1978; (iv) overwash fan 1948 - 1951; fan eroded and backbarrier smoothed, 1960; (v) narrowing due to backbarrier erosion, 1960 - 1966; (vi) inlet widening 1960 and 1978; (vii) port development, 1960 - 2001; (viii) relative stability 1978 - 2001.

Table 7.2: Summary, Segment 1.

Extent	Transects 1 and 2
Diagnostic Features	Wide flat crest Steep berm Steep littoral apron Vertical "step" on berm crest
Relevant Processes (Third Order)	Anthropogenic Activity Tidal inlet migration Interstitial ice

point (Fig. 7.3) and incorporating Transects 3 through 8 (Figs. 4.3 - 4.8). This was the narrowest barrier segment, with an average width of less than 30 m. The elevation was generally less than 3.5 m asl, but Transect 6 was artificially raised to over 4 m asl. Swash ridges were the dominant morphological features on the berm face and littoral apron.

Segment 2 experienced in-place narrowing due to tidal current-induced backbarrier scouring, Segment 1 progradation and RSLR. Narrowing rendered it vulnerable to breaches, which were repaired with an unsorted melange of silts to small boulders dredged from the channel (Plate 7.3 a). The fill has proven erosion-prone. Excess dredge spoil (cf. Plate 1.2 e, 6.4 b) was dumped behind the inflection point on the lagoonal apron

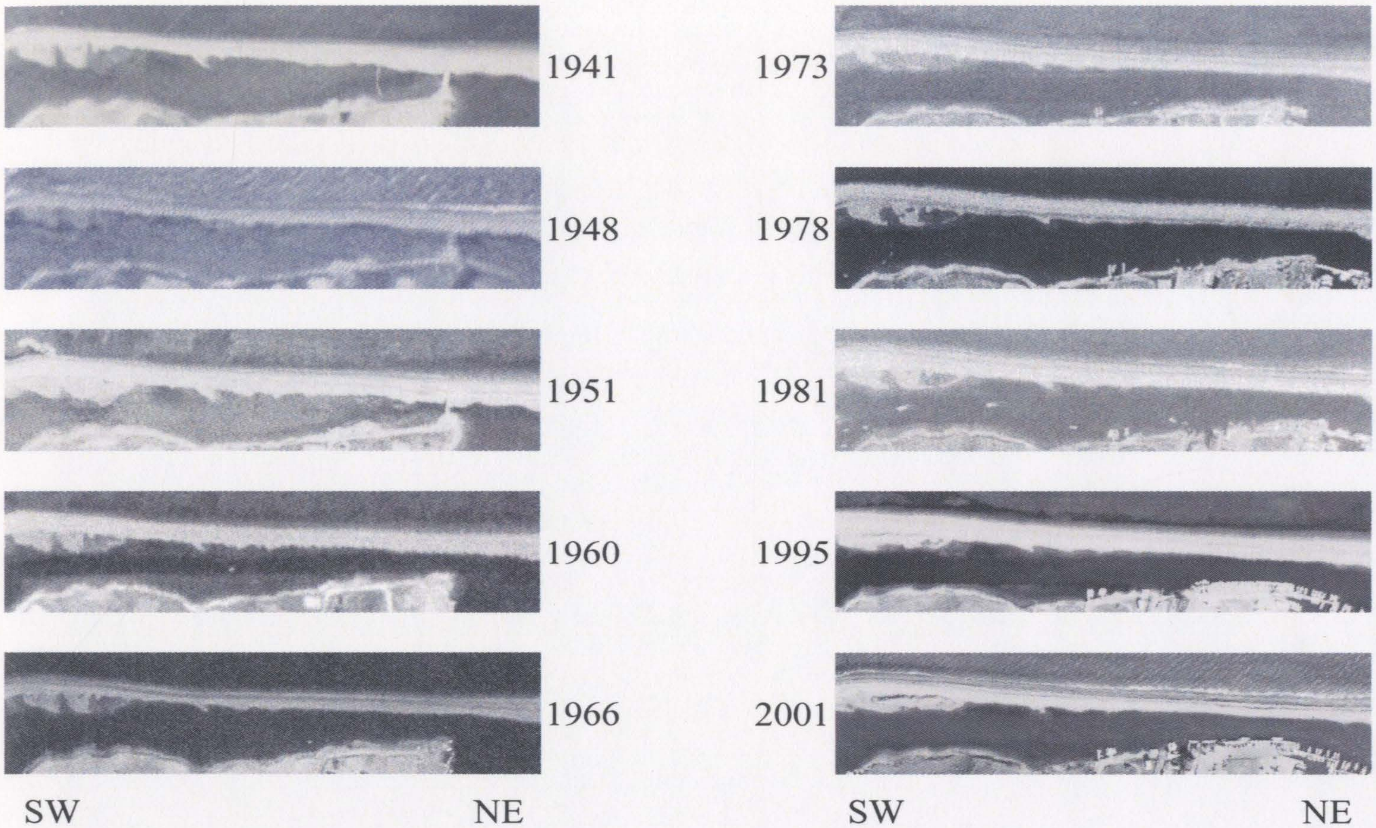


Plate 7.2. Time sequence of aerial photographs, Segment 2, 1941 - 2001 (Scale approximately 1:10,000). Note: (i) stability of mainland shoreline through entire sequence; (ii) barrier narrowing advancing NE; (iii) spit development on lagoon shore of inflection point (1941 - 1981) and dredge spoil body (1995 - 2001); (iv) removal of footbridge between 1951 and 1960 and subsequent evolution of marina facility; (v) localized channel narrowing due to spit development at footbridge, 1941 - 1951; (vi) channel dredging and removal of spit, 1960.

in 1992 (Plate 7.2), introducing a mobile sediment supply which formed spit and swale structures (Plate 7.3 b). The berm was reinforced with gravel borrowed from the adjacent beach in January 1998. Silt lenses and an irregular line of coarse clasts at the backbarrier breakpoint accumulated at the breach fill (Plate 7.3 c) and dredge spoil (Plate 1.2 e).

There were several large granite boulders lodged in the berm approximately 10 m north

Table 7.3: Summary, Segment 2.

Extent	Transects 2 through 8
Diagnostic Features	Narrow, particularly adjacent to yacht club Silts in berm structure Lagoonal apron spits
Relevant Processes (Third Order)	In-place narrowing Backbarrier tidal currents Local sediment supply depletion Barrier breach and repair

of Transect 8 (Plate 7.3 c). The boulders probably protected either the 1976 or 1992 breach repair site from incident extra-local waves. The boulders were near the site of a footbridge that spanned the channel until the early 1960's (Plate 7.2) but the bridge was not anchored to the crest, suggesting that the boulders were not the bridge foundation.

7.4.3 Segment 3

Segment 3 extended from the tidal channel through the stress point to circa 50 m south of Burnt Island (Fig. 7.3), incorporating Transects 8 through 12 (Figs. 4.8 - 4.12). The berm measured 3.2 m asl on average, decreasing slightly from south to north. The crest height increased slightly (less than 20 cm) from east to west and the cross-shore width exceeded 30 m. Silts were localized in a berm segment south of Transect 10 and may have indicated the location of the 1910 channel excavation (Section 8.1). Segment 3 was defined by the occurrence of berm cusps, which did not form further south (Section 11.2).

Large cusps may facilitate barrier overwashing by focussing swash streams over the

Plate 7.3 a. Breach fill diamict, Transect 7. Note silt and debris content.

b. Spit and swale structures adjacent to dredge spoil, Segment 2.

c. Backberm of breach site, Transect 6. Line of coarse clasts at field assistant's feet, silt lens at knee level.

d. Boulders on berm and littoral apron, south of Transect 8.

e. Overwash fans highlighted by lagoonal ice, Transect 11.

f. Seepage hollows, Burnt Island sub-basin (located within dotted lines).

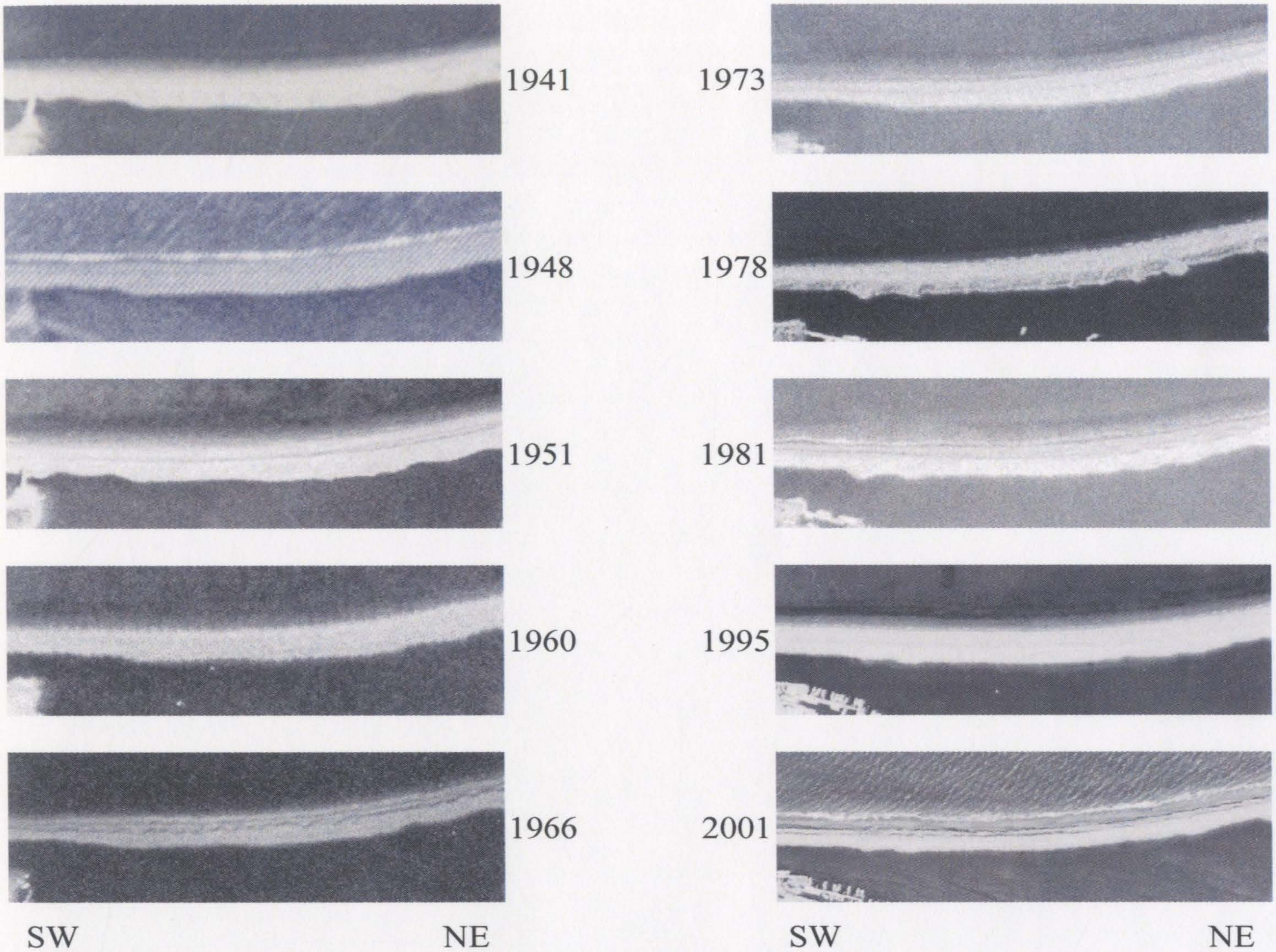


Plate 7.4. Time sequence of aerial photographs, Segment 3, 1941 - 2001 (Scale approximately 1:7500). Note: (i) transition between Segment 2 and 3 (barrier widens) migrating north; (ii) berm cusps, 1966 and 2001; (iii) fresh overwash fans visible only on 1978 photo; (iv) overwash fans aligned southeast, reflecting slightly north of normal incident extra local wave alignment; (v) overwash fans visible on 1941 photos but resolution insufficient to qualitatively assess age; (vi) backbarrier smoothing, particularly between 1978 and '81.

crest and onto the backbarrier (Orford *et al.*, 1988). At Long Pond, berm cusps acted as overwash conduits during extreme storms. The last overwash event occurred in 1976

Table 7.4: Summary, Segment 3.

Extent	Transects 8 through12
Diagnostic Features	Berm cusps Perched compact overwash fans Backberm steeper than bermface Coarse lagoonal apron
Relevant Processes (Third Order)	Berm Cusps Barrier Planform

(Plate 7.4, 1978 photo), coinciding with Segment 2 breaching. Overwash fans were aligned south of normal, reflecting the slightly north of normal extra-local wave alignment. Overwash fan morphology is often characterized by broad, flat, lobate structures deposited beyond the beach crest (cf. Leatherman & Zaremba, 1987). Segment 3 fans were compact structures perched on the backberm (Plate 7.3 e), similar to those described by Duffy *et al.* (1989). Overwash fan position and morphology was a function of crest height, berm cusp position and backberm slope. During most storms, the berm physically blocked incident swash even when berm cusps were present, dissipating incident swash energy through frictional and gravitational resistance and water mass percolation loss. Berm cusps locally reduced frictional resistance and percolation loss, facilitating overwash during the most extreme storm events. Gravel streams that overtopped the crest were weakened due to frictional, gravitational, and percolation effects. Gravitational forces on the steep backbarrier were partially offset by frictional effects and enhanced percolation. This interaction of forces manifested a compact sediment body on the backbarrier.

Perched fans precluded a broad sedimentary backbarrier. Gravitational sorting moved gravel downslope from the fans during compaction, constructing a narrow lagoonal apron. Minor gravel reworking occurred on the backbarrier. The fine to medium pebble fraction could be transported by locally generated winds and, near Transects 8 and 9, tidal currents. In these reaches, the lagoonal apron was dominated by a coarse lag deposit.

7.4.4 Segment 4

Segment 4 encompassed the northernmost 500 m of the barrier (Fig. 7.3) including Transects 12 through 14 (Figs. 4.12 - 4.14). Segment 4 was defined by low elevation (2.5 m asl), gentle beachface and backbarrier, poorly-defined breakpoints, and berm cusps. The cross-shore width was comparable to Segment 1 but was much less massive.

Segment 4 was controlled by geological inheritance (Section 13.4). Adjacent bluffs retreated more slowly than the erosional front, inducing beach and barrier narrowing from 1941 to '76 (Plate 7.5). Prior to 1976 overwash fans resembled Segment 3 fans, implying that the barrier profiles were similar. This was also suggested by Plate 1.6 a, in which the barrier was visible through the Burnt Island forest cover.

The 1976 storm induced massive sluicing overwash (cf. Orford *et al.*, 1991a) on Segment 4, manifesting broad flat overwash fans on the sub-basin, in contrast to the compact fans further south. Overwash was not constrained by cusp bays and gravel "fanned out". The sub-basin barrier transgressed, widening the barrier. Overstepping was modified by contact with the impermeable Burnt Island and mainland substrates, which

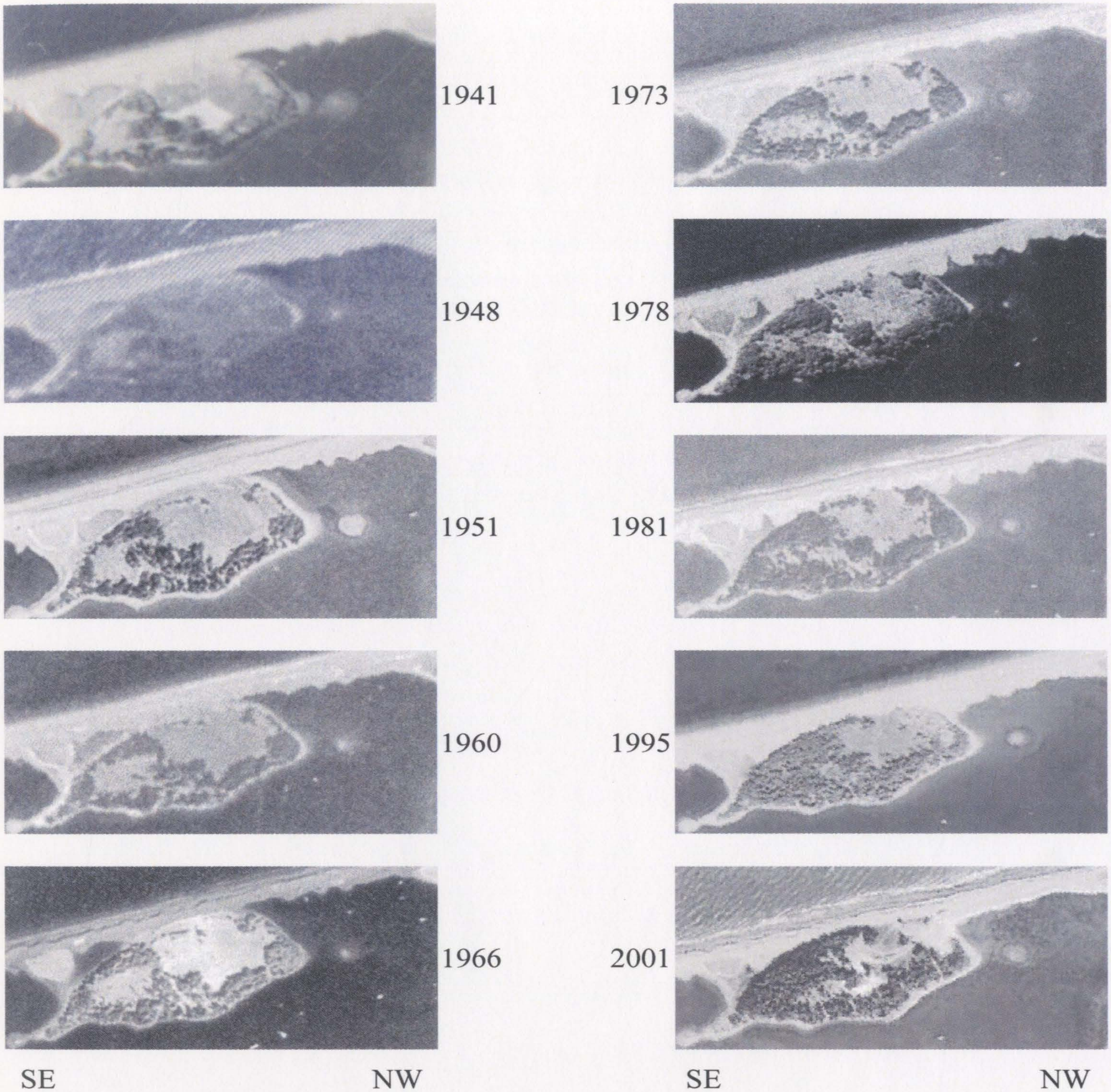


Plate 7.5. Time sequence of aerial photographs, Segment 4, 1941 - 2001 (Scale approximately 1:7000). Note: (i) beach narrowing at Burnt Island; (ii) beach narrowing at sub-basin 1941 - '73, widening by backbarrier retreat until 1995, and subsequent narrowing; (iii) possible overwash between 1948 and '51; (iv) massive overwash between 1973 and '78; (v) backbarrier smoothing; (vi) island narrowing, 1966 - 1973; (vii) access road, backbarrier armouring and residential development, 2001.

Table 7.5: Summary, Segment 4.

Extent	Transects 12 through 14 and north
Diagnostic Features	Burnt Island Low wide crest Gentle bermface and backberm slopes Simple profile shape Berm cusps Wide flat overwash fans (prior to development) Access road
Relevant Processes (Third Order)	Geologic Inheritance Sluicing overwash Lagoon ice Anthropogenic Activity

facilitated cross-shore swash extension. The barrier adopted the elevation and slope of the antecedent substrate, which also controlled the slope and elevation of the adjacent lagoon-backed barrier. Segment 4 was therefore the only Segment which did not reflect the vertical limit of swash extension. Ice-lift smoothed the fan margins between 1976 and 1999. The beach adjacent to Burnt Island had not advanced significantly onto the island while the beach width decreased, possibly indicating that an overwash event may be due.

Crest displacement facilitated the development of a wide littoral apron. Segment 4 could be vulnerable to overwashing during the coincident occurrence of an extreme storm with a spring tide, but the littoral apron has effectively dissipated much of the incident storm wave energy since 1976, preventing overtopping and overwashing. Overwash vulnerability occurred in cycles due to periodic beach and berm narrowing associated with erosional front progression (Plate 7.5). Reductions in berm and/or littoral apron width may effectively decrease the storm intensity required to overwash the barrier, increasing the associated hazard.

Access road construction superimposed a flat, impermeable structure on the backbarrier, narrowed the berm, and armoured the backbarrier (Figs. 4.14 a, b, Plate 1.2 d). Road construction effectively locked the barrier in place and will influence future evolution paths (Section 8.6) and constrain management options (Chapter 14).

Subaqueous sand and silt visible from the low water mark in the sub-basin, indicated that overwash fans were deposited on lagoonal sediments. Fetch limitations prevented gravel drawdown into the lagoon. Groundwater seeps were also observed (Plate 7.3 f). When bottom sediments were surveyed in 1965 (Christie, 1966) and 1973 (Wells, 1974), groundwater seeps were not recorded, suggesting that seeps were not common. The seepage hollows may have indicated cross-barrier flow that was a manifestation of the isolation of the sub-basin from terrestrial water inputs, tidal currents, and wave action.

8.0 Human Impacts

8.1 Early Impacts

Economic and population growth at Long Pond were initially tied to agriculture but road upgrades after WWII facilitated a quintupling the CBS population between 1951 and 2001 (Statistics Canada, 2002; Taylor, 1994). Land clearance can increase overland runoff and backbarrier sedimentation (Jennings *et al.*, 1998) which may deposit a basement structure that facilitates overstepping (Shaw *et al.*, 1993). At Long Pond, there was no evidence of a terrestrial basement that might have facilitated a barrier adjustment.

One of the most significant anthropogenic impacts occurred updrift when the railway was routed along the Foxtrap to Holyrood shoreline because the railway company could not negotiate an inland route with local landowners (Penny, 1988). Railway construction prompted coastline protective structures circa 1883[1].

Coastlines downdrift of protective structures become isolated from the primary sediment source and suffer net sediment losses (Bray, 1997). These coastlines display heightened sensitivity to further interference and the cumulative effects of rising sea level and storm activity. Downdrift erosion can occur because the littoral sediment transport capacity exceeds the reduced sediment load (Dean, 1988). Barrier retreat can accelerate (Forbes & Taylor, 1987), a curved planform can manifest due to barrier stretching (Carter

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Possibly as a result of a reduction in shear strength due to the periodic addition of the mass of passing locomotives or vibrations from locomotive transit, given that shoreline reinforcement was required so quickly after railway construction. Also, there may have been a pre-existing erosion problem related to the rate of sea level rise in Conception Bay.

et al., 1987b), and the barrier may breach (Boyd *et al.*, 1987, Carter *et al.*, 1989). Each of these impacts occurred at Long Pond. Barrier retreat can induce changes in barrier profile and/or cannibalization of existing sediments to supplement some or even all of the deficiencies in the sediment budget (Carter *et al.*, 1989). Barrier cannibalization due to decreased sediment flux would have had a greater impact on the southernmost barrier segment, increasing the vulnerability to a breaching event.

A gravel mining operation near Burnt Island in the early 20th century (R. Smith Sr, *pers. comm.* 1997) may have also reduced sediment flux. The gravel volume extracted was unclear but the operation persisted for several years and may have constituted a significant sediment sink. Sediment flux may have also been negatively impacted by an attempt to dredge an inlet (Public Works of Canada, 1910, Reprint) through the northern basin (M. Stavely, *pers. comm.* 2002; Plate 8.1 a). The plans depict the excavation and dredging of more than 15,000 m^3 of gravel which may have been lost from the system. A pre-existing inlet would have been a logical construction site and the depiction of a massive berm at the proposed construction site strongly suggests that the barrier breached sometime after 1910. The channel apparently filled in quickly, given the sediment flux, lack of protection, and the weak hydraulic head. The reapportioning of gravel to rebuild the profile depleted an additional 12 - 15,000 m^3 from the sediment budget.

Stretching stalled as the barrier planform adjusted to the new littoral flux although the poor textural sorting suggested that the barachois was not in complete equilibrium with the wave climate. A hypothetical straight line could be extended from the southwestern corner of the inlet through the inflection point and the stress point (Fig. 7.2) which indicates that rollover onto Burnt Island helped stall the barrier adjustment.

A bridge spanned the channel until the late 1950's (Plate 7.2) when the northwestern Long Pond Peninsula was acquired by the Yacht Club. The bridge had little impact other than slowing flood tidal currents, and facilitating shoaling. The bridge may have been related to the remains of an old fishing flake (primitive wharf) in Segment 3 (Plate 8.1 b). The flake has had negligible impact on shoreline morphology.

8.2 Port Development Impacts

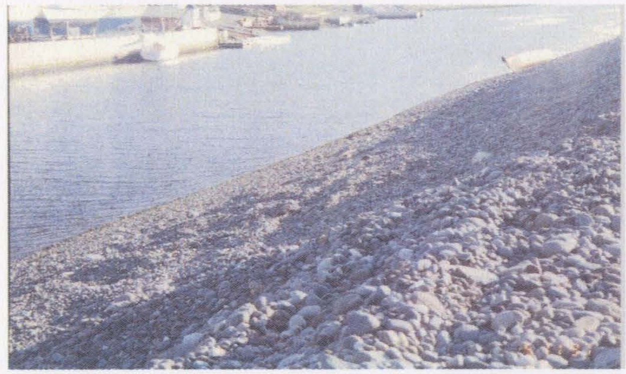
The port of Long Pond is a major economic base in CBS and has attracted commercial, industrial, recreational, and residential development. Development of the port facility began circa 1957 (Appendix 2). Flow constriction through the inlet controlled the rate at which the basin flooded/ebbed, but widening and dredging increased the tidal prism, enhancing the lagoon tidal range (Section 9.3). Channel currents were strengthened, enhancing backbarrier scour and ice-lift erosion in the northern basin (Section 12.2). Port development also modified the littoral cell structure (Section 7.2).

The modern port configuration was established by 1974 (Public Works of Canada, 1972) although maintenance operations have continued. The northern breakwater trapped gravel transported south during current reversals and shore-normal swash processes (Fig. 8.1). The adjacent barachois and shoreface became a sediment sink, facilitating the subaerial accumulation of 6,200 to 6500 m^3 of gravel between the breakwater and the

a

b

c



d

e

f

g

h

Plate 8.1 a. Probable site of 1910 channel excavation, located between Transects 9 and 10. Silt content is noticeably higher than in the adjacent berm. A berm cusp has developed nearby.

b. Remains of an old fishing flake, south of Transect 12.

c. Industrial litter on the lagoonal apron, tidal channel.

d. Backberm destabilisation by ATV, Segment 2.

e. Seawall-protected property and adjacent pier, northern basin.

f. Riprap-protected property with small sailboat, northern basin.

g. Residential litter on the lagoonal apron, Transect 3.

h. "No Wake" permitted by marina traffic in tidal channel, Segment 1.

inflection point and an unknown quantity in the nearshore (cf. 2 m contour, Fig. 1.2). The breakwater also generated a localized "piling up" effect on RSL by limiting wave propagation. Wave trains pushed trapped water, raising the water level and potential swash excursion height, and thus the potential for overtopping. This raised the barrier height, generating the vertical "step" observed along Segment 1 (Fig. 8.2) and steep berm slopes (Fig. 4.1) which enhanced swash percolation and stimulated deposition.

Segment 1 progradation depleted the sediment flux. Prior to 1974, most gravel transported south during current reversals resided in the nearshore (although some gravel was lost to the inlet, prompting periodic dredging). The resumption of longshore transport moved gravel north until the next current reversal. The post '74 port configuration altered this pattern. Although the sediment sink was not a closed system and some gravel passed north of the inflection point, the volume of available gravel decreased significantly. The impact manifested strongly in Segment 2, which had already

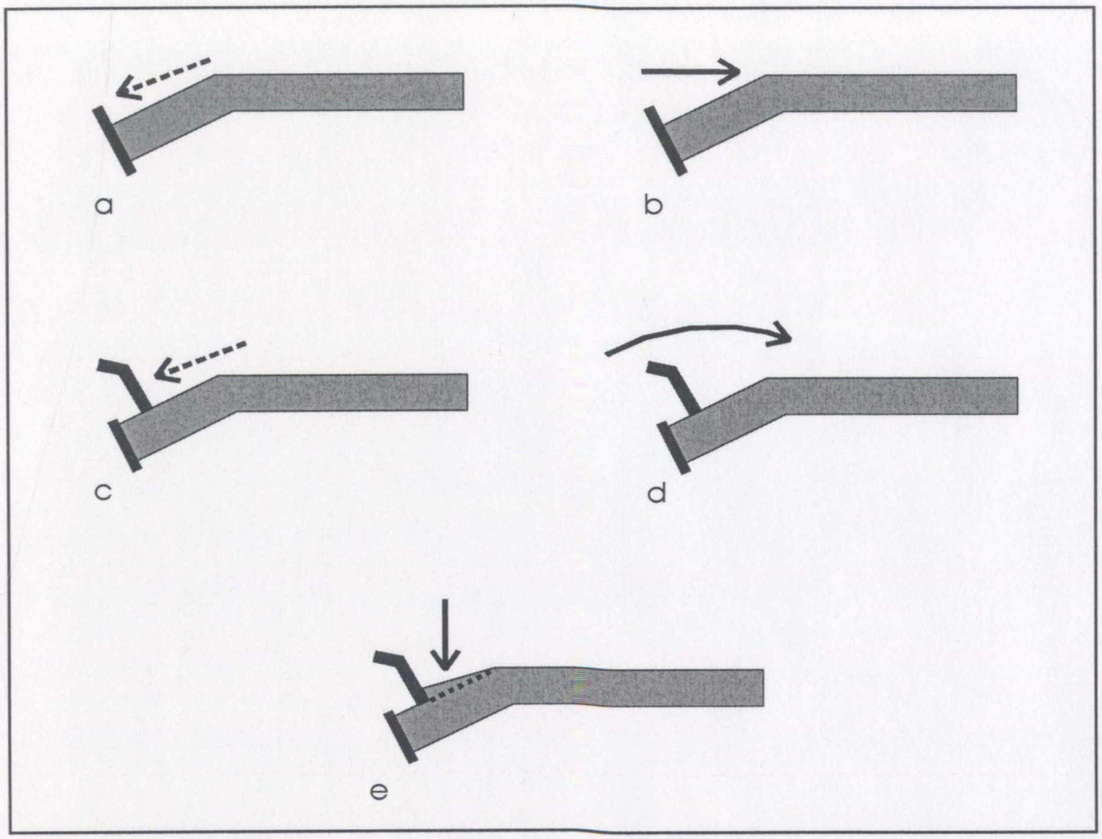


Figure 8.1. Schematic diagram of progradation at Segment 1. Prior to 1974, current reversals transported sediment south to the inlet (a), and longshore currents redistributed sediments north along the barrier (b), resulting in no net gain. After the breakwater was established, sediment transported by current reversals was trapped by the breakwater (c). The breakwater deflected longshore currents offshore (d) and sediment remained in the nearshore until swash transported sediment onshore, resulting in net progradation between the breakwater and inflection point (e).

narrowed due to backbarrier scouring. The barrier breached in 1976, less than 3 years later. The breach was repaired with silt-rich dredge spoil (Plate 7.3 a) which has proven very erosion-prone, breaching again in 1992, and eroding ever since (Section 10.5).

Barrier breaches often precede transgression (Carter *et al.*, 1990) or breakdown (Carter *et al.*, 1989; Carter & Orford, 1993; Orford *et al.*, 1996). Barrier repairs may be short-

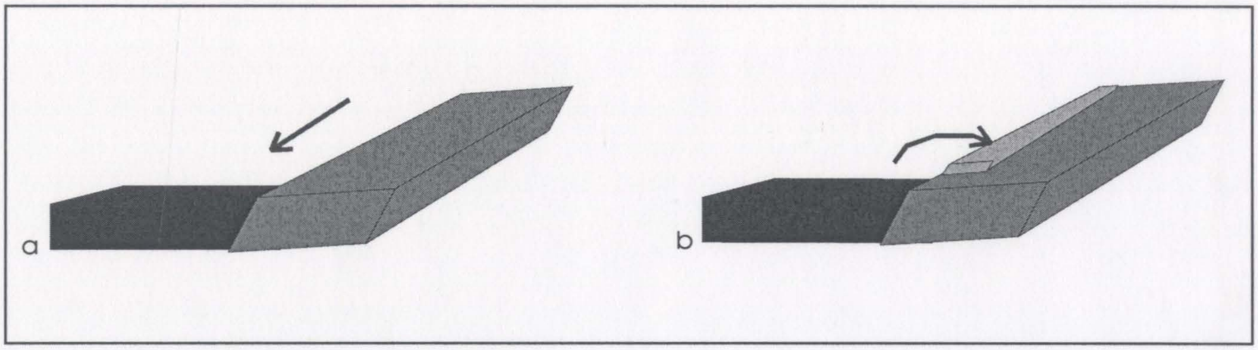


Figure 8.2. Schematic diagram of vertical construction at Segment 1. Incident waves meet the perpendicular juncture of the barachois and the breakwater (a). Wave momentum is expended against the juncture, locally raising the sea level and the base upon which subsequent waves operate, increasing swash excursion height and overtopping potential (b), manifesting a higher elevation (or step) at the crest lip.

lived due to the high silt content, but the repair has placed the barrier in a state of arrested breakdown, in which barrier breakdown has been stalled due to human intervention.

The port facility hosted considerable ship traffic (cf. Plate 1.6 e). There have been a number of small oil spills in the Long Pond basin (Taylor, 1994) and litter discharge is a concern (cf. Plate 8.1 c) in terms of environmental degradation. Given the prolonged stability of the tracer groups at Transects 6, 8, and 9 during heavy traffic periods (Table 6.1), ship wakes had little impact on shoreline morphology.

8.3 Day Use Impacts

Rapid population growth and increased leisure time have increased day use traffic. Foot traffic on the crest (aside from the breach site) and the littoral or lagoonal apron should have minimal impact due to the inherent stability of the substrate. Foot traffic on the bermface or backberm could potentially destabilize steep slopes.

Aside from noise pollution, ATV impacts at Long Pond were behaviourally dependent. The intertidal zone was probably robust to ATV transit owing to the frequency of gravel reworking. The gravel texture was not conducive to compaction and permeability impacts were probably minor. There was also little vegetation or fauna. ATV transit on the berm could have significant impacts due to the steep slopes and the infrequency of sediment reworking above the high water mark. ATV transit over steep slopes could dislodge gravel and move it downslope (Plate 8.1 d). This could narrow the berm, decreasing resilience to wave attack. The tracks also created irregularities in the berm face that could be exploited by heavy swash excursion, locally accelerating berm erosion.

8.4 Residential Development Impacts

Much of the adjacent mainland has been cleared for residential, commercial, and industrial development (Fig. 1.3) increasing the rate of runoff and basin sedimentation. Upscale residential properties have been developed in the remaining forest (cf. Plate 1.3 f). Long Pond was a sewage receptor but water and sewer infrastructure development have curtailed waste disposal in the basin. A number of residences hosted private piers and watercraft (Plates 8.1 e, f), increasing vessel traffic in the lagoon but had little adverse impact aside from potential oil discharges. Litter discharges from residences and the commercial district degrade environmental quality (Plate 8.1 g).

The mainland shoreline was susceptible to erosion by ice-lift scour and local wind waves. Many properties, particularly in the northern basin, have been protected by seawalls and revetments to prevent further loss (Plates 8.1 e, f, Fig. 1.3). Most protective structures armoured a single property but the undeveloped shoreline at the head of the northern basin was armoured as a community improvement initiative. Shoreline erosion did not contribute sediment to the barachois due to the lagoon bathymetry, the texture and thickness of the basin substrate, and the absence of strong currents away from the tidal channel. Shoreline armouring along the lagoon does not have any apparent negative impact upon Long Pond Barrier and may reduce the sedimentation rate within the lagoon.

8.5 Marina Development Impacts

The Royal Newfoundland Yacht Club extended two piers parallel to the tidal channel between 1973 and 1978 (Plate 7.2) but marina infrastructure probably exerted little impact. The marina boosted the volume of small vessel traffic in the basin. Vessels were prohibited from generating wakes in the tidal channel and the stability of Tracers at Transects 6, 8, and 9 during heavy traffic periods indicate that ship wakes had little physical impact on the lagoonal apron. Oil discharges and litter pollution (Plate 8.1 h) could potentially degrade environmental quality, however.

The marina armoured the northwestern corner of the Long Pond Peninsula with a seawall/pier in the late 1970's (Plate 1.5). The seawall was designed to protect the yacht club site and increase the docking capacity. The seawall locally stabilized the channel position while the remainder of the channel shoreline has experienced minor erosion.

8.6 Burnt Island Development Impacts

Burnt Island and the sub-basin were developed when the island and beach were rezoned from Open Space Conservation to Low Density Residential in 1999. A road was constructed on the graded backbarrier and fine-grained fill was added and compacted to provide a stable, impermeable substrate. The fire-killed trees on the northwestern corner of the island were removed to facilitate the access road (Plate 1.2 c, d). Northeastern Burnt Island and barrier were armoured (Plate 6.3 e) and a residence was constructed in 2000. Eastern Burnt Island did not contribute sediment to the barachois and armouring did not affect barrier morphology or stability.

Residential construction on the island should not impact the barachois in the short term. The house was 30 m east of the beach fringe and 2 to 3 m above the crest. The grade and forest cover should continue to slow the rate of barrier rollover and mitigate the storm hazard in the short term, although storm-tossed gravel may eventually pose a risk. The barrier had narrowed in front of Burnt Island since 1941 however (Plate 7.5), which has increased overwash and overstepping vulnerability during the coincident occurrence of a storm with an elevated water level (cf. Plate 6.3 f). The removal of the fire-killed trees and the extension of the access road onto the island has exposed the northwestern corner to extra-local waves, increasing the probability of overwashing.

Backbarrier armouring and road construction have stabilized barrier position. Massive sluicing overwash occurred in 1976 because of barrier narrowing (Plate 7.5) and transgression onto an impermeable substrate (Section 13.4). Overwash deposition

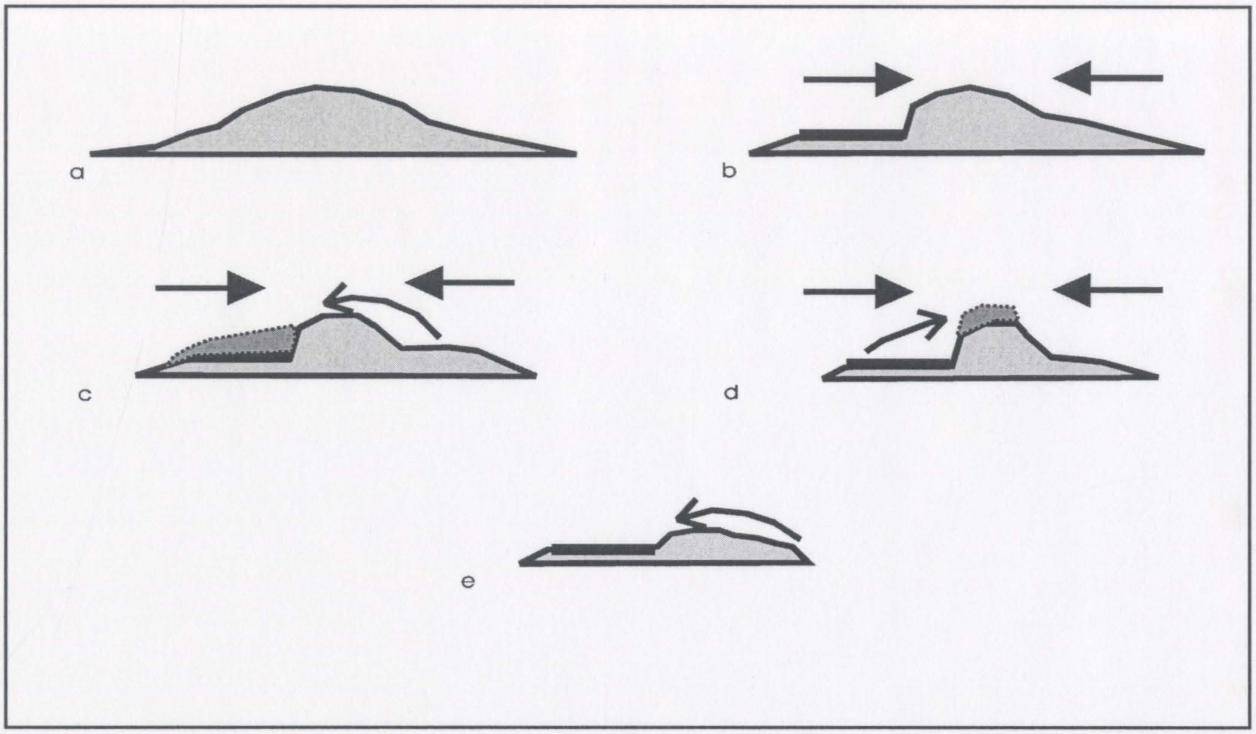


Figure 8.3. Schematic diagram of the impact of road construction. Prior to road construction, the barrier was low but wide (a). Road construction narrowed the berm and flattened and compacted the back-barrier while RSLR drives an erosional front that narrows the berm and littoral apron and raises the lagoon level (b). Berm and barrier narrowing facilitate massive overwash which extends to the road and beyond (c). The road is cleared, reducing potential accommodation space. Overwashed gravel is transferred to the narrowed berm with the aim of protecting the road from another overwash event, oversteepening the berm (d) and rendering the barrier prone to a rapid adjustment. Road maintenance and shoreline erosion will eventually eliminate accommodation space and a berm will not be tenable (e). In the absence of hard protection, overwash occurs regularly until the road is abandoned or the barrier breaks down.

widened the barrier and shifted the berm. Backbarrier grading narrowed the berm from the rear as barrier narrowing has continued in response to the erosional front (Fig. 8.3).

More importantly, a stable, impermeable structure was superimposed on the backbarrier, with several implications for cross-shore sediment transfer. Sluicing overwash occurred

Table 8.1: Summary of Human-Induced Impacts at Long Pond.

Activity	Consequence	Impact
Land Clearance	Increased runoff	Sedimentation of lagoon basin
Updrift Shoreline Armouring	Reduced sediment flux	Barrier breaching, Segment 1; Barrier stretching, curved planform Tidal exchange in lagoon; In-place narrowing, Segment 2; Port development
Gravel Mining	Gravel removed from system	May have reduced sediment flux on system adjusting to updrift armouring
Channel Construction	Gravel removed from system	May have reduced sediment flux on system adjusting to updrift armouring
Port Development	Tidal inlet stabilized; Tidal inlet, channel, and basins dredged; Infrastructure development	Economic benefits; Progradation, Segment 1; Enhanced in-place narrowing, Segment 2; Barrier breaching, Segment 2; Ice erosion of shoreline; Possible oil and litter discharges
Day Use	Foot and ATV traffic	Foot: little probable impact; ATV: noise pollution, little impact on intertidal zone, destabilize steep slopes
Breach Repair	Silt-rich dredge spoil used as fill	Arrested barrier breakdown; Continued erosion problems
Residential Development (Mainland)	Private piers; Property armouring	Increased boat traffic; Possible oil and litter discharges; Reduced rate of lagoon infilling; No apparent impact on barrier
Marina Development	Pier construction; Shoreline armouring	Economic benefits; Increased small boat traffic; Possible oil and litter discharges; Little apparent impact from boat wakes
Burnt Island Development	Access road and residence constructed; Berm narrowed	Increased overwash vulnerability; In-place narrowing, Impermeable road and road maintenance will facilitate sluicing overwash

in response to barrier rollover onto an impermeable substrate. As the road will undoubtedly be maintained, the smooth, impermeable surface may facilitate the extension of overwash into the lagoon. This gravel will be effectively lost to the system, negatively impacting the sediment budget and inducing in-place narrowing. Overwash also shifts the berm inland, eventually to the access road. A natural berm may not be tenable as the overwashed gravel deposited on the road will be removed. If this gravel is dumped into the lagoon, it too will be effectively lost from the system. The gravel may instead be placed west of the road as a protective measure. This will be a stop-gap measure: the gravel will be unsorted and prone to erosion during subsequent storms and the structure will oversteepen as the littoral apron narrows and accommodation space is lost.

Overwash vulnerability will increase over time and moderate storms may eventually pose risks. There was little evidence of overwashing between 1941 and 1973, but the profile changed dramatically in 1976. Burnt Island and the adjacent bluffs slowed the rate of overstepping but a disequilibrium can induce a strong response (Section 13.3) such as the 1976 overwash event. The bluffs have eroded in response to the erosional front and will eventually produce a disequilibrium response that will be exacerbated by bermface retreat and activity in the backbarrier. An overwash event may occur with the next 5 to 10 years, but may be short-circuited by an extreme storm.

9.0 Textural Sorting

9.1 Littoral Apron

Long Pond gravel did not display consistent alongshore or cross-shore textural sorting. There was little apparent correlation between slope and clast size (Table 4.2) and little apparent seasonality (Table 4.1, Figs. 4.1 - 4.14). Poor sorting may indicate that a barrier is not in equilibrium with the wave climate (Carter *et al.*, 1987b). Long Pond may not have adapted to the depleted sediment supply (Section 8.1), or littoral cell modification in the 1950's (Section 7.2). Different clast sizes respond differently to similar hydrodynamic conditions (Medina *et al.*, 1994). In a long sediment cell, coarser clasts can settle out of the wave column before finer clasts, manifesting alongshore fining (Bird, 1996b). Shorter cells, such as Long Pond, may not be capable of inducing strong separation.

Source gravels were glacigenic and a broad spectrum was fed into the system. Poor sorting also reflected the wave climate variability (Fig. 1.4), which generated inconsistent transport. Fairweather transport at Long Pond was longshore-dominated, but current reversals and shore-normal swash processes mixed gravels. In addition, energetic wave events could occur at any time of year, further mixing the gravels.

Long Pond Barachois was reflective and waves broke on or very near shore, transferring kinetic energy across-shore. Energetic swash could transport a broad spectrum of clasts. Differential clast response can induce cross-shore sorting (McKay & Terich, 1992) as a function of energy dissipation by gravitational and frictional resistance, and percolation. Swash transport potential decreases with energy and mass loss, and larger clasts usually fall out first while smaller clast sizes are transported further cross-shore. The open work gravel structure and limited accommodation space at Long Pond were not conducive to cross-shore sorting however. The open work structure enhanced frictional resistance and percolation, while the steep slope enhanced gravitational resistance and percolation in the absence of cusp formation. Incident wave energy diffused quickly over a small area relative to wave volume, which often translated into a rapid loss of sediment transport potential and little opportunity for size or shape sorting under most conditions. The wave diffusion area was positively correlated to the incident angle however (Carter *et al.*, 1987b), and strongly oblique incident waves could facilitate weak cross-shore sorting.

Some textural sorting occurred in spatially discrete units. Swash ridges were often well sorted, particularly when formed by small fairweather waves. At the swash limit where the finest clasts were transported, percolation facilitated deposition. Further seaward, less swash was lost to percolation, facilitating an energetic erosive backwash that was strengthened by continued deposition at the runup limit. Swash ridges formed by larger waves were not as well sorted, due to the greater transport capacity. Discrete size-sorted gravel pockets were common (Table 4.2). These pockets may have been formed by wave-induced clast separation but may also have formed when well-sorted swash ridges were reworked. Apron cusps could also induce temporary sediment sorting (Section 11.1).

9.2 Berm

The wave power required to overtop or overwash the berm could transport a broad spectrum of clasts. The berm consisted of poorly sorted (fine pebbles to boulders) open work gravel as a result which was, on average, coarser than the littoral apron except when littoral apron texture was particularly coarse. There was no apparent cross-shore or alongshore textural grading evident on the berm. Discs and blades can be preferentially transported cross-shore due to their comparatively high surface area/volume ratios, which also translates into a higher *in situ* preservation potential; spheres and rollers are more likely to be transported downslope in the backwash and under gravitational movement (Orford *et al.*, 1991b). At Long Pond, discs and blades were the most common clast shapes on the berm, but spheres and rollers were not scarce.

The Segment 2 berm was texturally complex. The berm was dominated by poorly sorted open-work gravels, but the 1992 breach site (Transects 6 - 8) was an unsorted diamict of silts to small boulders (Plate 7.3 a). The breach was filled with gravel overwashed into the tidal channel. Excess dredge spoil was dumped behind the inflection point on the lagoonal apron (Plate 7.2). Silt mixed with the overwash and the resultant structure has proven erosion-prone (Sections 8.2, 10.4). This berm segment was heavily scarped during most of the survey period but was reinforced with sediment borrowed from the adjacent beach after which it continued to erode.

Silt was evident throughout the repaired profile, but it locally accumulated in sufficient quantities to form a matrix which supported gravel clasts (Plate 7.3 d). Silts moved down-slope partially by kinetic sieving as the fill compacted under its own weight, realigning larger clasts and pore space. Kinetic sieving may have also been induced by vibrations generated by repetitive swash runup (Middleton, 1970). Gravitational sieving, assisted by percolating rainwater, sea spray and snow melt, also moved silts into pore spaces. Silt lenses formed when pore spaces filled to capacity, forming an impermeable layer that thickened as more silt collected. A line of coarse clasts, which were undermined and destabilized by fill compaction, accumulated at the backbarrier breakpoint. The dredge spoil was not directly surveyed but was texturally similar to the repaired breach and also developed silt lenses and a line of coarse clasts at the base of the slope (cf. Plate 1.2 e). Silt was also evident south of Transect 10 (Plate 8.1 a).

9.3 Lagoonal Apron

Most lagoonal apron gravel originated as poorly sorted overwash but breach site gravels originated as dredge fill. Fetch restrictions limited wave-induced transport but fine to medium pebbles were transported in the northern basin, leaving a coarse-textured lag deposit (cf. Plate 6.1 d). Fine gravels accumulated in the island - barrier juncture at Transect 12. Gravels in the sub-basin (prior to access road construction) were poorly sorted due to fetch limitations and isolation from tidal currents. Angular and subangular gravels on the Burnt Island shore platform were not reworked, attesting to low energy conditions (although limited number of well-rounded clasts were observed). Ice-lift smoothed the sub-basin backbarrier (Section 12.2), but did not induce sorting.

Cross-barrier flow occurs more efficiently through an inlet than by seepage (Carter *et al.*, 1987b) and flow was directed along the backbarrier, with the possible exception of the sub-basin. The southern basin was adjacent to the tidal inlet while the northern basin was comparatively isolated, manifesting a higher net water surface elevation. In the absence of tides, this configuration stimulated a north-to-south hydraulic gradient and current.

Tidal currents (cf. Plates 1.1 f, g) were induced by reversals in the hydraulic gradient associated with the semidiurnal Conception Bay tidal regime (Fig. 9.1). Flow constriction through the inlet and channel accelerated currents, but the flow capacity limited the rate at which basin flooding/ebbing occurred, creating a temporal lag. The tidal range of the northern basin was less than the southern basin which in turn was less than Conception Bay. Asymmetrical double-basined lagoons can produce nonlinear tidal distortions (McSherry & Eliet, 1993). Tidal flow in Long Pond was complicated by the asymmetry between the inlet and channel tidal prism, basin capacity asymmetry, the natural north-to-south hydraulic gradient, and fluctuations related to the lunar cycle and meteorological conditions (Fig. 9.2). Flood and ebb currents could persist past the theoretical peaks and nadirs (Canadian Hydrographic Service, 1997; 1998; 1999), such as occurred on 11/10/97 when the flood current persisted past the theoretical peak. Neither the tidal range nor current flow duration could be simply related to Conception Bay tidal patterns.

Currents are capable of moving gravel tracers without wave action (cf. Ferguson & Wathen, 1998). The tracer experiment (Table 6.1) confirmed that tidal currents transport gravel (Plates 6.1 a - d). Transect 3 tracers moved almost immediately and moved the furthest (Fig. 6.1), indicating that the strongest currents were generated when the ebb tidal current debouched into the southern basin, as suggested by the development of the wide

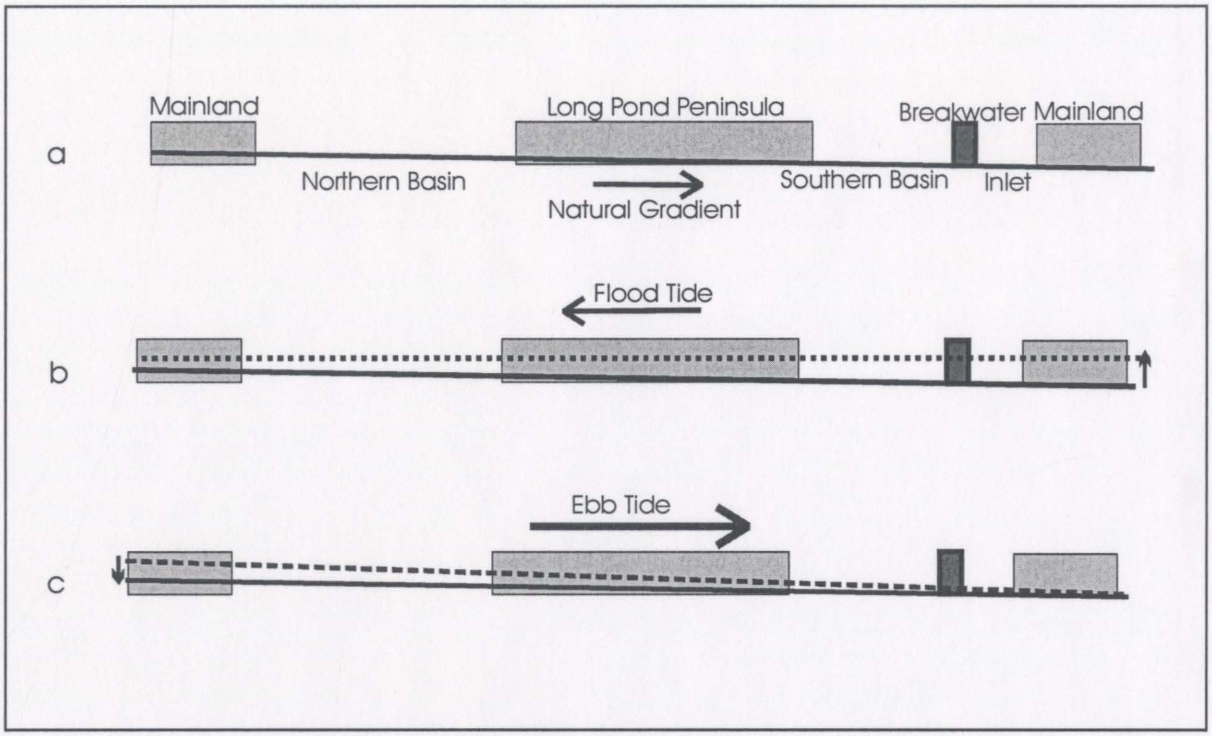


Figure 9.1. Schematic diagram illustrating changes in hydraulic gradient. The ambient hydraulic gradient (solid line) at Long Pond is oriented north-to-south, draining the basin (a). During flood tide, the hydraulic gradient is oriented south-to-north (dotted line), generating south-to-north flow. The ambient gradient is oriented against the flood gradient, decreasing the gradient height and weakening flood tidal currents (b). The ebb tidal hydraulic gradient is aligned north-to-south (dashed line), generating north-to-south flow. The ambient gradient is aligned with the ebb gradient, increasing gradient height and strengthening ebb tidal currents. Currents persisted until an equilibrium water level was achieved.

lagoonal apron. Apron reworking was accelerated when the dredge spoil introduced a fresh sediment source, and a series of alternating spits and swales aligned towards the inlet was formed (Plates 1.6 e, 7.3 b). Ebb currents also transported fine gravel to the inlet, generating fluctuations in lagoonal apron volume in Segment 1 (Fig. 4.1). Transect 6 tracers also moved south until they were drawn down into the channel. The initial limited transport implied that current velocities were weaker than at Transect 3 and transport may

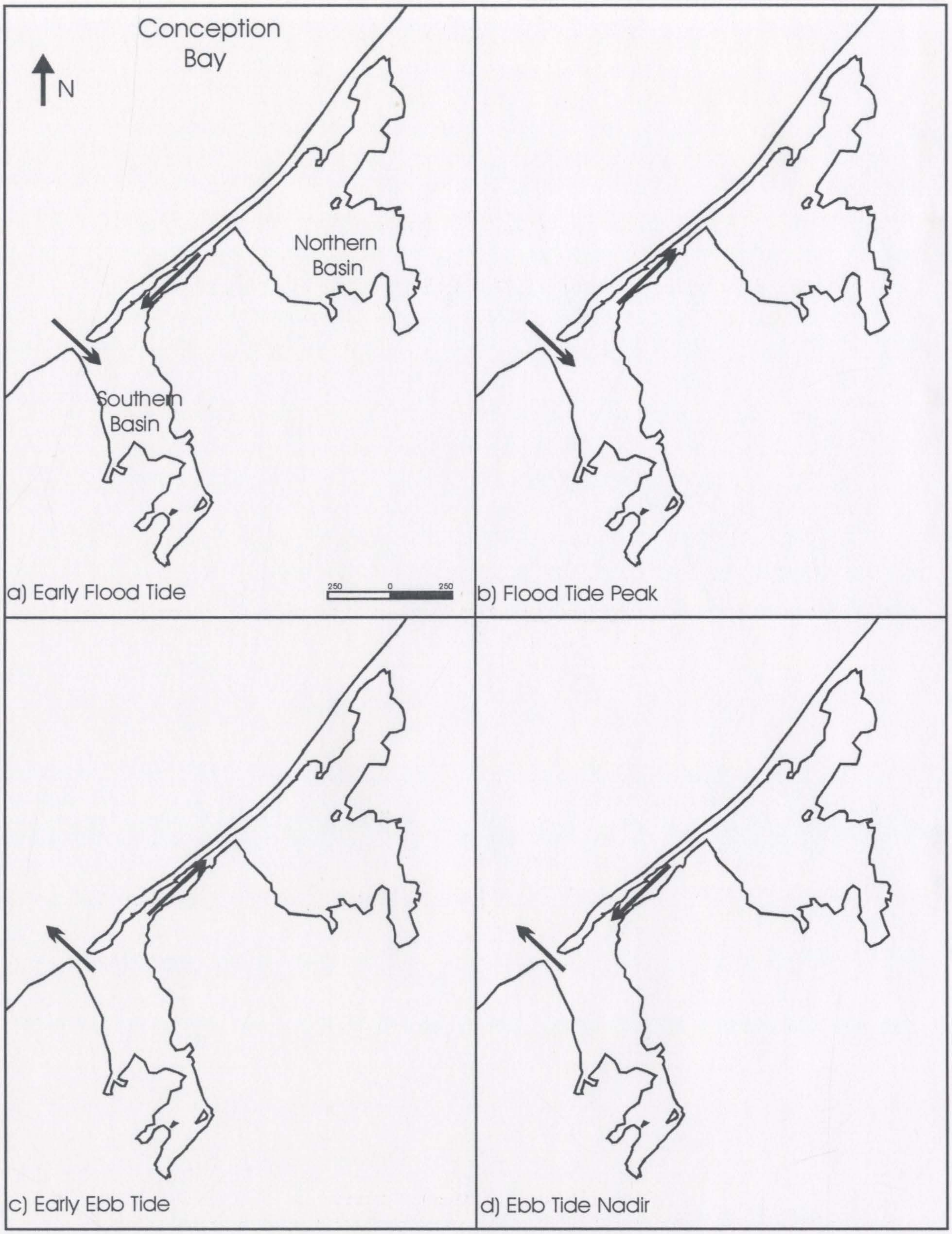

Conception
Bay
N
Northern
Basin
Southern
Basin
a) Early Flood Tide
250 0 250
b) Flood Tide Peak
c) Early Ebb Tide
d) Ebb Tide Nadir

Figure 9.2. Tidal currents in Long Pond are driven by reversals of the hydraulic gradient associated with the semidiurnal tide regime in Conception Bay. Tidal flow is complicated: i) flow constriction through the inlet and channel limit flooding/ebbing rates, ii) the inlet possesses a greater tidal prism than the channel, creating an asymmetry in flow capacity and the temporal lag, iii) the asymmetry of basin volumes, iv) the natural north-to-south flow pattern, and v) water level fluctuations associated with the lunar cycles and meteorological conditions. The net result is a non-linear relationship between the tidal range, which decreases from bay to southern to northern basins, and the duration and strength of tidal currents over the lunar cycle. In early stages of flood tide (a), a rise in Conception Bay tide initiates flooding into the southern, which remains below the northern level for a time and ebb currents persist in the channel. As the flood tide progresses (b), the southern basin is elevated above the northern basin, reversing the channel current. As the tide begins to ebb (c), the southern basin drains into Conception Bay but remains elevated above the northern basin for a time, and flood currents persist. As the ebb tide progresses (d), the water level in the southern basin falls below the northern basin and the channel current reverses.

have been limited to exceptionally high tides. Transect 8 tracers experienced a net northern shift until they were drawn down into the channel, indicating a stronger influence by flood tides. The initial limited transport suggested that flood currents were weaker than ebb currents and transport may also have been limited to exceptional tides. Transect 9 tracers experienced a net northern shift until they were drawn down into the channel, but there was a southerly transport component as well. It was unlikely that ebb currents could induce southern transport in light of the behaviour observed at Transect 8. The southward movement may have reflected local wind-wave movement, but the limited southward movement suggested that these waves barely exceeded the transport threshold.

Tidal currents within the channel could transport small cobbles and as there was no discernable pattern of preferential transport, the currents may transport coarser particles. Maximum current velocity occurred as flood tides discharged into the northern basin and ebb tides discharged into the southern basin. Current velocities strengthened from neap to spring tides. Storm surges probably elevated the water levels, strengthening flood tidal currents but weakening ebb tidal currents until the surge subsided.

Prior to tidal inlet formation (Section 10.1), Long Pond was a seepage barrier and did not host tidal currents. Wind-generated currents were weak and variable due to fetch limitations and inconsistent winds, and probably had little impact on backbarrier morphology. Direct tidal exchange stimulated currents in the channel which eroded the backbarrier, oversteepening, destabilizing and narrowing it. Narrowing was initially rapid and was evident in the 1941 air photo (Plate 1.4) when Segment 2 barrier width was compared to Segments 1 and 3. Eroded gravels were preferentially transported on the ebb tide and gravel was trapped at the inflection point due to the change in alongshore alignment. This manifested the broad apron that eventually served as a dump site for dredge spoil in 1992 (Plate 7.1). Shoals induced by the footbridge (Plate 7.4) dispersed soon after it was removed. Tidal currents were enhanced by port development as the inlet was dredged, widened and stabilized (Section 8.2). The enhanced tidal prism increased the magnitude of the hydraulic gradient, strengthening the current. The barrier has probably narrowed a short distance (less than 3 m), but was difficult to quantify due to the lack of suitable reference points for photogrammetric analysis.

10.0 Barrier Breaching and Tidal Inlet Behaviour

10.1 Initial Barrier Breach

Long Pond Barachois evolved from a straight-planformed seepage barrier (Orlebar & Kerr, 1868). Updrift shoreline armouring circa 1883 depleted the littoral flux, triggering stretching (Plate 10.1 a) and breaching. The sediment budget may also have been stressed by channel dredging and gravel mining in the early 20th century (Section 8.1). Plate 1.4 dates from 1941 and depicts a small tidal inlet and the inflection point.

The timing of the initial breach was unclear because no bathymetric charts, topographic maps or published descriptions from the period of 1910 to 1941 were located. The hypothetical straight line depicted in Figure 7.2 extended through the inflection point, which strongly suggests that the barrier breached at the inflection point and migrated to its current position (Section 10.2). The configuration displayed by Segment 1 indicates that basement structures were deposited in the backbarrier. This in turn suggests that the hydraulic head was oriented from the bay to the lagoon when the barrier breached. The breach was triggered by extra-local waves that punched through the barrier. There is a downward erosional limit beyond which erosion becomes horizontal (Fucella & Dolan, 1996). Extra-local waves undercut and oversteepened the berm. The open work gravel was prone to gravity-assisted mass wasting, which weakened the berm to the point where it could be completely dismantled.

Barriers can breach during moderate storms when sediment depletion oversteepens the berm (Orford *et al.*, 1995a). Breaching can also occur during a series of (temporally)

Plate 10.1 a. Barrier configuration looking north from southern breakwater.

b. Shoreline armouring, lack of accommodation space, and low sediment flux, looking south from southern breakwater.

c. Excavated channel, Chamberlains Beach. Note the steep barrier slopes on either side.

d. Arcuate scarping at Transect 7, pre-reinforcement.

e. Reinforced berm at Transect 7.

f. Arcuate scarping at Transect 7, post reinforcement.

closely-spaced storms inhibit post storm recovery and therefore enhance vulnerability (Forbes *et al.*, 1991). There was no apparent increase in the storm frequency during this period however (B. Whiffen, *pers. comm.* 2002). Given that the 1976 and 1992 breaches occurred during heavy storms, an extreme storm was probably the catalyst for the initial breach. There were two potential candidates: (i) November 1921 (Evening Telegram, 1921), prior to the 1923 revision of Orlebar & Kerr (1868), although a change in barrier configuration and/or tidal inlet formation would probably have been depicted because of the potential navigational implications for small craft; and (ii) October 1933 (Evening Telegram, 1933), which caused significant wave damage on the Avalon Peninsula.

The straight barrier planform extended between the anchor points (Fig. 1.9 a), suggesting that the barrier retreated in equilibrium with the adjacent bluffs prior to updrift armouring. Sediment supply depletion induced barrier cannibalization, which narrowed and oversteepened the berm. The barrier may also have begun to stretch prior to breaching, inducing further narrowing as the barrier length increased. Barrier retreat can outpace adjacent bluff retreat (cf. Fig. 1.7). Barrier transgression exceeded the rate of updrift bluff erosion, inducing an alongshore disequilibrium (Fig. 10.1). The longshore current refracted around the southeastern lagoon shoreline, exacerbating narrowing and oversteepening which progressed in the direction of longshore transport. The barrier probably breached during the 1933 storm when large extra-local storm waves exploited the narrowed barrier, probably at the northern limit of the refraction-induced narrowing.

As the breach evolved into a tidal inlet, it gradually separated the littoral cell into two

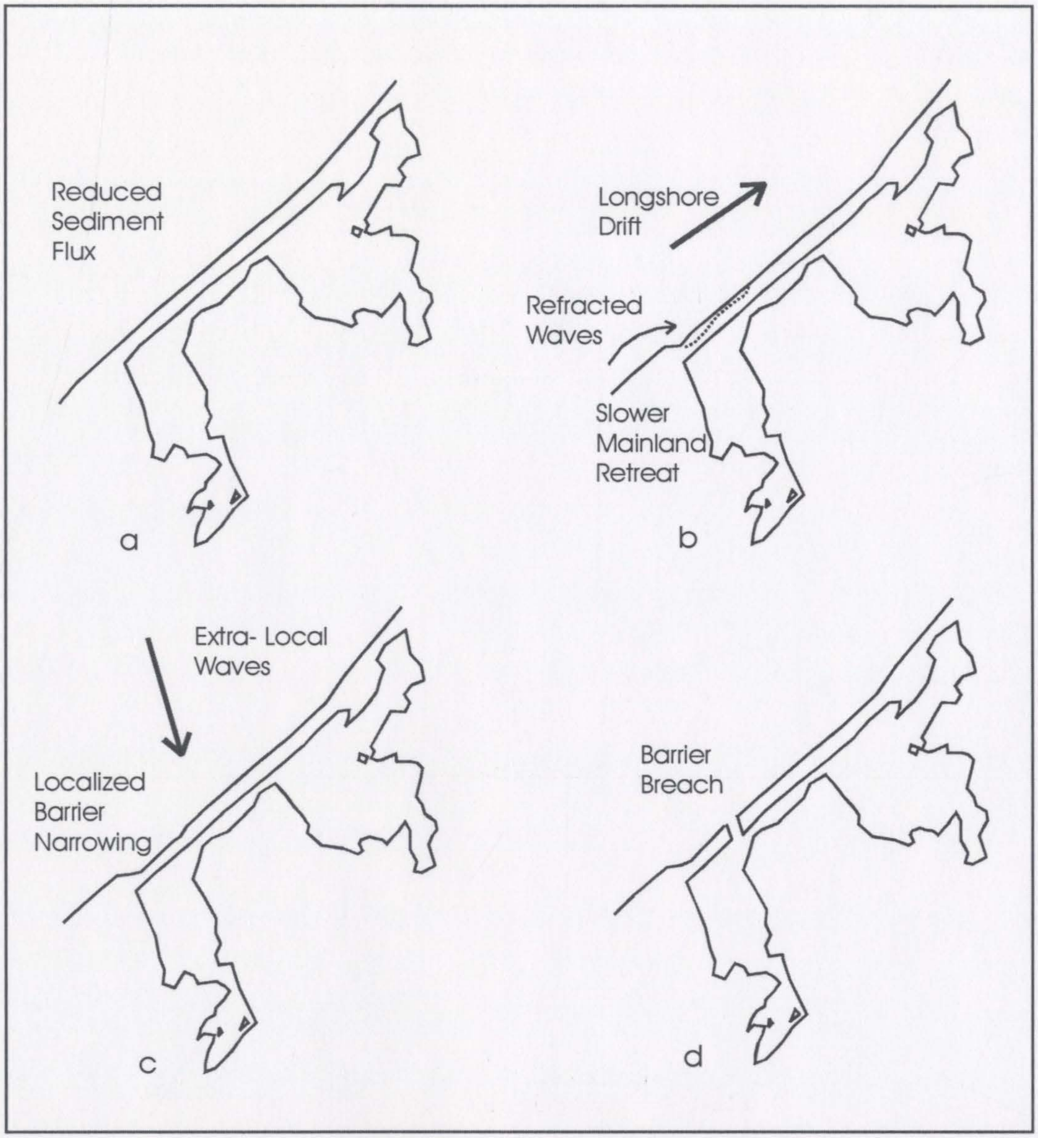


Figure 10.1. Updrift sediment flux reduction (a) induced a greater rate of barrier narrowing than adjacent bluff erosion (b). The disequilibrium refracted longshore waves which eroded and oversteepened the adjacent barrier (c). Extra-local waves breached the narrowed barrier (d).

distinct units (Section 7.2). This separation, coupled with the effects of shoreline armouring manifested a coarse, sediment-poor beach adjacent to the pyrophylite processing plant (Plate 10.1 b) and may have contributed to barrier stretching by further reducing the flux along the Long Pond barrier. It is interesting to note that the Orlebar &

Kerr (1868) depiction of Long Pond suggests that the great storm of 1775, with reported storm surges of 6 to 9 m in coastal waters[2] (Rappaport & Ruffman, 1999), apparently did not trigger breaching or stretching despite having impacted Conception Bay (Anspach, 1828). The 1921 and 1933 storms were not as extreme as the 1775 storm, but may have triggered a barrier response nonetheless.

10.2 Tidal Inlet Migration

Figure 7.2 indicates that Segment 1 configuration was modified by transgression that was not directly related to the erosional front. Shore-normal breakwaters and groynes are often associated with downdrift erosion and transgression (cf. Bruun, 1994; 2001; Nordstrom, 1987) but the inflection point predated port development (Plate 1.4). Tidal inlet-driven transgression is more rapid than overstepping because inlets are more efficient at delivering sediment to the backbarrier (Armon & McCann, 1979; Nordstrom, 1987). The inflection point was the morphological expression of a localized acceleration in the rate of transgression due to the updrift migration of the tidal inlet.

Flood tidal deltas can facilitate barrier transgression by acting as basements upon which subsequent deposition occurs (Leatherman, 1979; Orford *et al.*, 1991b). Embryonic tidal

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2

A 6 to 9 m storm surge would have been capable of inundating the Long Pond barrier and triggering a large adjustment or complete breakdown. The reported storm surge may have occurred at bay heads due to a piling-up effect, or may have actually have referred to the elevation of swash excursion on impermeable coasts. The 1775 storm was certainly capable of overwashing the Long Pond barrier and probably induced some transgression.

inlets are usually shallow, narrow and ephemeral (Fitzgerald *et al.*, 1987), conditions which are conducive to the rapid construction of flood tidal deltas. Flood tidal deltas can form during storms when the storm surge creates an elevated hydraulic slope that facilitates cross-shore sediment transport (Basco & Shin, 1999; Fitzgerald, 1988).

The magnitude of littoral sediment flux in CBS was illustrated when a 12.5 m wide drainage channel was excavated through Chamberlains Beach to alleviate local flooding in January 1999 (Plate 10.1c). Fairweather conditions persisted for the next 11 days, but the channel was sealed by the subaerial deposition of approximately 75 m^3 of gravel (Marine Institute, 1999), and an unknown subaqueous amount. Enough gravel was transported through the 1992 breach to repair the barrier and between 2000 and 2500 m^3 of excess gravel was dumped behind the inflection point (Section 10.4).

Flood tidal deltas can stimulate lateral inlet migration by reducing the hydraulic efficiency of the inlet (Dean, 1988; Fitzgerald *et al.*, 1987) although downdrift migration is most common. Tidal inlet migration in wave-dominated settings is often driven by longshore currents which shift the inlet in the direction of the current flow (Fenster & Dolan, 1996; Fitzgerald, 1988). Despite the frequency of longshore drift conditions at Long Pond, the inlet migrated updrift to the southern end of the barrier.

Updrift tidal inlet migration at Long Pond was swash-driven, propelled by energetic extra-local waves aligned slightly north of shore-normal. Upon breaching, gravel was propelled through the gap to the backbarrier, forming a flood tidal delta (Fig.10.2). The breach facilitated erosion south of the breach on two fronts. The breach exposed the

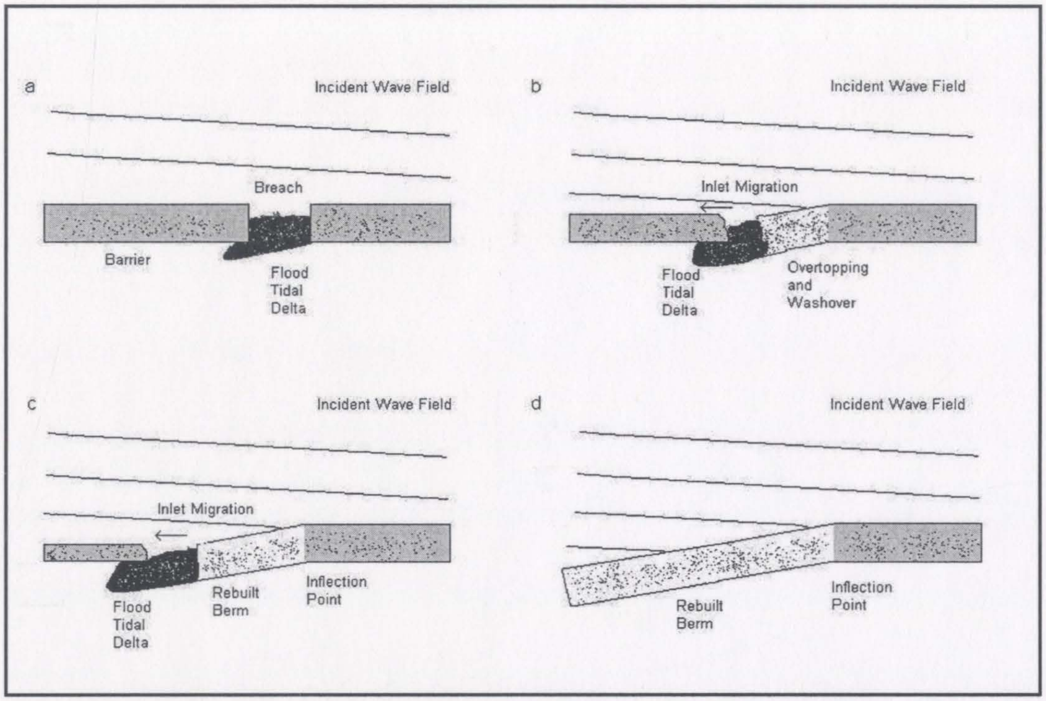


Figure 10.2. Schematic diagram of updrift tidal inlet migration. The storm surge deposits a flood tidal delta through the breached barrier (a). The delta provides a structural basement, attracting overtopping and overwashing by extra-local waves which shifts the barrier further inland while the updrift barrier segment is cannibalized and destabilized by incident waves, rendering it prone to further erosion (b). Extra-local waves erode the updrift barrier and deposit successive tidal deltas, each shifting the barrier further inland (c). The inlet eventually stabilizes and the berm is rebuilt by overtopping and overwashing but the alongshore orientation has been changed, generating an inflection point (d).

oversteepened barrier cross-section (cf. Plate 10.1 c as an example) to wave attack. Small storms contributed to inlet migration by undercutting the berm, causing gravity-assisted slope failures. Longshore flux had already been reduced and the inlet isolated this beach segment from the current reversal fluxes, intermittently at first. Barrier cannibalization accelerated, narrowing and oversteepening the berm alongshore. This weakened inertial resistance to inlet migration. As the berm eroded, the inlet shifted south to the end of the barrier and as the updrift inlet margin retreated, the throughflow capacity exceeded cross-shore flow requirements, facilitating downdrift gravel accumulation via overtopping and overwash. This was the reverse of the downdrift sedimentation mechanism described by Aubrey & Speer (1984) and Carter (1988). As the inlet migrated, the former breach site, now occupied by a backbarrier flood tidal delta, became the northern inlet shoreline. The inlet focussed swash flow across-shore and as the inlet migrated, flood tidal deltas were deposited progressively eastward until inlet migration reached its southern limit.

Overwash concentrates on former inlet positions due to the comparatively lower barrier height (Nordstrom, 1986). As the inlet migrated, the former position was rebuilt by overtopping and overwashing on the flood tidal delta. Berm construction was associated with weak to moderate storms. As berm height increased, overtopping potential decreased and deposition was more commonly restricted to the bermface. Backbarrier tidal currents and waves smoothed the lagoonal apron. Inlet formation and migration did not require exceptional storm frequency or intensity because the depleted littoral flux was the dominant control on tidal inlet behaviour.

Updrift tidal inlet migration has previously been attributed to: (i) over-efficient sediment bypassing of the inlet which results in the erosion of the updrift and accretion of the downdrift shore (Carter, 1988), (ii) swash bar attachment (welding) to the downdrift inlet shoreline, (iii) updrift breaching, or (iv) cutbank erosion of the updrift shoreline by oblique ebb tidal currents at the inlet throat (Aubrey & Speer, 1984).

Over-efficient sediment bypassing and swash bar welding are similar in that downdrift sedimentation triggers updrift migration. Downdrift sedimentation constricts throughflow and the updrift side passively erodes to maintain cross-shore flow requirements. Neither were viable migration triggers at Long Pond. In order for these mechanisms to trigger updrift migration, the downdrift side must be at least as resistant to erosion as the updrift side. This is feasible in a sand-rich littoral system where the relief differential between the swash bar and beach is small. The updrift side of the inlet was cannibalized prior to inlet migration, but nevertheless hosted a large berm. The former inlet position was initially much less massive than the updrift margin. Any erosion triggered by cross-shore flow requirements would have occurred at a former inlet position. This also precludes updrift breaching as an updrift migration mechanism as breaches preferentially occur in low or narrow barrier segments. Since the barrier migrated through a massive barrier segment, the updrift margin must have been actively eroded.

Updrift cutbank erosion can occur when the backbarrier tidal current approximately parallels the downdrift barrier planform, directing ebb flow against the updrift shoreline. Segment 2 was narrower than Segments 1 or 3 in 1941 due to tidal current scour in the channel (Section 9.3). The configuration of Segment 1 indicated that flood tidal delta construction controlled barrier position. Ebb tidal currents capable of eroding a massive berm structure would almost certainly have been capable of dispersing flood tidal delta deposits, which would therefore not have generated the west to east configuration that characterized Segment 1. Cutbank erosion may have contributed to updrift erosion by undercutting the berm however, particularly as the inlet evolved into a permanent feature.

Tidal inlets can attain positional stability when located in the lee of a headland (Hume & Herdendorf, 1992; Johnston & Orford, 1984) which protects the inlet from erosion and/or longshore sedimentation. The inlet at Manuels, for example, has apparently maintained a stable position for an extended period (cf. Orlebar & Kerr, 1868) due to the protection afforded by Manuels Head. Localized barrier transgression essentially transformed the southwestern corner of Long Pond into a headland (Plate 7.1) that facilitated bypassing of the recessed barrier. The headland effect was accentuated by the decreased longshore flux and by harbour development in the late 1950's.

The evolution of a permanent inlet lends credence to a sustained decrease in the sediment supply. In order for barrier stability to be maintained, the cross-shore drainage requirement must increase as the sediment supply decreases (Carter *et al.*, 1989). Cross-shore drainage was enhanced by an increase in the tidal prism. RSLR can also facilitate the development of permanent tidal inlets (Boyd *et al.*, 1987) and increase the area, depth, and hence the volume of the lagoon, further enhancing the tidal prism. Port development, in particular inlet stabilization and basin dredging, also enhanced the tidal prism by significantly increasing the lagoon volume and the tidal range (Section 9.3). Cross-shore flow was very efficient, indicating that the 1976 and '92 breaches were not manifestations of increased cross-shore drainage requirements but instead related to local processes.

10.3 Barrier Breach, 1976

Segment 2 was breached during an autumn 1976 storm (M. Stavely, *pers. comm.* 2002), opposite the marina (Fig. 1.2). The storm also induced massive sluicing overwash on Segment 4 (Plate 7.5) and cusp-related overwash on Segment 3 (Plate 7.4). A review of files from the *Evening Telegram* revealed that there were five major autumn storms on the northeastern Avalon Peninsula in 1976: October 19th, November 9th, 17th, and 22nd, and December 7th. Boat damage at Long Pond was reported after the October 19th storm.

The 1976 breach exploited the narrowest barachois segment. Segment 2 experienced in-place narrowing as described by McBride *et al.* (1995). The crest position remained stationary while the shorelines on either side retreated. Tidal currents were generated in the channel after the formation of the tidal inlet (Section 7.2) and were enhanced by port development. Barrier overstepping requires a suitable sedimentary basement (Shaw *et al.*, 1993). Channel currents narrowed Segment 2 by removing gravel from the lagoonal apron (Section 9.3), oversteepening and destabilizing the backberm. This precluded the development of a suitable basement for overstepping. Narrowing was exacerbated by RSLR, which raised the bay and backbarrier water levels.

The timing of the 1976 breach was interesting in that it occurred within 3 years of the 1973 inlet modifications (Public Works of Canada 1972; Plate 7.1). Prior to 1973, Segment 1 was lower and narrower than at present (Plates 1.6 b, d). Gravel transported south by current reversals was available for entrainment upon the resumption of longshore transport. The 1973 inlet stabilization infrastructure stimulated the vertical and horizontal accumulation of 6200 to 6500 m^3 of gravel between the inflection point and the northern breakwater (Section 8.2), becoming the most massive barrier segment by 1978. The sudden appearance of this sediment sink stressed the already sediment-poor littoral flux.

Sediment depletion may trigger narrowing of the lower beach as the barrier cannibalizes existing sediments to supplement some or even all deficiencies in the sediment budget (Carter *et al.*, 1989). This can alter the barrier profile, particularly if the sediment supply decreases suddenly (Orford & Carter, 1995). Segment 2 was located directly downdrift of the sediment sink and experienced the greatest amount of cannibalization. Littoral apron narrowing allowed incident extra-local waves to break closer to the berm, facilitating undercutting and avalanching which narrowed, oversteepened, and destabilized the berm. A small increase in surge magnitude could therefore trigger a major barrier crest collapse.

The berm breached after net erosion became horizontal rather than vertical (Fucella & Dolan, 1996), which further narrowed and oversteepened an already vulnerable segment. Gravel was initially drawn down but upon barrier disintegration, the storm surge generated a landward hydraulic head through the breach. Gravel was pushed into the channel and thrown into the yacht club slips and docks. Channel sedimentation was exacerbated by onshore transport by storm-decay swells as well as tidal fluctuations.

Overwashed gravels rendered the tidal channel unnavigable. A second inlet through a barrier beach can induce shoaling in the original inlet due the altered hydrodynamic regime (Friedrichs *et al.*, 1993). Breaching compromised the barrier's effectiveness as a protective structure and altered the tidal circulation patterns. Both problems were addressed by dredging sediment from the channel (Public Works of Canada, 1977). The dredged sediments, which consisted of unsorted silts to small boulders, were used to reconstruct the berm, similar to beach renourishment. In the short term, the yacht club infrastructure was physically protected and the tidal circulation (and navigability) within the lagoon was restored. Although the channel and inlet were dredged during the intervening time, the barrier was effective as a protective structure for the next 16 years.

10.4 Barrier Breach, 1992

The berm breached again on October 6, 1992, damaging yacht club infrastructure and watercraft. Although the storm caused significant damage in CBS (Catto, 1994), it did not stimulate overwashing at Long Pond. This strongly suggests that the breach occurred due to site-specific vulnerability, namely the persistent erosion of the repaired barrier. The large silt fraction impaired berm permeability and responsiveness. The gravel fraction was also emplaced haphazardly and the clasts, because they were not swash-lain, were easily dislodged. Swash, instead of percolating through open-work gravel, was instead confined to the surface. Incident swash energy was expended directly on the berm face, loosening and dislodging surficial sediments. The impaired permeability effectively preserved swash volume which transformed into a massive energetic, gravity-driven backwash. This swung swash asymmetry in favour of the backwash, eroding and scarping the berm. Undercutting induced mass wasting of the bermface. The eroded sediments, instead of being size and shape sorted on the berm (which may have added an element of protection to the structure), were removed to the shoreface. The berm was again repaired with dredge spoil from the channel (Public Works of Canada, 1992),

Table 10.1: Summary of breach stimuli, Long Pond Barachois.

Breach Stimulus	**Tidal Inlet Breach**	**1976 Breach**	**1992 Breach**
Storm Wave Erosion	Yes	Yes	Yes
Overwash[1]	Yes	Yes	Yes
Storm Surge	Yes	Yes	Yes
Backbarrier Flooding	No	No	No
Tidal Lag	No	No	No
Depleted Sediment Supply	Yes	Yes[2]	No
Sediment Cell Border	No	No	No
Barrier Height	Yes	No	No
Barrier Cross-Section	Yes	Yes	Yes
RSLR	Yes	Yes	Yes
Berm Cusps	Indeterminate	No	No
Aspect	No	No[3]	No[3]
Bathymetry	No	No	No
Mainland Topography	No	Yes[4]	No
Planform Geometry	No	No[3]	No[3]
Pre-Existing Inlet	No	No	Yes
Texture	No	No	Yes
Basal Saturation	No	No	No
Permeability	No	No	Yes
Wave Refraction	Yes	No	No

1 Overwash occurred after the barrier crest had been broken down.
2 Localized.
3 While the aspect and planform varied alongshore, they did not trigger the breach.
4 Refers to reconfiguration of inlet stabilization infrastructure.

restoring barrier function and navigability. Erosion problems have persisted.

The October 6 storm coincided with an apogean tide (Canadian Hydrographic Service, 1992) instead of an exceptionally high tide. The storm was an effective erosive agent for several reasons. The apogean tide generated an elevated low tide which, along with the associated storm surge, minimized wave dissipation by the littoral apron and facilitated wave breakage at or near the berm. The low tidal range also focussed storm erosion over a narrow vertical band, enhancing undercutting potential. The remainder of the barachois was sufficiently robust to withstand the storm but the low permeability at the breach site enhanced swash excursion while it was being undermined. Consequently, an extreme storm, regardless of its occurrence in the lunar tidal cycle, is capable of inducing heavy erosion on any low-permeable feature on the CBS shoreline, including the breach site.

10.5 Current Breach Vulnerability and Hazard Mitigation

When the survey was initiated, the breach site was easily identifiable for three reasons:

- the artificial berm had been built marginally higher than the natural berm;
- the texture was haphazard and hosted a high silt content; and
- the entire breach site was heavily scarped.

The berm narrowed at a faster rate than could be accounted for by in-place narrowing, especially since the barrier width had not significantly decreased. Transect 7 represented the most heavily eroded berm segment at the beginning of the study period, characterized by a cusp-shaped arcuate indentation that had nearly eroded through the berm (Plate 10.1

d). This was not a cusp but marked the point where berm erosion was initiated. This carved a topographic low that preferentially attracted swash during subsequent storm and swell events, stimulating a positive feedback loop. Had the correct combination of tide and storm occurred prior to berm reinforcement in January 1998, the berm might have breached again, less than 7 years after reconstruction. Had the berm not been reinforced, it might have breached prior to the completion of this study.

After the January 1998 reinforcement (Plate 10.1 e), storm waves induced noticeable berm erosion by October. Another arcuate erosional scarp formed, the locus of which was less than 1 m north of the pre-reinforcement locus (Plate 10.1 f). This again indicated where erosion initially occurred, and positive feedback mechanisms were stimulated. The remainder of the breach site had scarped as well.

The reinforced berm continued to erode for three reasons: (i) the berm permeability was still impaired, (ii) the gravels were not swash-lain, and (iii) the pre-reinforcement slope face was an erosional contact and the reinforcement gravel was not incorporated into the berm structure but merely rested on the berm at an unstable angle of repose (Fig. 10.3). The texture of the repaired berm will pose problems for years to come.

The breach site behaviour was remarkably similar to the behaviour of gravel beach nourishment schemes at Whitstable and Hayling Island in the U.K. (McFarland *et al.*, 1994). These beaches were nourished with dredged gravels that contained a high percentage of fines. McFarland *et al.* described cliffing of the nourished profile, which was attributed to the presence of a compacted, fine-grained sediment matrix. The cliffing

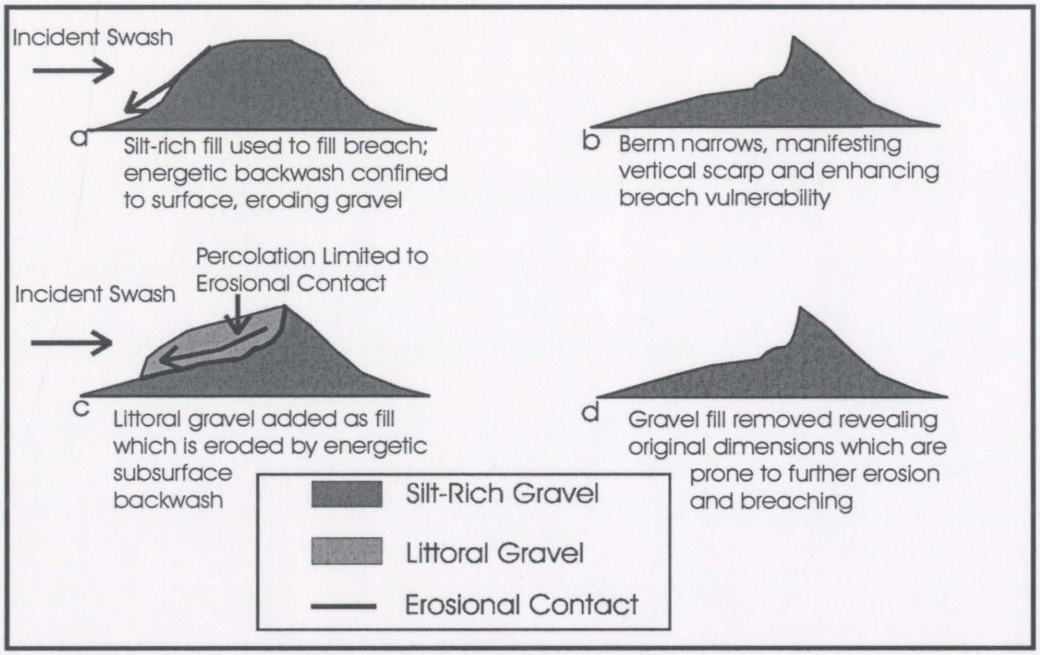


Figure 10.3. Schematic diagram of erosional problems associated with silt rich dredge spoil. Silt-rich dredge spoil was used to rebuild the barrier (a) and proved very prone to erosion, narrowing the berm and posing a breach risk (b). Gravel was borrowed from the adjacent beach to reinforce the berm but was not incorporated into the berm structure. Instead it rested on an erosional contact. Swash percolated through the littoral gravels but again could not penetrate the impermeable silt-rich berm, eroding the loose littoral gravel until the berm was again vulnerable to breaching.

was a manifestation of the low permeability of the matrix, which impaired the capacity to absorb surface water and reduced profile responsiveness to wave attack. Obviously, the presence of a large silt fraction in gravel beach renourishment/reconstruction schemes has a serious detrimental impact on the effective longevity of the project.

Additional sediment inputs to a nourished beach are commonly required due to losses from natural processes (Cooper, 1998) and erosion often occurs because the profile is out of equilibrium with the wave climate (Eitner, 1996). Erosion of the nourished profile is therefore a disequilibrium response, the rate of which decreases as the profile moves towards equilibrium (Leatherman, 1996). While it can be argued that the rebuilt profile at Long Pond was not in equilibrium with the wave climate, breach site erosion narrowed the crest, moving the profile further away from a theoretical dynamic equilibrium. Sand-based renourishment projects typically avoid fine sediments because of their instability and tendency to be winnowed offshore. At Long Pond and in gravel beach renourishment/reconstruction schemes in general, fine sediments apparently have the opposite effect - they impart too much stability which impairs profile responsiveness, rendering the berm vulnerable to continued or even accelerated erosion.

While utilizing dredged sediment to repair the breach was an effective short term solution, over the long term, berm repair has proven to be a temporary solution to a problem that may ultimately be unsolvable. (i) RSLR will continue to drive the erosional front, meaning that the seaward margin of the barachois will be forced east while the backbarrier position at best stalls, and at worst shifts west. In-place narrowing will therefore continue, rendering this segment ever more vulnerable to storm breaching. A potential acceleration in the rate of RSLR due to global climate change may in turn accelerate the process. (ii) The repaired berm was impermeable and has proven very susceptible to erosion. Reinforcement does not rebuild the berm but merely dumps sediment on a steep erosional contact. Rapid erosion will continue.

The majority of beach nourishment strategies have been engineered for sandy beaches (Committee on Beach Nourishment and Protection, 1995). The majority of gravel beach nourishment projects seem to have been implemented on fringing beaches, commonly backed by cliffs or seawalls (Bird, 1996a). The narrow cross-shore dimensions at Long Pond and the unique combination of littoral processes that act on the breach site may preclude any soft engineering solutions other than short term repairs.

Should the barachois breach again, basin circulation would be substantially altered. Alongshore tidal currents in the channel would be replaced by cross-shore circulation, facilitating the development of a sedimentary basement. Altered tidal circulation would also impair current velocity in the original tidal inlet, possibly facilitating sedimentation and impairing port navigability.

In gravel barrier evolutionary cycles, in-place narrowing often precedes overstepping or barrier breakup. Barrier breaches are often symptomatic of this morphological change (Bray, 1997; Orford *et al.*, 1996), and trigger the change by remobilizing sediments near the breach site (Carter *et al.*, 1989). Overstepping in Segment 2 is unlikely, given the low potential for overwash (absence of cusps) and the low preservation potential for basement sediments (due to tidal currents). The 1976 breach may have been the initiation of the barrier breakup phase. Normal evolutionary patterns were stalled by human intervention, namely the breach repair. This has allowed the barachois to retain its protective capacity for much longer than may have otherwise been possible. The barachois breached again 16 years later in 1992. By 1997, the barachois was again vulnerable to breaching, provoking a berm reinforcement response. This response was simple and inexpensive - an excavator drove out onto the barachois and borrowed gravel from the surrounding beach. This gravel apparently eroded during the first major storm.

The next repair will be more complex and expensive. The adjacent berm volume precludes further gravel borrowing. The 1998 reinforcement event also borrowed from the littoral apron. This should not be repeated: (i) While the gravel may be replaced under fairweather conditions, energetic wave events can influence this coastline at any time and a depleted littoral apron would not effectively dissipate incident wave energy, dramatically increasing the risk of accelerated berm erosion and possibly breaching, and (ii) The berm texture is, on average, coarser than the littoral apron texture due to the incident wave power differential. Breach site permeability is already low. If the borrow area is dominated by relatively small clasts, fine to medium pebbles for example, the combination of low permeability and small average clast size would result in rapid erosion of the breach site during energetic wave events.

The dredge spoil (Plate 7.3 b) contains an adequate reserve for at least one repair but hosts a large silt fraction, which has been demonstrated to impair the effective lifespan of reconstruction. The dredge spoil is also located adjacent to a tern nesting site although breaching seems to occur preferentially during the autumn so this may not be a source of concern. The repaired berm, at the conclusion of the study, was too narrow to support an excavator. A ship-based excavator or dredger, with a draught shallow enough to navigate the channel, would have to be employed. This would be costly.

Once the dredge spoil reserve has been exhausted, the situation becomes problematic.

Long Pond is a single-crested gravel ridge and a low available sediment supply is implicit in the morphological expression. Coupled with a relatively small sediment cell, it would probably be unwise to borrow sediment from the shoreface. A sudden decrease in available littoral sediment may destabilize the entire system, possibly leading to catastrophic barrier disintegration. The tidal inlet and 1976 breaches, for example, were linked to decreases in the littoral sediment budget. An external marine sediment source or possibly an inland source will have to be located, further increasing the cost of barrier maintenance. The gravel, if borrowed from a marine source, should be washed over a sluice to remove as much of the fine fraction as possible.

The addition of gravel to the breach site, regardless of the source, will not address the problems associated with the silt fraction already within the berm. If and when the breach site fails again, the priority will again be upon sealing the breach as quickly as possible, which would probably entail dredging the channel for sediment and repeating the mistakes of 1976 and 1992. The problem with rebuilding the berm is that beach nourishment in this particular setting (gravel, narrow ridge, lagoon-backed) has not been well documented. A possible, albeit extremely risky alternative, may be a controlled destruction and reconstruction of the berm. Over the long term, increased stress on the barrier from RSLR, a depleted sediment source, and human activities will trigger barrier breakdown, and barrier function will have to be replaced by a hard engineering structure to maintain the viability of the port facility.

11.0 Beach Cusps

11.1 Apron Cusp Synthesis

Apron cusps were generated by fairweather incident waves aligned approximately normal to the general coastline orientation but slightly oblique at the shoreline. Apron cusps could be stimulated by westerly winds or small extra-local swells refracted into a shore-normal incidence by the adjacent islands. Cusp formation was inhibited when wind waves intersected incident swells. Intersecting wave trains generated constructive and destructive wave interference which inhibited regular swash excursion and thus cusp cell circulation. Intersecting wave trains (Darlymple & Lanan, 1976; Monfort *et al.*, 2000) did not manifest apron cusps at Long Pond. On 11/11/97, for example, cusp formation was restricted to Segment 1, which was partially sheltered from wind waves.

The superimposition of wind waves on background swells can constructively interfere, generating larger, more energetic waves. Masselink & Pattiaratchi (1998a) described this phenomenon as cusp-destructive on sandy beaches but as demonstrated on 15/12/97, on coarse clastic beaches it may stimulate cusp development due to the higher transport threshold of gravel and the inherent inertia. In the absence of swells, shore-normal north-westerly winds could stimulate cusps along the entire barachois, as occurred on 23/02/98.

The slightly oblique incident angle combined with the arcuate beach planform added an alongshore element to cross-shore swash excursion, establishing a primitive circulation cell. This process, referred to as topographic deflection, (Fig. 11.1 e) was superficially similar to sweeping swash (Fig. 11.1 d) but could occur during fairweather and storm

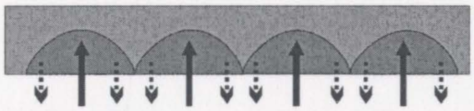
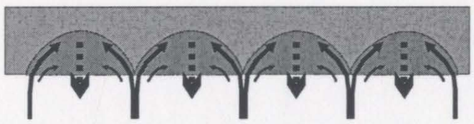
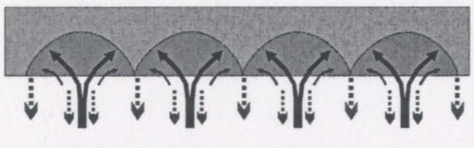
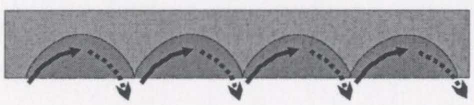
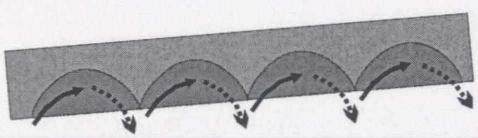
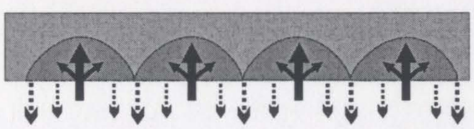
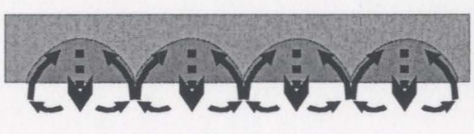
Swash Water Circulation	Description
a) 	**Oscillatory** • Predominantly two-dimensional flow up and down the beach • Weak flow divergence on cusp horns • Weak flow convergence in cusp embayments • Fairweather or waning storm conditions
b) 	**Horn Divergent** • Swash runup is diverted from cusp horn to embayment • In the embayment, flows meet to form a concentrated backwash • Mini rips form opposite cusp embayments • Fairweather or storm conditions
c) 	**Horn Convergent** • Swash runup enters the cusp embayment with the bore front aligned with the embayment contours • Uprush spreads laterally to the horn and forms backwash • Mini rips form opposite cusp horns • Fairweather conditions
d) 	**Sweeping** • Swash runup sweeps obliquely across the beachface • Backwash follows a parabolic arc • Littoral drift is pronounced • Storm conditions
e) 	**Topographic Deflection** • Shore-normal swash deflected by arcuate beach planform • Backwash flows a parabolic arc or recedes through embayment depending on incident wave conditions • Sediment transport in the direction of beach alignment • Fairweather or storm conditions
f) 	**Horn Convergent Swash Jet** • In the embayment, strong backwash retards incoming swash until it has sufficient head to overwhelm the backwash flow and rush up the beach as a narrow jet in the center of the embayment • Swash runup in the form of a swash jet fans out laterally as in (c) • Storm conditions
g) 	**Horn Divergent Swash Jet** • In the embayment, strong backwash retards incoming swash when the cusp circulation period is in phase with the wave period • Interference differential between embayment and cusp horns generates lateral pressure gradients that drive currents towards the cusp horns • Converging flows rush up to the horns as a swash jet and diverge into the embayment as in (b) • Fairweather or waning storm conditions

Figure 11.1. Cusp cell circulation (adapted from Masselink & Pattiaratchi, 1998b).

conditions. The curved planform laterally deflected incident swash in the direction of the shoreline aspect, generating cusp skews that were not pure reflections of the incident

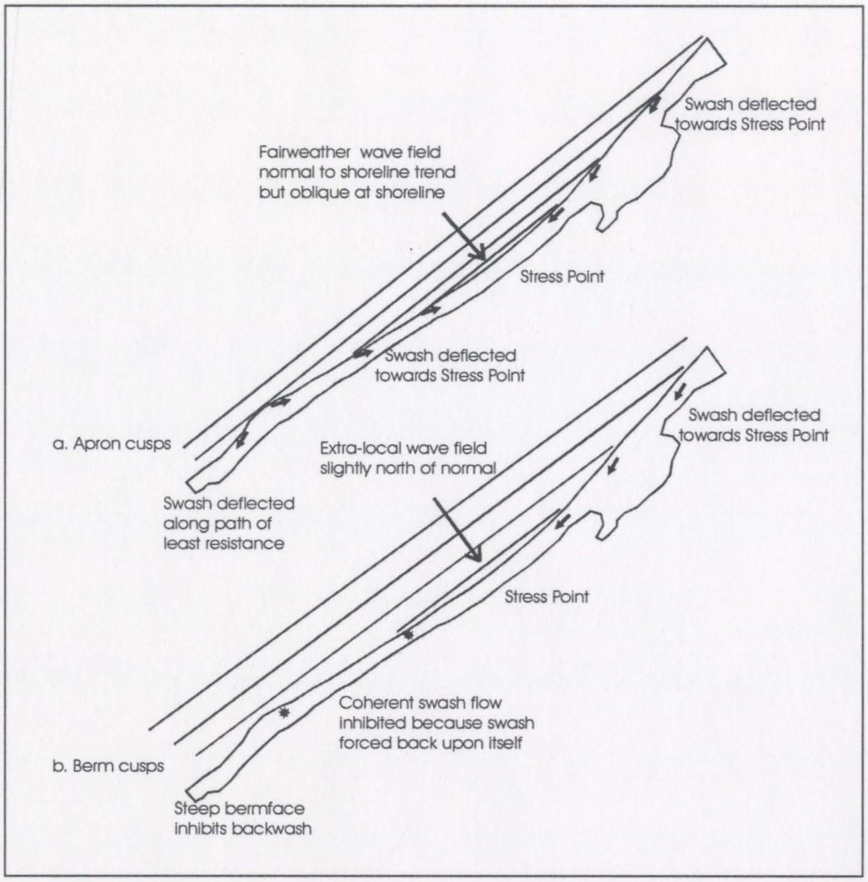


Figure 11.2 a. Fairweather waves are aligned normal to the average shoreline trend. Swash is deflected along the path of least resistance, generating opposing apron cusp skews on either side of the stress point.

b. Extra-local waves are aligned slightly north of shore-normal to the average shoreline trend. North of the stress point, swash is deflected alongshore in coherent circulation cells that generate berm cusps. South of the stress point, swash is forced back upon itself, precluding coherent circulation cells from forming.

wave angle. As fairweather waves broke along Segments 2 and 3, swash was deflected towards the stress point by the curved planform (Fig. 11.2 a). This constituted the path of least resistance while cross-shore momentum persisted. Fairweather waves did not possess sufficient energy to manifest symmetric cusps and the backwash instead receded through the embayment, generating opposing cusp skews on either side of the stress point. Shore-normal waves could therefore generate cusp skews in excess of 15°. Apron cusps were skewed south along Segment 1 and north along the fringing barrier, reflecting the path of least resistance in each case. Cusps were symmetric near the stress point since topographic forcing would have been weak at this point. Over time, cusp circulation evolved to horn-divergent flow (Fig. 11.1 b), as indicated by the eroded cusp horn points (cf. Plate 5.1c). As the tide ebbed, cusp circulation became oscillatory (Fig. 11.1 a).

The variation in apron cusp distribution and morphology at Long Pond indicates that, aside from shore-normal incident waves, cusp development was not governed by a single set of parameters. Surging breakers, which have a weak vertical component, stimulated shallow, flat bayed cusps with depositional horns that could be reverse graded (cf. Plate 5.1 a). The reverse graded horns may indicate that weak swash jets were manifested by differential interference between the cusp bays and the incident swells (Section 11.2.2). This interval was short-lived as the falling tide extended the circulation period, moving it out of phase with the wave period. Plunging breakers have a stronger vertical component and etched deep parabolic erosional cusps into the substrate (cf. Plate 5.2 b). Cusp horns were erosional although the horn tips may have been subjected to limited deposition.

Cusp formation can manifest sediment sorting (cf. Masselink *et al.*, 1997; Sherman *et al.*, 1993) and cusp bay texture is often finer than the cusp horns (Antia, 1987; Chafetz & Kocurek, 1981). This sorting pattern was observed on 15/12/97 (although texture south of Transect 13 was not observed) but did not occur on 11/11/97, which may indicate that textural sorting is stronger when cusp horns are depositional. On 23/02/98, apron cusp bays were sand-dominated from Transects 10 to 13, but were not strongly sorted elsewhere. This suggests that heterogenous gravels do not sort well during erosional cusp formation but sand-gravel sorting can manifest where sufficient sand is available.

Statistical testing did not support the stimulation of rhythmic apron cusps by standing subharmonic or synchronous edge wave templates. Given the difficulty in determining appropriate measurement parameters (Holland & Holman, 1996) and the possibility that the signature may be masked by other processes, edge waves cannot be conclusively eliminated as a potential cusp stimulator at Long Pond without direct hydrodynamic measurements. The edge wave mechanism does appear unlikely, however.

Self-organization emerged as a viable mechanism for apron cusp generation (Fig. 5.2 a). Apron cusps displayed strong self-organizational support because (i) the cusps matured quickly since the volume of eroded gravel was not large (less than 40 m^3), and (ii) swash length was negatively correlated to slope, indicating that cross-shore swash excursion was unimpeded. The wavelength/swash length ratio was positively correlated to slope but although the correlation was significant, it was weak, implying that other controls such as topographic deflection and breaker type influenced cusp development. Percolation was probably minor in comparison to the volume of the cusp circulation cell and probably did not exert a major influence on cusp form.

The self-organization relationship improved when the 15/12/97 cusp, which was formed by plunging breakers, was removed from the dataset (Fig. 5.2 b). Cusp circulation on

15/12/97 displayed elements of weak horn-divergent flow (Fig. 11.1 b) and standing waves at the bay mouth, which are indicative of self-organization (Masselink, 1999; Holland & Holman, 1996). The breaker type therefore exerted a control on cusp morphology and self-organization mechanisms, and self-organization did not consist of a single set of feedback mechanisms but was instead site- and event-specific.

11.2 Berm Cusp Synthesis

11.2.1 Environmental Parameters

Berm cusps were formed by energetic extra-local waves aligned slightly north of shore-normal. Wave refraction and diffraction by Kelly's and Little Bell Island and possibly Bell Island (Fig. 1.5) were probably critical for inducing berm cusp development because the steep shoreface may not have been capable of refracting incident extra-local waves into shore-normal incidence. Plunging breakers etched deep cusps into the berm, which was the most common form observed. Some Segment 4 cusps were characterized by shallow bays with steep floors and may have been generated by surging breakers.

Berm cusps usually occurred in a single tier at a consistent elevation except for the rare occurrence of stacked cusps. The cusp bay nadir approximated local RSL during cusp building, indicating that berm cusps developed during elevated sea levels. Shear stress generated by onshore storm winds can cause water to "pile up" against the shoreline (Coch, 1994). Elevated sea levels occurred when storms made landfall, but storms in the north Atlantic could elevate the water level in Conception Bay without making landfall, as occurred on 15/03/97 (Plate 5.2 c) and 30/11/97 (Plate 6.3 f).

Wave energy expenditure is directly related to the distance from the breaking wave (Kirkgoz, 1995). Berm cusp formation could involve the reworking and removal of more than 150 m^3 of coarse gravel. Reflective morphodynamic conditions were required to transfer sufficient energy across-shore, implying that incident waves broke on or very near the berm. Intertidal structures can induce dissipative conditions during energetic wave events (Carter & Orford, 1993; Forbes *et al*., 1995). At Long Pond, wave dissipation would have inhibited berm cusp development. Wave reflection from a berm can generate pressure gradients that drive offshore currents (Héquette *et al*., 2001), transporting sediment away from the beach. Gravel drawdown from the littoral apron, such as occurred prior to 15/12/97 (Plate 5.1 a), in conjunction with the elevated RSL, may have inhibited wave dissipation at Long Pond during berm cusp building events.

Beaches can exhibit a downward erosional limit beyond which maximum erosional changes become horizontal (Fucella & Dolan, 1996). At Long Pond, this transition was critical in establishing cusp cell circulation. Vertical erosion was controlled by the local RSL which controlled gravel saturation. Saturation limited percolation, preserving much of the swash and backwash volume in the circulation cell. Unsaturated gravels were prone to percolation, particularly as the elevation above and distance from the breaking wave increased. Percolated swash induced clast buoyancy, reducing interclast frictional inertia. Gravels positioned above RSL could be reworked and eroded horizontally.

Overwash fans on Segment 3 (Plates 7.3 e, 7.4) indicated that swash could exceed cusp bay circulation capacity. Under less extreme conditions, the cusp lip does not necessarily represent the swash excursion limit because the upper backwall and, under some conditions, cusp horns can remain subaerial during cusp building. Cusp depths measured up to 3 m which, as indicated by the absence of overwash during the survey period, was above the swash excursion limit. Horizontal erosion occurred primarily by undercutting and avalanching. Incident swash eroded the slope toe, undercutting and destabilizing the open work gravels, triggering gravitational mass movements. Avalanched clasts were initially deposited at the toe of the back- and side-walls. Basal slope deposits can slow undercutting, and hence the rate of erosion (Bray & Hooke, 1997). Waves broke outside the cusp bay and as the swash length increased, progressively less energy was expended on the backwall due to increased frictional and gravitational resistance and enhanced fringe percolation in a process that was ultimately self-limiting in all but the most extreme storms. The coarser fraction of the avalanched clasts often exceeded the transport threshold of the backwash, remaining in the cusp bay as a coarse lag deposit.

There was little statistical support for berm cusp stimulation by standing subharmonic or synchronous edge wave templates. Although the selection of an appropriate beach slope by which to assess cusp genesis is problematic (Holland & Holman, 1996), the magnitude of the discrepancy between measured and derived wavelengths (Table 5.6) may imply that the statistical tests described by Inman & Guza (1982) are not applicable beyond some slope threshold that was exceeded at Long Pond. In addition, many field measurements used to assess cusp development relate to the cusp horn apex (Fig. 3.3).

Since much of the berm cusp bay erosion at Long Pond occurred by undercutting and avalanching, the horn apex often remained subaerial during cusp-building and did not represent swash height. Erosional cusp horn height may not be an appropriate benchmark by which to assess cusp genesis via edge waves. Depositional horns were submerged during formation and may be viable process indicators. Edge wave theory does not account for depositional horns (Masselink *et al.*, 1997), which again may render the use of horns in edge wave assessment problematic at Long Pond. The edge wave signature may also have been masked by other formative processes.

Of the six tests conducted, only the 21/03/97 dataset supported the self-organization mechanism (Fig. 5.4 b) despite the inclusion of 21/03/97 cusps in other datasets. During their formation on 15/03/97, cusp cell circulation displayed qualitative elements of self-organization, notably horn-divergent circulation (Masselink, 1999) and standing waves at the embayment (Holland & Holman, 1996).

The difficulty in linking Long Pond berm cusps to a statistical model was related to the variability in cusp form. Cusp wavelength, swash length, and depth varied alongshore per survey and per location over the survey period (Fig. 5.3 a, b, and c respectively). Swash length did not correlate well with beach slope (Table 5.3). The wavelength/swash length ratios, which self-organization theory holds should range from 1 to 3, instead ranged from 1 to 6 (Fig. 5.3 d). While many cusp horns were obviously erosional structures, some were obviously depositional in origin, and some of these were reverse graded.

Orford & Carter (1984) contended that non-rhythmic cusp spacing on coarse clastic beaches may be attributable to the variation of wave energy in a storm spectrum which may be so chaotic that the chances of developing a single clearly defined edge wave are low. Instead, a series of overlapping stationary and progressive edge waves dependent on the rapid shift of incident wave periods which normally appear in a storm may occur. This would generate a complex morphology not readily decomposed into a single wavelength. It was not possible to determine whether this occurred at Long Pond. It is critical to note that on 15/03/97, under decidedly non-chaotic conditions, there was significant variability in the alongshore swash excursion length (cf. Plate 5.2 a, f), which was reflected by the variability of cusp form recorded on 21/03/97. Not only was there no mechanism to excite a broad spectrum of edge wave frequencies but, as discussed below, there was strong evidence that edge waves did not occur at all at this time.

Cusp formation is non-linear and may be dependent upon the sequence of input conditions rather than on the statistics of such conditions (Coco *et al.*, 2001). Neither the edge wave nor the self-organization models incorporate avalanching, topographic forcing, or cusp maturity within the formative models. Neither theory explains berm cusp distribution at Long Pond either. Cusp formative mechanisms, for berm cusps at least, must therefore be inferred from non-quantitative morphological signatures.

11.2.2 Berm Cusp Evolution

Many berm cusps observed at Long Pond were erosional structures. Cusp horns were remnants of the original berm and reflected the antecedent slope and texture. Erosional cusps were observed on a sandy beach at Duck, North Carolina during the initial stages of cusp formation (Miller *et al.*, 1989). This suggests that erosional berm cusps at Long Pond represented an early stage of cusp development. Holland (1998) observed that cusp formation that was associated with energetic incident waves and storms, whereas other authors including Antia (1989), Masselink *et al.* (1997), Miller *et al.* (1989), and Rausch *et al.* (1993) observed that cusps developed as incident energy waned and the morphodynamic regime became dominated by swells. The sheer three-dimensional size of the Long Pond cusps and the coarse texture suggested that cusp formation required prolonged exposure to incident swash. Swash exposure was temporally limited due to the supratidal cusp position, suggesting that cusp initiation began in the early stages of the storm. Cusp growth was partially controlled by rising water levels and storm intensity.

Topographic deflection (Fig. 11.1 e) stimulated berm cusp formation at Long Pond. North of the stress point, the arcuate planform deflected incident swash laterally from north to south (Fig. 11.2 b) until a loss of momentum due to frictional and gravitational resistance diverted the swash seaward as backwash. This facilitated a coherent across-shore and alongshore flow pattern that accentuated the transformation of energetic swash into energetic backwash and eroded a shallow (> 3:1 wavelength/swash length ratio) symmetric cusp form. The erosional form was often preserved at Long Pond by waning hydrodynamic conditions or tides and many cusp measurements represented immature cusps. Swash excursion was therefore not simply related to cusp spacing and wavelength/swash length ratios could vary alongshore and vary over time (Fig. 5.3 d).

Given the surface roughness of Long Pond barachois, it seemed unlikely that cusps were generated at random depressions, as per Werner & Fink (1993). Cusps probably formed where slightly oblique incident waves contacted the berm, scouring the substrate. The scour attracted subsequent swash, enlarging the depression until a coherent cusp cell could form. While this process could theoretically have been assisted by an edge wave template, edge waves are oriented perpendicular to the incident wave field (Carter & Orford, 1993). Incident extra-local waves were oriented slightly north of normal, implying that edge waves would be aligned south of normal. The elevated hydraulic head associated with edge wave activity would have a tendency to direct swash south of normal, inhibiting lateral swash deflection north of the stress point and enhancing it to the south, possibly facilitating cusp cell circulation. This strongly suggests that edge waves were not a factor in cusp formation at Long Pond. The elevated cross-shore hydraulic head associated with edge wave activity would also not stimulate cusps characterized by large wavelength/swash length ratios (Fig. 5.3 d).

Cusp spacing was variable for a number of reasons. The angle at which swash deflected alongshore varied due to the arcuate beach planform and local variations in the incident wave angle associated with chaotic storm conditions which could also change the relative angle of wave incidence while the cusp formed. The main reason for the variation in cusp spacing was related to the north to south topographic swash deflection. The northernmost cusp developed without significant external interference (Fig. 11.3). As swash was deflected laterally southward, the backwash from a northern cusp interfered destructively

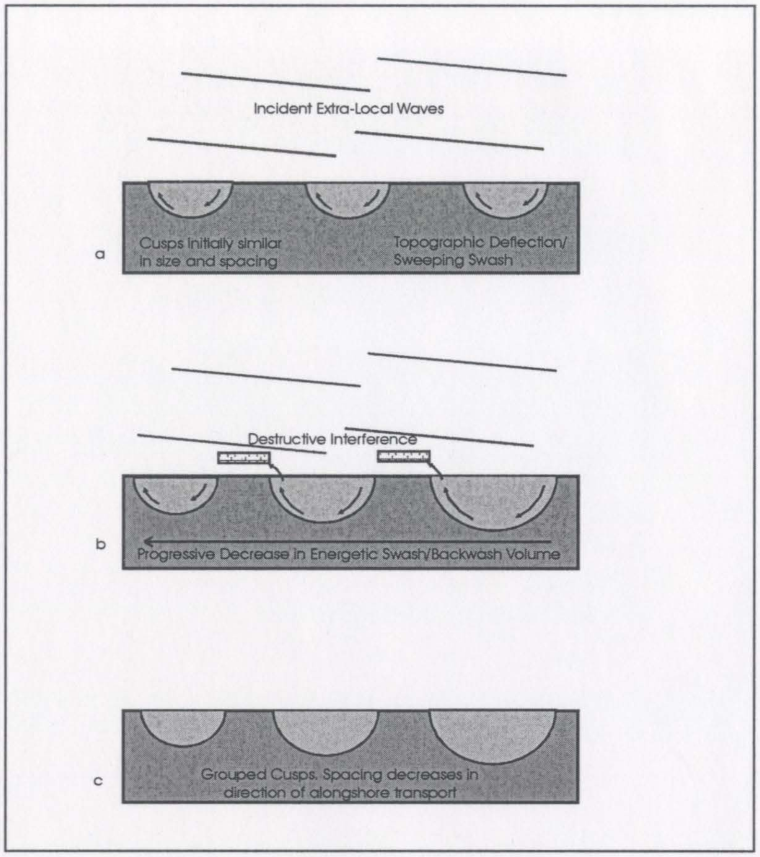


Figure 11.3. Schematic diagram of cusp grouping. Slightly oblique incident swash is topographically deflected, initially generating similar cusps (a). Backwash from the northern cusp destructively interferes with adjacent cusp circulation, reducing incident energy and cusp growth (b). This occurs progressively until incident swash energy is depleted, facilitating deposition at the southern end of the cusp group. The net result is a discrete cusp group with spacing that decreases from north to south.

with the swash moving into the adjacent southern cusp. Cusp spacing is related to the magnitude of the incident swash energy (Dubois, 1978). At Long Pond, the weakened swash carved a smaller, shallower cusp, which in turn interfered with its southern neighbour, perpetuating southward until the swash was weakened to the point at which it could no longer form a coherent cusp cell, resulting in net deposition on the berm. This

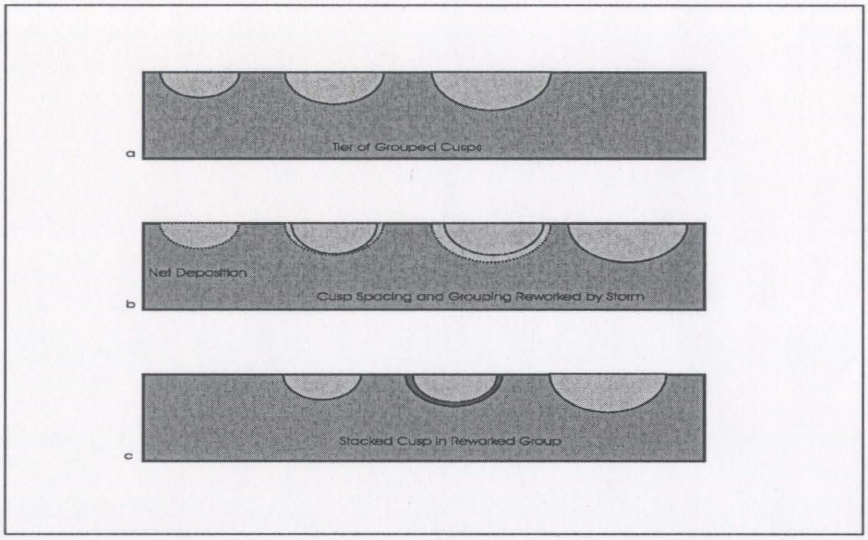


Figure 11.4. Schematic diagram of cusp stacking. A cusp group persists (a) until a subsequent storm establishes a new spacing (b). Cusp stacking occurs when a small cusp evolves at a site occupied by a larger one from a previous event (c). The circulation cell does not completely rework the larger cusp preserving an "upper" cusp.

formed a distinct group of non-rhythmic cusps. The pattern was repeated further south, beyond the influence of backwash interference from the adjacent northerly group.

Cusps can be destroyed and replaced with new cusp tiers during subsequent storms (Seymour & Aubrey, 1985). Stacking occurred when new cusp spacing was not in phase with the antecedent spacing and a small cusp evolved within a larger antecedent cusp bay (Fig. 11.4). The new circulation cell did not completely rework the larger cusp, preserving a truncated "upper" cusp. Stacked cusps occurred in groups of ones and twos, forming where the southern margin of a cusp group was superimposed upon the northern margin of a previous group. Stacked cusps did not form where the new cusps completely reworked the previous cusp form. Phase differences were probably responsible for the instances where berm cusps were skewed north. The development of a new cusp tier out of phase with a pre-existing tier could generate a northern skew when the previous cusp bay was positioned just to the north, providing a low-resistance pathway for swash.

Berm cusps did not occur on Segment 2, despite the similarity of the slope with Segment 3 and the potential for Kelly's Island to refract waves from the head of the bay into a shore-normal approach pattern. The absence of berm cusps indicated that fetch limitations precluded berm reworking by locally generated waves and also precluded the intersecting wave train mechanism (Darlymple & Lanan, 1976; Monfort *et al.*, 2000) as a possible berm cusp-generating mechanism at Long Pond. During extra-local wave events, the planform deflected swash (which was aligned slightly north of shore-normal) back upon itself, dissipating swash momentum and preventing coherent cusp cells from forming. Segment 1 was aligned parallel to Segment 3 but did not support berm cusps. The high, steep berm slope enhanced percolation, precluding the establishment of an energetic coherent backwash and the erosion of an embryonic cusp bay.

As topographically deflected flow carved the berm cusp bay, the depression began to preferentially attract incident swash. Cusp cell circulation evolved from topographic deflection to shore-normal horn-divergent flow, representing a transition from an immature to a mature cusp and the onset of self-organization processes. It is important to note that the change in circulation pattern was induced by the evolution of the cusp form and not by a changing hydrodynamic regime. Cusp maturation could occur during a single storm if it was of sufficient duration. Forbes *et al.* (1995) and Holland & Holman

(1996) observed that cusps may act as templates that stimulate subsequent cusp development. The coarse clastic texture at Long Pond lent an inherent stability to the cusp form, such that the cusp could be reworked during subsequent smaller storms (large storms could obliterate and replace the cusp field) or by large swell events (as occurred on 15/03/97), even if it had partially matured during the formative event.

Horn-divergent flow (Fig. 11.1 b) is typical of steep reflective coarse clastic beaches (Sunamura & Aoki, 2000) and is indicative of cusp self-organization (Masselink, 1999). During horn divergent flow, swash deflected by adjacent horns meets swash flowing into the cusp bay at the backwall, forming a massive energetic backwash that erodes the cusp bay (Masselink *et al*., 1997). Cusp reworking increased the swash length because the cusp bay provided a low-resistance pathway to the backwall. Waves broke outside the cusp and as the swash length increased under horn divergent flow, progressively less energy was expended on the backwall due to enhanced fringe percolation. Cusp growth was ultimately self-limiting unless tides, storm surge or storm intensity increased over time, and the cusp acted as a conduit for washover (cf. Plate 7.4).

Horn-divergent flow had little impact on berm cusp spacing. Cusps evolved into semicircular forms with wavelength/swash length ratios between 1:1 and 3:1, given sufficient exposure to swash. Cusp maturation did not occur uniformly alongshore. Cusp growth is triggered when the swash volume exceeds the bay volume, impairing its capacity to circulate swash and backwash (Seymour & Aubrey, 1985). Berm cusp spacing was non-rhythmic and consequently, the capacity to circulate swash varied despite similar hydrodynamic conditions. Whereas a large cusp could circulate incident swash without significant erosion, more or less preserving the wavelength/swash length ratio, the same swash volume would exceed the circulation capacity of an adjacent smaller cusp, forcing it to expand through erosion of the backwall, extending the swash length and reducing the wavelength/swash length ratio. This accounted for the variability in the wavelength/ swash length ratios within a single cusp tier (Fig. 5.3 d) and the poor correlation with beach slope (Table 5.3). Where the cusp volume exceeded the swash volume, swash deflected along the cusp walls collided and decelerated, decreasing the sediment transport capacity and depositing a triangular structure (Plate 5.2 g, h; Flemming, 1964).

The cusp horn apex could remain subaerial during horn-divergent flow and persist as an erosional structure, although deposition occurred lower on the horn. Depositional horns occurred when the horn apex was submerged. Incident swash eroded surficial sediments, leaving an erosional core. Depositional horns form when backwash was concentrated in the bay and minimized on the horn, promoting deposition and vertical construction as the backwash recedes (Masselink & Pattiaratchi, 1998a). At Long Pond, depositional horns were characterized by gentler slopes and distinct grading as compared to the adjacent berm. Textural grading was a function of the available sediment supply and the transport capacity of the incident swash under most horn-divergent flow conditions.

Horn-divergent swash jets (Fig. 11.1 g) were observed on 15/03/97 (Plate 5.2 c, d) when swells reworked a pre-existing cusp tier (Plate 5.2 a). The swash jets were triggered by interference between incident 2 m swells and massive energetic cusp backwash. Wave

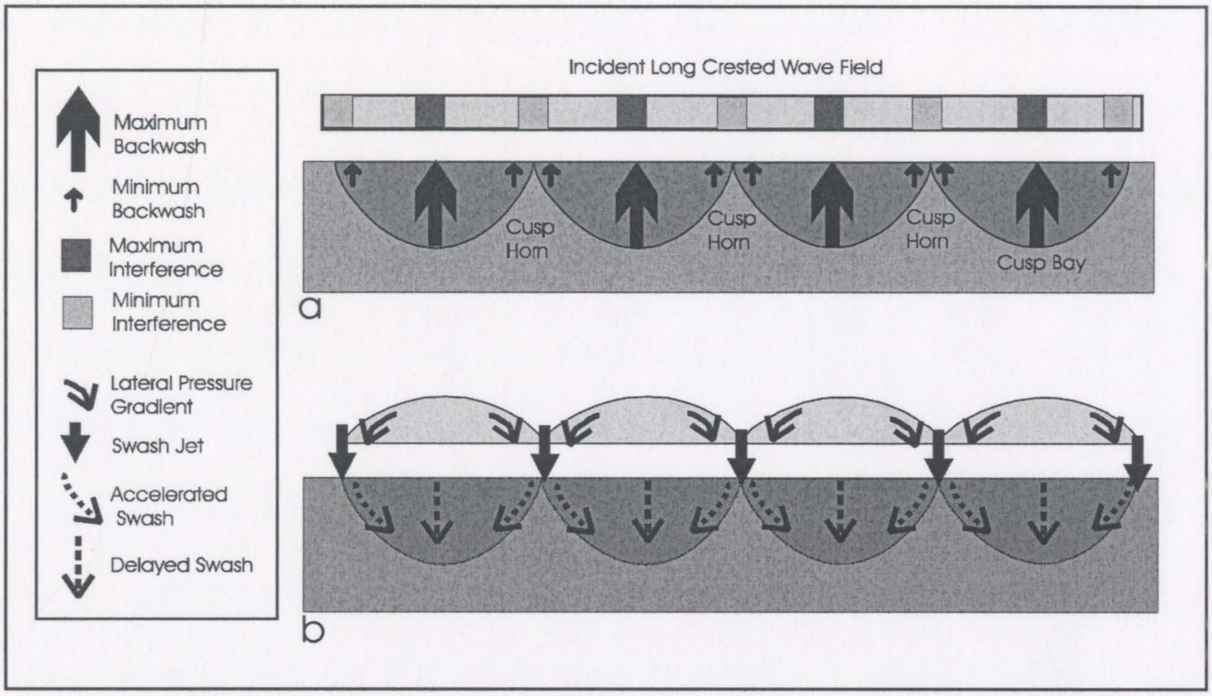


Figure 11.5. Schematic diagram of swash jet generation. Differential backwash volumes generate differential interference with incident waves when the cusp cell circulation period is approximately in phase with the wave period (a). This stimulates lateral pressure gradients which accelerate flow towards the interference minima (b). The interference minima direct converging flows cross-shore as swash jets, centred on the horns. Swash in the bay is sluggish and lags behind the jets, facilitating an energetic backwash that induces cusp bay erosion.

interference occurred on a massive scale and generated alternating zones of interference maxima and minima, coinciding with cusp bays and cusp horns respectively, when cusp cell circulation was in phase with the wave period (Plate 5.2 c).

As berm cusps matured under horn-divergent flow, the cusp cell circulation period was initially shorter than the incident wave period and backwash energy dissipated prior to wave breakage. As the swash length increased, the circulation period increased, moving the circulation period into phase with the wave period. Wave interference was maximized at the cusp bay mouth because the large cusp volume facilitated a massive backwash, and minimized at the horns due to a low backwash volume (Fig. 11.5 a). The differential wave interference created lateral pressure gradients (Fig. 11.5 b). Incident kinetic energy propagated along the gradient, accelerating the flow towards the interference minima. Lateral flows converged at interference minima and quickly overwhelmed the backwash, stimulating a very energetic cross-shore swash jet. The swash jet became progressively more energetic as the cusp circulation period and incident wave periods moved closer into phase. The accelerated swash jet submerged the horn (Plate 5.2 e), diverging to either side, and eroded surficial gravel, leaving a streamlined gravel core. The remainder of the cusp circulation consisted of a typical horn-divergent flow pattern. Wave interference persisted until the swash waned due to reduced incident energy, falling tide or relaxation of the storm surge. This represented the most mature phase of cusp evolution.

Standing waves generated by interference between swash and backwash at the cusp mouth have been described by Antia (1987), Holland & Holman (1996), Longuet-Higgins & Parkin (1962), Masselink *et al.* (1997), Orford *et al.* (1991), and Rausch *et al.* (1993). On shallow cusps, typical of sandy beaches, the backwash is not as massive as occurred at Long Pond. Pressure gradients, and therefore flow accelerations, generated by shallow cusps would be much weaker and could not form swash jets. There may however, be more subtle flow accelerations on the horns that are not easily detectable.

Long Pond swash jets were similar to swash jets described by Masselink & Pattiaratchi (1998b), based upon observations by Eliot & Clarke (1986) who described swash jets at the centre of the cusp bay mouth (Fig. 11.1 f). Although cusp circulation was horn-convergent, a significant backwash would have drained from the embayment because of its lower elevation. In order to generate swash jets at the interference maxima, subharmonic edge wave antinodes were probably superimposed on the incident wave field. Edge wave templates constructively interfered with incident waves, superelevating the hydraulic head at the centre of the embayment. These energy "spikes" directed flow across-shore instead of laterally along the pressure gradients. The edge waves may have stimulated cusp formation or the cusp field may have stimulated the edge wave frequency by controlling nearshore circulation, as described by Sherman *et al*. (1993). The pattern of swash jet activity at Long Pond indicated that standing edge waves did not develop on 15/03/97 and horn-divergent swash jets were therefore indicative of self-organization.

Reverse graded horns observed on 21/03/97 were generated by the 15/03/97 swash jets. The wave interference differential increased as the cusp circulation period and the incident wave period moved closer into phase, progressively increasing the velocity and transport threshold of the swash jet. The swash bedload became coarser over time. The coarsest clasts fell out first while the increased velocity transported progressively coarser clasts beyond the horn. Progressively coarser clasts accumulated on the horn, which accreted in a reverse graded sequence. As the cusp cell circulation and incident wave periods moved out of phase, the swash jets weakened, particularly when the transition was associated with waning energy conditions or a falling tide. The reverse graded sequence, which represented the most mature phase of cusp evolution, was preserved until the next storm or swell event. This mechanism is superficially similar to the temporal increase in particle size described by Hand (1997), although the temporal aspect of the sediment supply in that study was attributed to slower transport rates typical of coarser clasts in an extended flow setting. Although shallow cusps would not form swash jets, flow accelerations on the horns might be capable of inducing reverse grading of sands.

Reverse grading has also been attributed to dispersive pressure (Legros, 2002) or lateral migration of the horn over an adjacent bay or vertical growth of the horn sequence (Chafetz & Kocurek, 1981). Dispersive pressure sorting involves the separation of large particles away from a solid boundary because of the action of the dispersive pressure existing in a rapid granular flow (Legros, 2002). Swash jets were a series of brief, spatially limited flows which were probably not conducive to dispersive sorting. Lateral migration of the horn across finer bay sediments would have been reflected by an abrupt structural transition between the lower bay sediments and the horn sediments (Chafetz & Kocurek, 1981). This pattern was not observed at Long Pond. Berm cusps displayed no evidence of positional migration, not surprising given the limited size of the development zone. Furthermore, there were instances where the cusp bay consisted primarily of very coarse lag deposits. Simple vertical accretion of the horns would apparently increase the slope, permeability, and coarseness of the horn as it aggraded, presumably generating a coarsening up sequence (Chafetz & Kocurek, 1981). The reverse graded horns at Long Pond were noticeably coarser than the surrounding berm which was a much larger depositional structure. A simple vertical growth mechanism was therefore unlikely.

12.0 Ice Processes

12.1 Sea Ice and Icefoot

Between 1983 and 1996, Conception Bay usually experienced heavy winter ice cover (Table 1.2). The lack of sea ice cover during the study period was atypical. There was no opportunity to directly observe the impact of sea ice on barrier morphology, but the lack of preserved ice-push and ice-lift structures suggested that if these features developed, they were quickly reworked. A recent survey of the southeastern Conception Bay shoreline did not document ice-push or ice-lift features (Paone, 2003), implying that ice did not exert a significant control on coastal morphology or that the influence was subtle.

Wind wave development can be severely inhibited by heavy concentrations of sea ice (Forbes & Taylor, 1994). The influence of pack ice on Long Pond Barachois may have been limited to dampening of incident extra-local wave energy. Wave dampening could occur within Conception Bay during heavy ice years, but would have been confined to the adjacent continental shelf during the study period.

The 1992 barrier breach was preceded by an extremely heavy ice season (DeYoung & Sanderson, 1995). Nearshore ice cover can promote hydrodynamic shoreface scour, which may manifest a profile adjustment (Barnes *et al.*, 1994; Forbes & Taylor, 1994), enhancing breach vulnerability. While heavy ice cover may have steepened the shoreface profile in the short term, littoral sediment flux during the intervening 5 - 6 months probably allowed the shoreface to recover prior to the October breach.

An icefoot can dissipate incident wave energy and lock sediment in place, protecting the beachface (Forbes & Taylor, 1994). The 1997 littoral icefoot at Long Pond appeared to have accreted *in situ* (Plate 6.4 d, e), as there was little to no pack ice that could have been stranded above the water line. The icefoot was vertically scarped (Plate 6.4 d, e) by wave-induced thermoerosion. Icefoot scarping has little to no morphological expression on the subaerial beach profile but the vertical ice face can amplify wave reflection. Barnes *et al.* (1993, 1994) asserted that wave reflection induced shoreface erosion at Lake Michigan, releasing sediment into the littoral zone. A vertical icefoot may have induced shoreface erosion at Long Pond but scour features were not preserved due to their proximity to the shoreline and the energetic, wave dominated nature of the barrier. Milder conditions in winter 1998 were not conducive to littoral icefoot development (Plate 6.4 f).

12.2 Lagoon Ice

Despite minor variations in basin salinity (Christie, 1966; Wells, 1974), winter ice cover was restricted to the northern basin and the inner reaches of the southern basin during the study period (Fig. 6.3). Ice formed when water temperatures fell below -2° C, the freezing point of salt water. Ice cover was influenced by the degree of shelter from waves and currents and by the bathymetry, which controlled the rate of water column cooling.

The northern basin was shallow (Fig. 1.2) and was sheltered from Conception Bay. The water column cooled rapidly because of the shallow depth and little water column mixing. The low energy environment also inhibited wave-induced erosion and dispersion of the ice surface. Strong currents inhibited ice cover in the tidal channel. The port facility, which was exposed to Conception Bay and dredged to 8 m in depth, was ice-free during the study period. Water column cooling was inhibited by wave- and tide-induced mixing (cf. Plate 1.1 a - c) and by the basin depth. The inner southern basin was sheltered and was not dredged, which facilitated a thin ice cover. The absence of shoreline armouring suggested that tidal ice fluctuations did not induce significant erosion.

A thin icefoot, stranded by falling tides, was perched along the entire backbarrier during the winter of 1997 (Plate 6.4 a). The icefoot exerted little influence on backbarrier morphology, in part because the icefoot was thin and poorly developed, and in part because backbarrier sediment transport was limited (Section 9.3).

Local wind waves may have induced some shoreline erosion in the northern basin, but ice-lift scour was a more effective erosional agent. The loss of the NLGS benchmark in the sub-basin graphically illustrated the potential influence of ice-lift. Port development enhanced the tidal prism and probably accelerated ice-lift erosion to the point where property armouring was necessary (Section 8. 4). Ice-lift also eroded eastern Burnt Island. The adjacent shore platform was up to12 m in width, indicating the island's former dimensions. Most gravels on the platform were angular and subangular, indicating that there had been little reworking subsequent to deposition. These clasts were lag deposits derived from bluff erosion and indicated that locally-generated waves were not an important erosive element. The greatest amount of erosion appeared to have occurred between 1966 and 1974 (Plate 7.5). Inlet dredging enhanced tidal exchange in the basin. Accelerated shoreline erosion occurred in response to the greater tidal range, increasing the basin capacity to accommodate the new tidal regime. While most of the erosion was probably ice-related, the tidal adjustment was probably sufficient to induce some local wind wave erosion due to the elevated water levels. Erosion slowed as the basin grew to the point at which it could accommodate the new tidal regime.

Rapid erosion was indicated by exposed tree roots, and undermined and toppled trees (Plate 6.3 a). Ice usually undercut the bluffs but occasionally, during spring tides or storm surges, ice-lift may have scoured the entire bluff face. Landslide deposits, associated with undercutting (Quigley *et al.*, 1977), were not observed, suggesting that the sediments were removed by ice or locally generated waves. Small alluvial and talus fans indicated that overland runoff and viscous grainflow accounted for minor erosion, but were probably incapable of inducing vertical scarping or undermining trees (Wilcock *et al.*, 1998). The discrete, poorly sorted gravel ridges on the platform (Plate 6.3 b) were ice-related. Ridges are usually associated with wind-assisted ice-push (Forbes & Taylor, 1994; Gilbert, 1990) but the quiescent conditions precluded wave action and the ridges were ice-lift features.

Isolated well-rounded clasts were interspersed with the *in situ* platform gravels (Plate 6.3 c) and amongst tree roots on the island (Plate 6.3 d) up to 2 m asl. None were observed beyond this elevation but moss and understorey cover were extensive. Local waves and currents were incapable of transporting gravel from the barrier to eastern Burnt Island and overwash could not transport gravel more than 100 m through thick forest cover. The early 20th century gravel mining operation was focussed on the western margin of the island and it seems unlikely that gravel would have been deliberately transported to the eastern island in such small quantities and then scattered haphazardly.

The well-rounded clasts were probably ice-lifted. Basal adfreezing can transport pebbles and cobbles (Dionne, 1993; Forbes & Taylor, 1994) and may have transported small amounts of gravel from the sub-basin shoreline. During spring thaw, winds and weak tidal currents moved ice out of the sub-basin. Some ice was stranded on the platform, depositing the sediment load. The scarcity of well-rounded clasts suggested that this did not occur frequently. Ice-lift deposited gravel on the island itself. Ice-thrust has been observed to deposit beach clasts inland with little to no damage to the surrounding vegetation (Pyökäri, 1981). Stranded ice was under-ridden and lifted by more ice. The process may have been repeated several times until ice was stranded above the shoreline, depositing well-rounded clasts amongst the tree roots.

The massive overwash fans deposited in the sub-basin during 1976 were reworked and smoothed prior to backbarrier armouring (Plate 7.5). Fetch limitations precluded wave-induced transport. Ice-lift smoothed the backbarrier and reduced the slope, drawing sediments toward the lagoon. Ice-lift therefore provided an important component of barrier widening subsequent to overwash. The northern juncture of the barrier and Burnt Island focussed ice across-shore, generating a flatter slope. Shoreline armouring has modified ice processes in the sub-basin but may be prone to undermining through the cumulative impact of tidal variations in pressure, complemented by a large cold surface upon which ice can freeze. These fluctuations may in effect rock the riprap clasts back and forth and eventually destabilize them, increasing the cost of road maintenance.

South of Burnt Island, ice-lift exerted a comparatively minor influence, in part because of the influence of tidal currents and/or wave action and in part because the basin was not as confined as the sub-basin and the same pressure was not exerted against the shoreline. Steep backberm slopes limited the cross-shore extent of ice-lift to the intertidal zone and any resultant structures, if they formed, were not preserved. The southern juncture of the barrier and Burnt Island (Transect 12), like its northern counterpart, focussed ice across-shore, but generated a wider, steeper lagoonal apron (Fig. 4.12).

12.3 Interstitial Ice

Interstitial ice was observed in Segment 1 (Plates 6.4 e, f). Interstitial ice development in Long Pond Barachois was closely tied to local climatic conditions and berm texture and volume. Interstitial ice developed in open-work gravels due to their permeability and ample pore space. The large, cold clasts were nuclei for ice development (Fig. 12.1). A prolonged cold period cooled the gravel complex to ambient atmospheric conditions. The cold period was probably followed by alternating freeze-thaw periods. Gravels buried in the interior of high, wide berms were insulated by the surrounding clasts and did not experience rapid temperature changes. During brief thaws, exposed gravels warmed above 0° C, but internal clasts remained below freezing. Precipitation or snow melt percolated to the colder buried gravels and froze, forming an impermeable layer which grew as subsequent percolation was trapped and frozen. The interstitial ice may have been augmented with swash spray when temperatures were below -2° C , although there was no

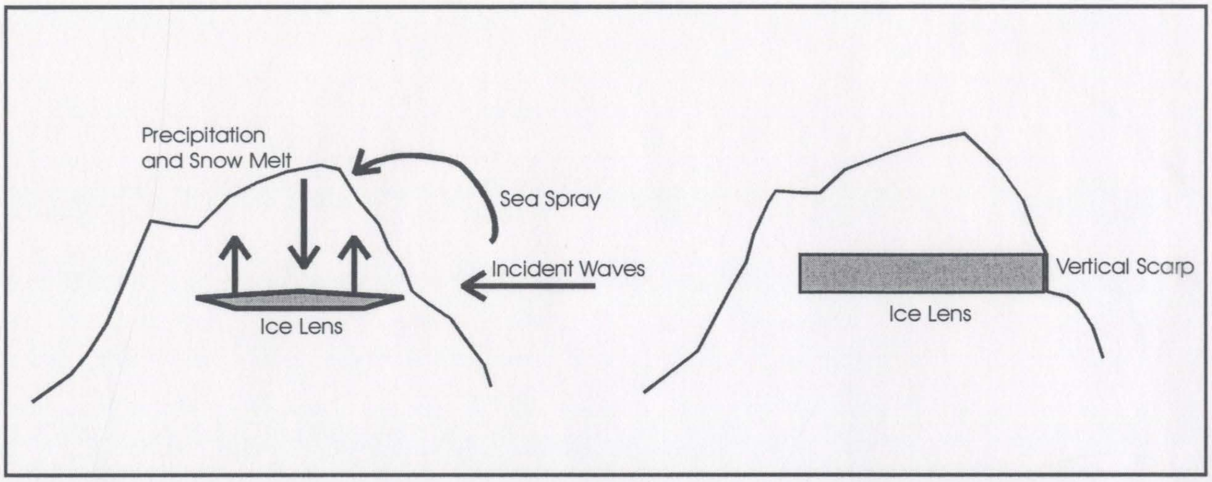


Figure 12.1. Schematic diagram of interstitial ice development. An ice lens forms when the interior barrier cools to the point where clasts act as nuclei for ice development. Precipitation, snow melt and possibly sea spray percolate to the lens, which grows vertically, forming an impermeable three-dimensional structure that locks gravels in place. Incident waves thermoerode the side of the lens, producing a vertical scarp that persists until the ice melts.

evidence of salt rejection from the ice.

Interstitial ice was exposed in near-vertical scarps on the bermface (Plate 6.4 d). Scarping was manifested because: (i) the ice body acted as a temporary sediment matrix, holding the gravel above the normal angle of repose, and (ii) the ice body was a three-dimensional impermeable structure and incident wave energy was expended directly on the surface, physically and thermally eroding the bermface.

The ice matrix disintegrated as the interstitial ice thawed. Gravel which had been held at a near-vertical angle was released and the berm face retrograded in response. The volume of gravel released was dependent upon the alongshore and vertical ice dimensions. Slope adjustments may have extended a short distance beyond the limit of

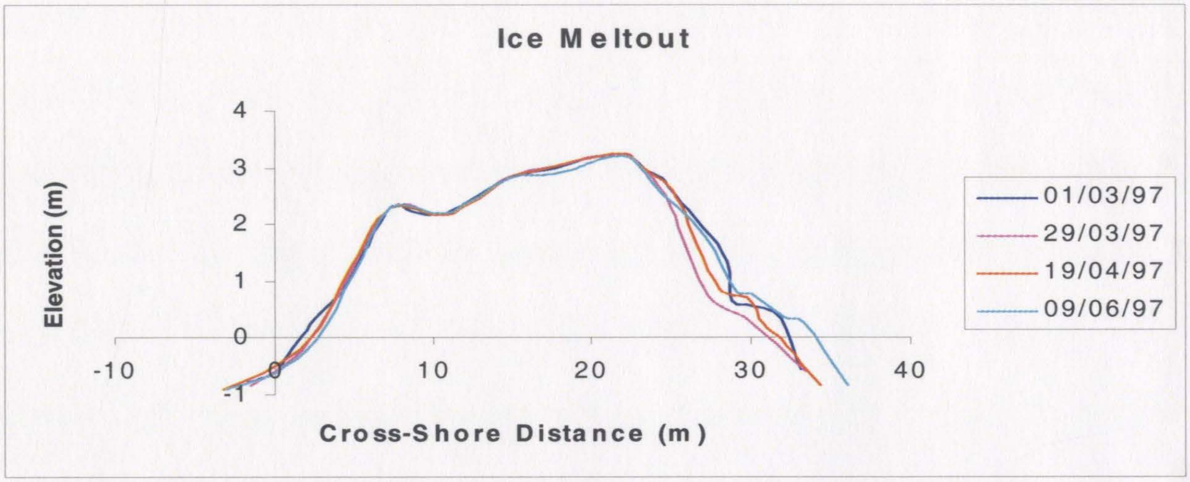


Figure 12.2. Interstitial ice-related scarping of the bermface (01/03/97). The bermface retreated after the interstitial ice melted before 15/03/97 but had recovered by 09/06/97.

interstitial ice development as meltout may have destabilized the adjacent bermface. The thickness of the interstitial ice body influenced the magnitude of the slope adjustment. A small scarp generated a large berm height-to-scarp ratio. Although meltout could undermine overlying gravels, a relatively small volume would have been released into the littoral zone since a smaller slope adjustment to the angle of repose was required. A large scarp generated a smaller berm height-to-scarp ratio. A larger volume of gravel could therefore be released into the littoral zone since a larger slope adjustment to the angle of repose was required. The adjustment may have been sufficient to influence the position of the crest lip and hence berm position, at least in the short term. The scarps observed at Long Pond were up to 0.7 m in height, as compared to berm heights of 2.5 to 3 m (above the littoral apron). The berm height-to-scarp ratio (approximately 4:1) proved insufficient to stimulate a major adjustment and the bermface recovered by June (Fig. 12.2).

The preservation potential of meltout gravels depended on the subsequent wave climate and tidal regime. Meltout structures may have been preserved under quiescent conditions, particularly near neap tide. Energetic conditions and/or high tides could rework and possibly remove meltout gravels. At Long Pond, post-meltout morphology was not observed due to the unpredictable timing, but the littoral apron lost volume subsequent to ice meltout, indicating erosion which probably occurred during the 15/03/97 swell event.

Storm waves induced thermoerosion of frozen gravel in an artificial causeway in Alaska (Kobayashi & Aktan, 1986). Thermoerosion occurred normal to the original melting surface and could be significant if the storm was capable of removing the eroded gravels from the site. Although not stated explicitly, the erosive vulnerability was probably due to the rapid destabilisation of the sedimentary structure due the loss of the ice-supported matrix, possibly exacerbated by a lack of sorting of the causeway gravels. If the meltout gravels were not completely removed from the site however, they could insulate the remaining frozen gravels, thereby limiting the rate of thermoerosion. Thermoerosion rates could also be limited by a pre-existing unfrozen gravel body between the frozen gravel body and the adjacent water body (Kobayashi *et al.*, 1999).

Although Kobayashi and Aktan (1986) dealt with a site in arctic Alaska, their findings had several implications for Long Pond and perhaps a broader range of boreal paraglacial coastlines. Ice meltout did not initiate significant retrogradation at Long Pond. This suggested that the littoral apron provided a measure of physical and insulative protection for the ice-supported matrix. It was also implied by Kobayashi & Aktan (1986) that the shoreline position retreated when meltout was driven by wave-induced erosion. It follows that the meltout mechanism, which determined the rate of meltout, was paramount in determining the rate of transgression. Storm-induced thermoerosion could generate rapid meltout and transgression, at least in the short term. Transgression was induced by clast destabilization as pore spaces contracted due to the loss of the ice matrix, shear stress from the storm waves and undercutting of the ice matrix. Large volumes of gravel would have been destabilized and moved downslope, at which point they would have been removed by oblique offshore-directed currents (Héquette *et al.*, 2001). Atmospheric warming would not have generated rapid meltout. While clasts were destabilized due to the loss of the ice matrix, the melt rate was slow enough to facilitate some settling and sorting, reducing the sediment volume that moved downslope. Wave-induced shear stress and undercutting did not occur, which not only mitigated the volume of gravel moved downslope, but preserved the meltout structure, not only providing a measure of protection against subsequent storm events but also possibly acting as a ramp, facilitating the transfer of sediment up to and possibly over the berm lip.

The stability of the bermface position at Long Pond implied that atmospheric warming degraded the interstitial ice and wave-induced thermoerosion was limited to the surface. Ice was not observed on 15/03/97. Snow cover in some cusp bays (cf. Plate 5.2 a) implied that berm reworking had commenced a short time previous to the survey and had occurred for an insufficient duration to thermoerode Segment 1. Meltout therefore predated the swell event. The passive nature of atmospherically-driven meltout did not significantly destabilize the berm, which was able to maintain position.

The presence of interstitial ice in boreal, subarctic, and arctic gravel barriers could render the bermface vulnerable to significant retrogradation during winter storm events due to rapid wave-induced thermoerosion coupled with normal physical erosive processes. A possible reduction in the extent and thickness of winter pack ice development due to regional climate change, which would compromise the dampening effect of the ice cover on winter storm waves, could therefore induce significant shoreline retrogradation at sites that host seasonal interstitial ice bodies. There would, under this scenario, be a greater amount of erosion induced during a storm event as compared to an unfrozen shoreline and hence, greater retrogradation. On a barrier beach that hosts localized interstitial ice, such as Long Pond, this would introduce an alongshore disequilibrium in the bermface. The heavily eroded segment may recover after the storm, prograding to an equilibrium position. This would be especially possible at Long Pond, as the presence of interstitial ice was tied to a sediment catchment area. An alternate equilibrium-driven response would consist of the heavily eroded segment triggering alongshore retrogradation of the bermface along the remainder of the barachois. The magnitude of the beach response to a winter storm event in this case would dramatically exceed the beach response to a storm of similar magnitude that occurred when interstitial ice was not present.

13.0 Geological Inheritance

13.1 Bluff Erosion Mechanisms

Erosional fronts control shoreline position (cf. Carter *et al.*, 1989), potentially along several littoral cells. Coastal armouring (Section 8.1) has locked updrift bluff position in place since the 1880's, which may have slowed the erosional front on the adjacent shoreline. The Long Pond bluffs eroded at a slower rate (cf. Fig. 1.7) than the 0.5 m/yr average that typified the Manuels to Topsail coastline (Paone, 2003).

Bluff retreat mechanisms at Long Pond (outside the flanking scour) were confined to the slope face during the study period. Most erosion occurred due to sediment saturation. Overland runoff during heavy precipitation and snowmelt was channelized, manifesting rivulets and channels on the bluff face. Fine-grained alluvial fans were deposited on beach gravels at the bluff toe (Plate 6.2 d). Coarser sediments were undermined and moved downslope. Changes in pore space volume generated by changes in soil moisture content could also destabilize surficial sediments. During dry periods, soil cohesion decreased in the absence of hydrostatic forces, stimulating viscous grain flow.

The Long Pond bluffs should have been susceptible to undercutting. Waves broke at or near the toe and mobile gravel appeared to have been available as an abrasional agent. As evidenced by the low erosion rate and the absence of wave-cut notches and deep-seated slides or flows (cf. Wilcock *et al.*, 1998; Plates 1.3 a, 6.2 c), undercutting did not occur frequently, although it did occur between Manuels and Topsail (Marine Institute, 1999; Paone, 2003). Despite their proximity to a minor sediment source, the bluff-adjacent beaches were flat, narrow and sediment-poor in comparison to the barachois (Plate 6.2 c). The flat beach slope may have inhibited drawdown of the coarsest sediment fraction. As summarized in Dickinson & Woolfe (1997), for porous gravels, foreshore slopes of at least 14 ° are necessary for boulders and cobbles to roll seaward (McLean & Kirk, 1969) while 3 to 4 m waves are necessary to move boulders up to 0.5 m in diameter shoreward (Oak, 1984; 1986). The bluff toe was protected by the accumulation of large cobbles and small boulders, which dissipated incident wave energy (cf. Bray & Hooke, 1997). Beach gravel mobilization and removal may have been facilitated by the acceleration of backwash by wave reflection from the boulders and bluffs during storms, but the boulders should have also inhibited backwash and beach gravels thrown over these clasts should have accumulated. This did not occur, suggesting that other processes were at work.

Offshore sediment transport can be enhanced on bluff-adjacent beaches by storm surge and wave set-up, which stimulate strong seaward-directed horizontal pressure gradients that drive offshore bottom currents (Héquette *et al*., 2001). At Long Pond, the fines were winnowed offshore, as per Bray (1997) and Carter *et al*. (1987a) and most of the gravels mobilized during storm buildup were drawn down. When waves broke at or near the bluff toe, mobile sediments were scarce, minimising the abrasion potential and the magnitude of undercutting. Once gravel was transported offshore, extra-local waves directed the transport vector towards Long Pond. Normal post-storm recovery processes stimulated minor gravel accumulation adjacent to the bluffs as the storm subsided.

Offshore bottom currents are weaker where overwash processes occur (Héquette *et* *al*., 2001). Overwash (and possibly submergence) facilitates the removal of excess water from the nearshore zone, limiting storm surge set-up and hence the magnitude of seaward-directed pressure gradients. Less sediment is transported offshore as a result. This mechanism accounted for the development of a steeper, more sediment-rich beach in the interbluff area, while the bluffs themselves exhibited poor beach development.

Bluff retreat is often cyclical (Bray & Hooke, 1997; Quigley *et al*., 1977) and the study duration may have been insufficient to document the full range of behaviour. Bluff undercutting could probably occur when the bluff-adjacent beach narrowed in response to the erosional front. Beach narrowing probably occurred slowly however, due to the drag effect of updrift shoreline armouring on the rate the erosional front progressed. The Cherry Lane seawall, by locking part of the bluff position in place, demonstrated that bluff erosion occurred at nearly the same rate as beach transgression. This suggested long intervals between periods of undercutting vulnerability due to beach narrowing. An extreme storm could potentially manifest wave undercutting, however.

13.2 Cherry Lane Seawall

A vertical seawall was constructed in response to property erosion at Cherry Lane during the late 1980's. The wall fixed the property line while the adjacent bluff eroded (Plate 6.2 e). The wall deteriorated and was reinforced with boulders before it was rebuilt in 2001. Seawall deterioration was linked to poor design and beach narrowing.

While bluff-adjacent beach dimensions appeared stable in response to bluff retreat, the seawall-adjacent beach narrowed and decreased in sediment volume. In this context, the seawall constituted a localized response to a broader erosional trend. A seawall that fixes a position on a transgressing shoreline will eventually lose the beach in front of it (Tait & Griggs, 1990). The seawall locally stalled bluff retreat, resulting in sediment volume loss and beach narrowing in front of the wall to the point where it was impassable at high tide.

Vertical, impermeable seawalls induce basal scour, mobilizing beach sediments and undermining the wall (Twu & Liao, 1999). Wave reflection also induces strong seaward-directed bottom currents (Héquette *et al.*, 2001) which can remove mobilized sediments. Seawalls can also inhibit onshore oscillatory transport (Miles *et al.*, 2001), hindering post-storm sediment recovery. As the beach narrowed, the frequency and intensity of wave attack increased. Direct wave attack, possibly with entrained gravel, contributed to seawall deterioration. Ironically, boulders were dumped in front of the seawall as a protective measure against further deterioration.

Wave reflection from seawalls can scour the laterally adjacent beach. Flanking (end) scour consists of a localized erosional acceleration at the end of a seawall, usually as a crescentic or log-spiral shape (Tait & Griggs, 1990). Flanking scour can contribute to seawall deterioration and/or collapse (Sexton & Moslow, 1981). Flanking scour destabilized the Cherry Lane seawall by leaving the northern seawall end unsupported.

Flanking scour occurred primarily by localized undercutting. The scour did not host a significant gravel accumulation (although boulders were dumped to prevent further erosion) which suggested that undercutting was not abrasion-assisted. Undercutting instead occurred due to elevated hydraulic pressure (Carter & Guy, 1988). The beach volume and slope limited percolation and minimized gravitational resistance. As swash was focussed into the scour zone, compression locally elevated the hydraulic pressure to a magnitude sufficient to undercut the bluff, causing slope failure (Fig. 13.1). Eroded sediment was transported out of the scour zone by backwash and runoff. The net result was an oblique log-spiral gouge in the berm face, recessed 6 m from the wall and 2 to 3 m from the adjacent bluff (Plate 6.2 f). Seawall reconstruction was prompted by deterioration along two fronts in order to avert a catastrophic failure.

Flanking scour commonly occurs on the downdrift margin (Tait & Griggs, 1990). Technically, this seawall scour was located on the downdrift margin, but scour was induced by extra-local storm waves instead of longshore currents. Local wind wave swash could not extend to the head of the flank even during spring tide. The seawall limited the southward propagation of extra-local wave swash, focussing it on the adjacent bluff which had developed a shore-normal scarp due to continued bluff erosion (Fig. 13.1). As the scour grew, swash became more focussed elevating the hydraulic pressure which in turn accelerated erosion in a positive feedback loop. The seawall may also have focussed overland runoff, particularly once the scour had been initiated. The scour was also used as an access path to the beach and foot traffic probably weakened the slope face.

Flanking scour can be limited by the length of the seawall (Tait & Griggs, 1990). Scour growth may have ultimately been self-limiting due to the establishment of a negative feedback mechanism where continued expansion reached a threshold beyond which swash

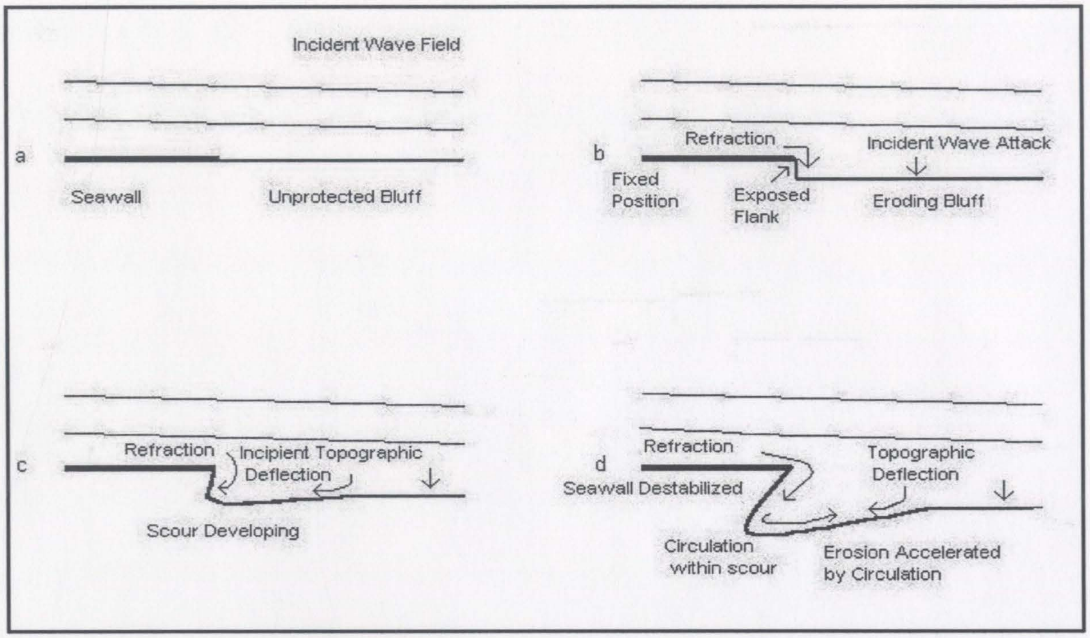


Figure 13.1. Schematic diagram of flanking scour. While the seawall protected the property, adjacent bluffs continued to erode (a) manifesting a scarp oriented approximately normal to the seawall (b). The scarp was exposed to energetic extra-local waves and preferentially attracted swash (c) which accelerated erosion. This further focussed swash and established a circulation pattern (d), generating flanking scour.

could not be focussed as efficiently, and the resultant hydraulic pressure was incapable of undercutting the bluff, except perhaps under extreme storm conditions. Boulder dumping in the scour may actually have constituted an unnecessary expense.

The seawall and flanking scour induced an alongshore disequilibrium. Bluff erosion accelerated with proximity to the scour zone. While this may have been related to scour zone growth, it may also have indicated that the bluffs were moving back into a state of dynamic equilibrium. The bluff may have been retreating to match the back wall of the scour. The reconstruction and cross-shore extension of the seawall has complicated the situation, by once again focussing swash runup and thus increasing the erosional potential.

In 2001, the seawall was reconfigured into a two-tiered structure, with the upper tier recessed 1.5 m from the lower face. The wall extended to the rear of the flanking scour zone. Construction material was obtained by cannibalizing the seawall, exposing a segment of bluff south of the seawall which has begun to erode. The seawall extension will merely shift the location of the flanking scour zone and may actually accelerate property loss by extending the scour behind the seawall.

Continued bluff erosion/beach transgression will eventually result in the complete loss of the adjacent beach and will overextend the wall, even with continued maintenance. Catastrophic seawall failure and subsequent property loss may induce an alongshore disequilibrium. The littoral apron adjacent to the sub-basin may narrow due to the rapid landward shift of the lower low water mark, dramatically increasing berm vulnerability to overwash. Generally, an extreme storm, coupled with favourable tidal conditions, is required to generate overwash. In this scenario however, storms of moderate strength, which occur more frequently and would ordinarily have little long term impact, may suddenly be capable of generating overwash and triggering rapid transgression.

13.3 Bluff Erosion - Barrier Adjustment Cycles

Bluff erosion triggered cyclic barrier overstepping on the sub-basin shoreline. As the erosional front forced bluff-adjacent beach narrowing, the barrier's littoral apron narrowed due to increased exposure to energetic extra-local waves. Narrowing inhibited wave dissipation by the littoral apron and oversteepened the berm, enhancing vulnerability to overtopping and overwashing. This facilitated overstepping, which forced berm transgression and opened accommodation space for a wider littoral apron. This in turn reduced overwash vulnerability until the apron again narrowed in response to continued bluff erosion. This pattern was evident in Plate 7.5, in which a large barrier adjustment on Segment 4 (1978 photo) was preceded by barrier narrowing (1973 photo). Overstepping at Long Pond was therefore very episodic in nature, with short overstepping periods followed by extended quiescent periods.

13.4 Structural Control, Segment 4

Segment 4 was structurally controlled by Burnt Island and the adjacent mainland. Exposed glaciofluvial sediments (Plate 13.1 a) confirmed that barrier rollover did not destroy the antecedent substrate. These sediments were prone to swash erosion and the preservation of this structure and the vegetation atop it suggests that overtopping and burial occurred rapidly - the sediments were not exposed to prolonged wave exposure. Beach gravels have also overridden a fence located a short distance north of the barachois (Plate 13.1 b). On Burnt Island, stunted spruce trees and stumps rooted in glaciofluvial soil protruded from the beach gravels (Plate 13.1 c). Marine gravel swaths in the forest fringe likewise attested to barrier rollover.

Segment 4 narrowed during an extended period with little to no overwashing (Plate 7.5), oversteepening the crest and rendering the barrier vulnerable to an adjustment. The 1976 storm overwashed much of the barrier. Berm cusps facilitated overwashing in Segment 3

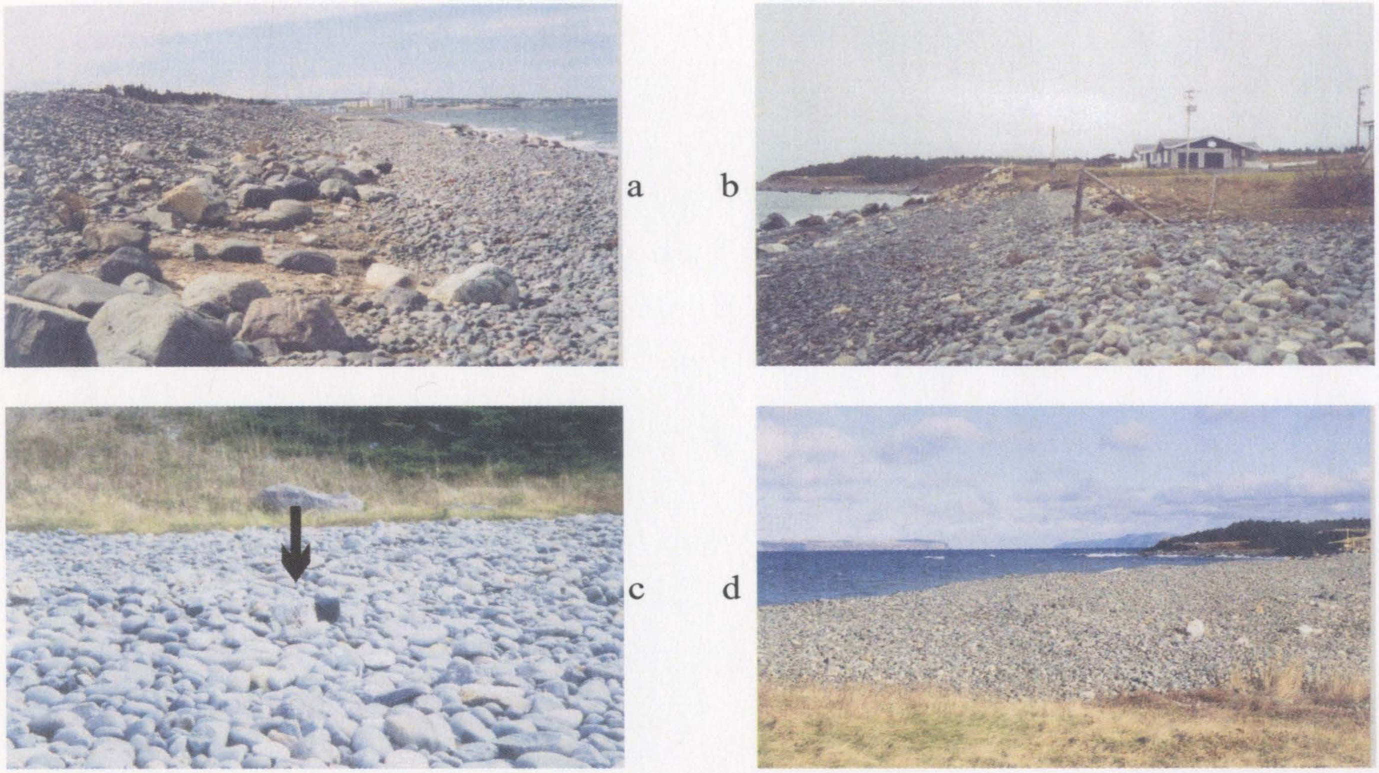


Plate 13.1 a. Exposed glaciofluvial deposit. Coarse boulders are probably lag deposits as crest retreats.

b. Gravel transported past fence post, north of Long Pond. Bluffs are visible in the background.

c. Tree stump (denoted by arrow), Burnt Island.

d. Crest elevation consistent with elevation of glaciofluvial structure, north of Long Pond. Bluffs are visible in the background.

and may have initiated the process in Segment 4. The open-work gravel was prone to swash energy dissipation due to percolation. Gravels overwashed onto the glaciofluvial structures encountered a substrate that was much less permeable than the open-work gravels (Fig. 13.2). Overwashing swash retained more mass and energy, transporting sediments further across-shore. Overwashed gravel draped the antecedent topography

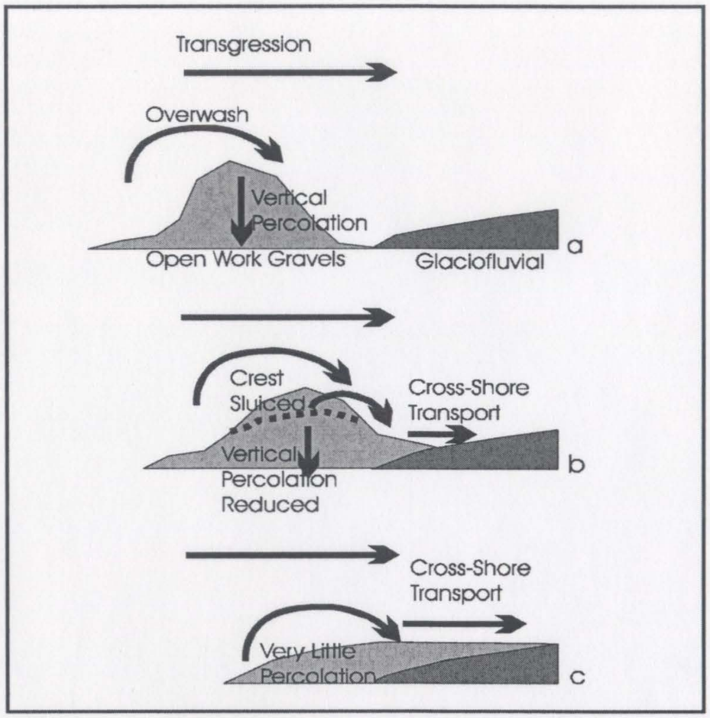


Figure 13.2 a. Schematic diagram of topographic control. Transgression forces the barrier towards the glaciofluvial basement. Overwashed swash is partially lost to percolation, facilitating the retention of a high crest.

b. The barrier rolls over the impermeable basement, which reduces percolation loss. Swash retains energy which is transferred cross-shore, sluicing the crest.

c. The barrier adapts the slope and elevation of the substrate as it continues to overstep. The substrate will eventually be exposed on the bermface as overstepping continues.

(Plate 13.1 b, d). Minimal swash percolation facilitated sluicing overwash (cf. Orford *et al.*, 1991a) which planed off the crest, mimicking the antecedent topography.

Structural control generated a variation in the crest height (Fig. 13.3). Adjacent to the sub-basin, the barrier may have initially resembled Segment 3. Extra-local waves, aligned slightly north of shore-normal, sequentially planed off the crest from north to south, and

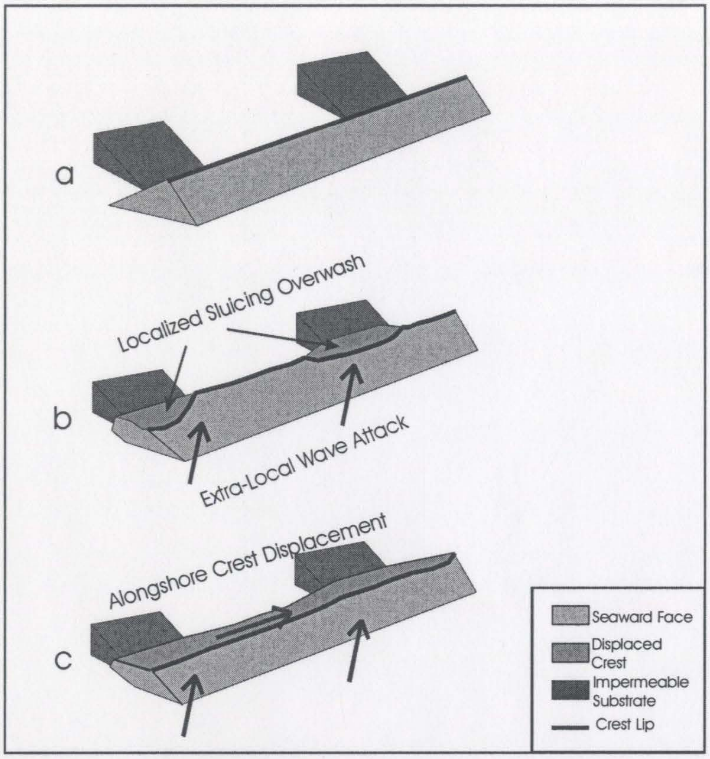


Figure 13.3 a. Schematic diagram of alongshore crest displacement. Extra-local waves and RSLR drive the barrier towards Burnt Island and the laterally-adjacent mainland.

b. Sluicing overwash occurs as per Figure 13.2 at the topographic obstacles, displacing crestal sediment to the backbarrier. The lagoon-backed barrier crest becomes elevated above the sluiced crest, becoming vulnerable to sluicing overwash due to the exposure to extra-local waves. Crestal displacement widens the barrier.

c. Sluicing overwash erodes the entire barrier segment to the height and slope of the glaciofluvial deposits. This influence also extends a short distance south of Burnt Island, due to the incident extra-local wave angle.

the effect extended south of Burnt Island to Transect 12. The lagoon-backed barrier on Segment 4 therefore had the same elevation and slope as the adjacent mainland and Burnt Island. This southward erosional effect was essentially the same process that directed tidal inlet migration southward in Segment 1, but probably occurred more quickly.

14.0 Potential Barrier Evolution

Repeated barrier breaching at Segment 2 was probably a precursor to barrier breakdown as cross-shore flow requirements were being met. During the study period, the barrier was in a state of arrested breakdown due to artificial breach repairs that stalled the breakdown process. Arrested breakdown cannot persist indefinitely, especially in light of continued anthropogenic stress and predictions of accelerated sea level rise and increased storm frequency due to regional climate change (cf. Hanson *et al.*, 2004). Segment 2 will eventually break down, causing a large and possibly catastrophic barrier adjustment. As the barrier breaks down, the basement geometry determines the potential for barrier reformation (Orford *et al.*, 1996). Segments 1 and 2 will probably eventually disintegrate and not reform, due primarily to the dredged depth of the southern basin (Fig. 14.1). Port maintenance will require extensive engineering infrastructure, possibly including a shore-parallel breakwater that mimics the function of the barachois.

The barrier may reform at the northern basin, although dredging may forestall this as well. If the barrier reforms, it will probably be as a seepage barrier since the hydraulic head is not sufficient to maintain a tidal inlet (Section 8.1). The barrier would be anchored by Burnt Island and the northwestern corner of the Long Pond Peninsula where the yacht club is currently located. The orientation of the new barrier will be conducive to cusp development and it may overstep rapidly, transgressing over Burnt Island in the process. Burnt Island is composed of glaciofluvial sediments and will erode quickly as the beach transgresses and glaciofluvial sediments are exposed on the beachface.

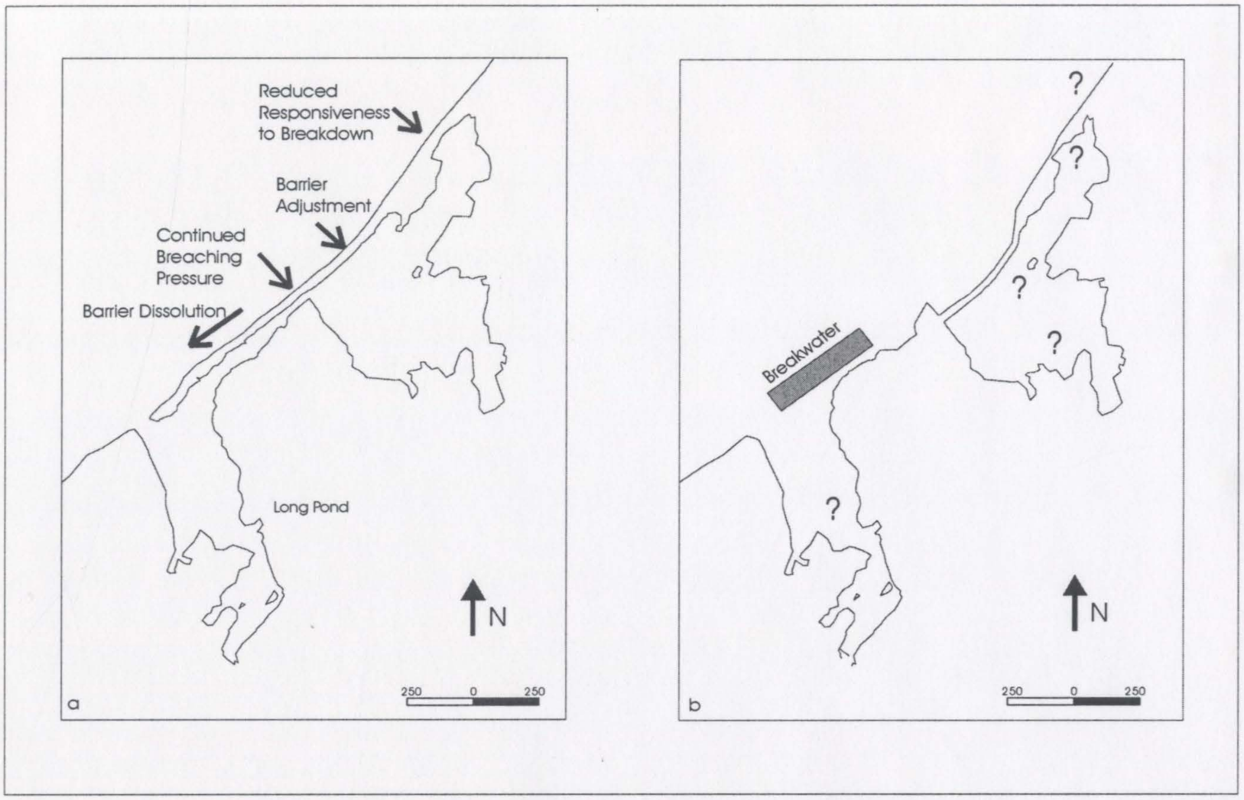


Figure 14.1. a. Continued breaching pressure due to RSLR, in-place narrowing, and high silt content will eventually trigger barrier breakdown. Segments 1 and 2 will disintegrate as they migrate into the deep backbarrier.

b. The barrier may reform north of the Long Pond Peninsula, but dredging may forestall this. The yacht club site will not be tenable at its current location. Rollover onto Burnt Island will accelerate. The access road will reduce the responsiveness of the northern barrier, impairing its ability to overstep and adapt to changing conditions, particularly if rollover onto Burnt Island does occur. A hard breakwater will probably be constructed at the port facility to replicate barrier function.

An event capable of triggering barrier breakdown will certainly overwhelm the sub-basin barrier in light of continued RSLR, the low crest elevation, barrier narrowing by the erosional front and berm narrowing by the access road. The access road will reduce barrier responsiveness and adaptability and will facilitate sluicing overwash, delivering much of the bulk of the barrier into the lagoon. Barrier breakdown will also put pressure on the access road, particularly if rollover onto Burnt Island is accelerated. This in turn will accelerate bluff erosion between Long Pond and Manuels, possibly stimulating headland erosion and transferring the impact further alongshore.

Although the barrier cannot be maintained indefinitely, the consequences of barrier adjustment or destruction dictate that the beach be preserved for as long as possible. The port facility is completely dependent upon shelter imparted by the barrier. The cost of constructing and maintaining replacement infrastructure will be significant.

The tidal current minimizes sedimentation and maintains navigability. Barrier breakdown will separate the basins, significantly reducing the size of the port basin. This will reduce the hydraulic efficiency of the tidal inlet, reducing current velocity (assuming engineering structures will be constructed), and increasing the potential for sedimentation, especially since much of the former barrier will be mobilized. Frequent dredging will be required to maintain the port.

Barrier adjustment will expose the basins to storm wave activity during the adjustment period. Long Pond hosts an upscale residential neighbourhood, with some of the highest property values in Conception Bay South. These properties consist of low-relief glacio-fluvial deposits. Some properties have been reinforced with riprap, as protection against ice scour. Exposure of the Long Pond shoreline to storm activity will induce property damage. Should the barrier disintegrate rather than readjust, damage may be catastrophic.

The Royal Newfoundland Yacht Club would be untenable at its present location.

Damage to the club infrastructure and to private watercraft occurred during both breaches, primarily as a result of large clasts being thrown onshore. The barrier beach is the only protection available to the yacht club from storm waves. As the barrier breaks down and adjusts, the yacht club will be exposed to storm-thrown clasts and eventually the full force of storm waves. There is no accommodation space for beach development on the western shore of the yacht club: it is completely protected by seawalls. The northern basin contains a great deal of recreational boating infrastructure which is dependent upon the tidal channel to access Conception Bay. Previous attempts to maintain an inlet in Segment 3 failed because a lack of shelter and a small hydraulic head induced rapid sedimentation in the dredged inlet. A stable inlet may have been possible north of Burnt Island. The island, with enhancement by shore-normal breakwaters, may facilitate a headland effect, providing some protection from longshore sediment transport, although the sub-basin would require dredging. Access road construction seems to have precluded this option.

15.0 Conclusions and Implications

The preceding study has demonstrated the complexity of the Long Pond barrier - lagoon system. The principal findings of the research have been listed below.

15.1 Barrier Context, Pre-Port Development

Barrier formation was probably initiated shortly after the post-glacial lowstand, circa 6,000 BP. The headlands at Foxtrap and Manuels probably formed a re-entrant trap, facilitating drift-aligned shoal deposition. The shoals eventually coalesced into a gravel barrier. RSLR inundated two adjacent river valleys, forming the Long Pond basin, and forced barrier transgression to its current position.

Updrift shoreline armouring in the 1880's depleted the sediment supply and by fixing the bluff position in place, may have slowed the erosional front. This in turn has slowed shoreline transgression, although the impact may have decreased with distance downdrift. Gravel barriers are often characterized by long periods of slow evolution punctuated by periods of rapid reorganization (Forbes *et al.*, 1995). Barrier stretching due to differential alongshore overstepping rates can move a gravel barrier into equilibrium with a depleted sediment supply (Carter *et al.*, 1987b). Sediment depletion triggered a barrier adjustment at Long Pond in the early 20^{th} century as the barrier cannibalized itself to accommodate the alongshore transport requirement, as per (Carter *et al.*, 1989). Sediment depletion can also manifest a composite beach profile (Orford *et al.*, 1988) and higher cross-shore drainage requirements (Carter *et al.*, 1989). At Long Pond, sediment cannibalization drove the barrier position back further than the adjacent updrift mainland, inducing an alongshore disequilibrium. Wave refraction and the reduced sediment supply narrowed the barrier, facilitating a breach while the greater cross-shore drainage requirement maintained cross-barrier tidal flow. Breaching and inlet formation probably altered the littoral cell. Barrier stretching was stalled, at least in part, by the slow moving erosional front, vertical crest building, and the slower rate of rollover onto Burnt Island.

15.2 Alongshore Profile and Process Variations

The alongshore morphological variation exhibited by Long Pond Barachois was remarkable in that it occurred within a relatively short alongshore distance (< 2 km) without significant changes in sediment shape, texture or mineralogical composition and without significant changes in wave exposure. Long Pond exhibited four distinct profiles, defined by the site-specific interaction of coastal processes and the resultant morphology.

Segment 1 extended from the inflection point to the tidal inlet. The inflection point marked the tidal inlet inception point, and the segment configuration traced the updrift migration path. The configuration facilitated the development of a sediment sink after the 1974 inlet modifications and by isolating it from longshore drift, transformed Segment 1 into the most strongly swash-aligned segment of the barrier. Breakwater construction stimulated progradation and vertical construction, and Segment 1 was the most massive barrier segment. The steep slope inhibited berm cusp development but facilitated massive interstitial ice, which seasonally manifested ice-supported vertical scarps in the berm.

Segment 2 was adjacent to the tidal channel. Backbarrier tidal currents were constricted and accelerated, scouring and oversteepening the backbarrier after the tidal inlet evolved. Current strength was enhanced when the port configuration was modified, particularly after 1974. Backbarrier scour, in conjunction with RSLR, has induced in-place narrowing. Rapid progradation in Segment 1 after 1974 locally depleted the sediment supply. The barrier breached in 1976 at the narrowest barrier segment. The breach was repaired by using silt-rich dredge spoil. This has proven to be very erosion-prone, facilitating another breach in 1992, which was again filled with silt-rich dredge spoil. The breach site was reinforced with gravel during the study period but continues to pose a breaching hazard due to continued erosion. This will eventually lead to barrier instability, triggering a major barrier crest collapse by a small increase in surge magnitude.

Segment 3 was located between the tidal channel and Burnt Island and hosted the stress point. This segment was characterized by berm cusp formation. Segment 3 was last overwashed in 1976 during the same event that breached Segment 2. Overwashing was facilitated by berms cusps (cf. Orford *et al*., 1988) and manifested perched, compact overwash fans similar to those described by Duffy *et al*. (1989).

Segment 4 extended from Burnt Island to the sub-basin. Barrier morphology was controlled primarily by geological inheritance. Barrier rollover onto an impermeable substrate facilitated sluicing overwash in 1976, which displaced the crest. The substrate preserved swash volume and momentum, manifesting a greater cross-shore transport vector. Overwashed sediments draped the antecedent topography at Burnt Island and the northern fringe as the barrier transgressed, mimicking the slope and elevation. The sub-basin barrier crest was sluiced and displaced to the backbarrier. Extra-local waves sluiced the crest from the lagoon-backed barrier in an equilibrium response that extended the structural control the length of the sub-basin and south of Burnt Island to Transect 12.

Sluicing overwash was preceded by barrier narrowing which enhanced overwash vulnerability. Narrowing occurred in response to the erosional front and to the erosion of adjacent bluffs. Crestal displacement widened the sub-basin barrier, but Burnt Island and the northern fringing beach (highlighted by an increase in the exposure of a glaciofluvial deposit) continued to narrow. The low crest elevation rendered Segment 4 vulnerable to overwashing, but the wide littoral apron has dissipated much of the incident wave energy. Overwash vulnerability will increase over time and eventually, even moderate storms may be capable of overwashing the crest, particularly as access road construction narrowed the berm and superimposed a flat impermeable substrate on the backbarrier.

15.3 Major Geomorphic Processes

15.3.1 Sediment Transport Regimes

Prevailing southwesterly winds drove south to north longshore currents in Conception Bay. Fetch limitations precluded local wind waves from reworking the berm. Sediment transport was variable however, as extra-local waves could induce current reversals or a shore-normal vector. Extra-local waves were not fetch-limited, and could be sufficiently large to rework the berm, particularly when aligned approximately shore-normal. The berm was therefore a swash-aligned structure. The littoral apron was primarily drift-aligned, but was influenced by shore-normal swash processes and current reversals.

The barrier consisted primarily of coarse open-work gravels. The gravel was poorly sorted, which suggested that the barrier was not in equilibrium with the wave climate (Carter *et al.*, 1987b). The source gravels were glacigenic and a broad spectrum of clast sizes and shapes have been fed into the littoral system. Incident waves were often capable of transporting a broad spectrum of clast sizes. The transport regime was also quite variable, and while longshore currents predominated, current reversals and shore-normal swash processes were common. The littoral cell, which probably extended between the inlet and Manuels Head, was relatively short (but probably not closed) and alongshore drift transport did not extend a sufficient distance to induce alongshore clast grading.

The berm was vertically constructed to the limit of swash runup by overtopping, except for Segment 4, in which the wide littoral apron dissipated incident swash. Larger waves extended further cross-shore, but kinetic energy depletion by gravitational and frictional resistance and by percolation promoted deposition, vertically building the crest. Berm texture was predominantly well mixed open work gravel due to the magnitude of wave energy involved, and hosted a significant coarse fraction. The breach site by contrast was an unsorted, silt-rich diamict, due to its origin as dredge spoil.

Backbarrier sediment transport and grading were primarily associated with tidal channel currents, which scoured and narrowed the lagoonal apron. The net transport vector was north to south, which built a wide lagoonal apron adjacent to the inflection point prior to dredge spoil dumping. The newly available mobile gravels were reworked into a series of alternating spits and swales. Gravels at the northern end of the channel could be moved north by flood tidal currents before being directed south in the channel thalweg. Some wind-wave transport may have occurred, primarily in the northern basin, when smaller gravels were entrained, leaving coarse lag deposits on the lagoonal apron.

15.3.2 Barrier Breaching

The barrier breached at the inflection point in the early 20th century due to sediment flux depletion by updrift armouring. A permanent tidal inlet evolved because higher cross-shore flow requirements were associated with the reduced sediment supply. The inlet migrated updrift because extra-local waves preferentially eroded the southern inlet shoreline. The barrier shifted eastward due to the construction of sequential flood tidal deltas which drove barrier transgression at a faster rate than overstepping.

The barrier breached in 1976 at the narrowest segment, which had the least resiliency to storm activity. Narrowing was induced by RSLR which raised water levels on both sides of the barrier and by backbarrier tidal currents, and the creation of an adjacent updrift sediment sink. The 1976 breach was filled with silt-rich dredge spoil. The diamict was impermeable, which reduced profile responsiveness, and was therefore very erosion-prone. The barrier breached again in 1992 during an apogean tide and was not accompanied by overwashing or overtopping elsewhere on the barrier. This breach was also filled using silt-rich dredge spoil. The breach site was heavily scarped during most of the survey period until it was reinforced with gravel borrowed from the adjacent beach in January 1998. This also eroded and the barrier remains vulnerable to breaching.

The breach site continued to erode for three reasons: (i) the permeability of the berm was impaired, (ii) the gravels were not swash-lain, and (iii) the pre-reinforcement slope face was an erosional contact and the reinforcement gravels, instead of being incorporated into the berm structure, merely rested on the berm at an unstable angle of repose. The textural structure of the breach site will pose problems for years to come.

15.3.3 Cusps

Cusps were stimulated by incident plunging or surging breakers oriented approximately normal to the shoreline trend but slightly oblique at the shoreline. Based upon position and incident wave energy, there were two basic swash cusp forms at Long Pond: apron cusps and berm cusps. Rhythmic apron cusps developed on the intertidal littoral apron under fairweather conditions. These cusps developed rapidly but rarely persisted beyond a single tidal cycle. Apron cusp dimensions did not statistically support edge wave templates as a formative mechanism as per Inman & Guza (1982) but did statistically support the self-organization mechanism as per Coco *et al.* (1999) and Werner & Fink (1993). The variation in apron cusp form and formative oceanographic conditions implies that self-organizational feedback mechanisms may vary site- and event- specifically. Apron cusps formed when incident swash was topographically deflected by the curved planform in the direction of the shoreline trend, forming a coherent cusp circulation cell.

This manifested opposing skews on either side of the stress point. Over time, cusp circulation evolved into horn-divergent flow as the cusp bay began to preferentially attract incident swash, and finally to oscillatory flow as the tide ebbed.

Single tiers of arrhythmic cusps were etched into the berm by extra-local waves refracted and diffracted by the adjacent islands. Berm cusp elevation was controlled by local RSL at the time of formation. Berm cusp dimensions did not statistically support the edge wave template or the self-organization mechanisms. Berm cusp formation may have been non-linear and did not subsequently match any statistical models.

The poor statistical support was linked to the inclusion of at least three stages of cusp maturity in the dataset, each marked by a distinct circulation pattern. Topographic deflection controlled cusp initiation. Extra-local waves were aligned slightly north of shore-normal. North of the stress point, the planform deflected incident swash from north to south, establishing a primitive circulation cell that carved a shallow symmetric cusp. Swash did not always fill the cusp bay as the steep open work gravels were prone to undercutting and avalanching, which generated coarse lag deposits on the cusp bay floor. Cusp horns were remnants of the antecedent berm, displaying similar slope and texture. These immature cusps were arrhythmic because cusp backwash could interfere with the incident swash of its southern neighbour, depleting the incident wave energy.

Cusp maturation was marked by the onset of horn-divergent flow when cross-shore swash processes replaced hydrodynamic forcing as the dominant developmental control and self-organizational feedback mechanisms began to dominate cusp morphology. This could occur during a single storm, but the inherent stability of the coarse clastic structure meant that cusps could be reworked by subsequent events. Cusp maturation did not proceed uniformly since the arrhythmic cusps did not circulate swash uniformly.

Horn-divergent swash jets were generated under incident swells when the cusp cell circulation period approximately equalled the incident wave period and swash-backwash interference generated standing waves. Interference was maximized at the bay and minimized at the horn, generating lateral pressure gradients that converged at the horn and were directed across-shore in an accelerated swash jet. This was the most mature phase of cusp development. Progressively more energetic swash jets could build reverse graded cusp horns. Swash jets at Long Pond were indicative of self-organization. Horn-convergent swash jets described by Eliot & Clarke (1986) occurred at the interference maxima and may have been indicative of edge wave forcing.

15.3.4 Ice

The study period coincided with light sea ice conditions, but given the lack of ice-push and -lift features on the seaward shore, sea ice appears to have had little impact on barrier form, aside from possibly dampening wave energy from the adjacent shelf. An icefoot developed on the littoral apron during the 1997 field season, but had little apparent morphological impact. No icefoot development occurred during the 1998. An icefoot occurred along the entire lagoonal apron but was poorly developed and exerted little influence on shoreline morphology.

The northern basin and shallow quiescent areas in the southern basin developed ice cover during the study period. Deeper, more energetic reaches did not freeze. Ice thickness could exceed 1 m in the northern basin. Ice-push had little impact due to fetch limitations but ice-lift scoured Burnt Island and the mainland. The uprooting and loss of the Transect 15 benchmark by tidally-driven ice fluctuations graphically illustrated the potential impact of ice activity. On Burnt Island, ice-lift manifested vertical scarps up to 2 m in height. Burnt Island and many mainland properties were armoured in response. The rate of erosion may have accelerated when tidal exchange was enhanced by port development, but the greatest amount of erosion seemed to have occurred between 1966 and 1973 when the inlet was widened and the port basin dredged.

Basal adfreezing of pebbles and cobbles transported small amounts of gravel from the sub-basin shoreline. During spring thaw, winds and weak tidal currents moved ice out of the sub-basin. Some ice was stranded on the platform, depositing well-rounded clasts, while other clasts were pushed and lifted into the forest cover up to 2 m asl.

Interstitial ice scarps seasonally developed in Segment 1. Large, cold clasts acted as nuclei for ice development and freeze-thaw cycles expanded ice thickness. The extent of interstitial ice reflected the role of berm height and cross-sectional volume in ice formation and clast insulation. The ice body acted as a temporary matrix, holding gravel in place above the normal angle of repose. The resulting three-dimensional impermeable structure caused incident wave energy to be expended directly upon the surface gravels, physically and thermally eroding the bermface.

The generation of an ice-supported matrix could render the bermface vulnerable to significant retrogradation during winter storm events due to rapid wave-induced thermoerosion coupled with normal physical erosive processes. A possible reduction in the extent and thickness of winter pack ice development due to regional climate change, which would compromise the dampening effect of the ice cover on winter storm and swell wave activity, could therefore induce significant shoreline retrogradation at sites that host seasonal interstitial ice bodies. On a barrier beach that hosts localized interstitial ice, such as Long Pond, this would introduce an alongshore disequilibrium in the bermface.

15.3.5 Geological Inheritance

Bluffs eroded an average of 0.5 m/yr in CBS (Liverman & Boger, 1994). In contrast, the mean erosion rate between Long Pond and Manuels was estimated to have been 0.1 to 0.2 m/yr. Erosion was slower because it was limited to the surface. Overland runoff during heavy precipitation and snowmelt was channelized, manifesting rivulets and channels on the bluff face. Fine-grained alluvial fans were deposited atop beach gravels at the bluff toe. Coarser sediments were undermined and moved downslope. Minor bluff erosion occurred by viscous grainflow during dry periods. These mechanisms were confined to the slope face. Undercutting was not effective at inducing erosion because of the low sediment volume, which did not provide an abrasive sediment load. Bluff retreat is often cyclical (Bray & Hooke, 1997; Quigley *et al.*, 1977) and the duration of the study period may have been insufficient to document the full range of behaviour of this system.

A vertical seawall was constructed at Cherry Lane during the late 1980's in response to property erosion, fixing the property line while the adjacent bluff eroded. The seawall deteriorated and was reinforced with boulders before it was rebuilt in 2001. The beach narrowed in front of the seawall until it became impassible during high tide. Continued bluff erosion/beach transgression will eventually result in the complete loss of the beach and will overextend the wall, even with continued maintenance.

15.4 Geomorphic Impacts and Implications of Human Activity

Human activities, notably updrift coastal armouring and port development, have altered littoral processes at Long Pond. Sediment depletion triggered tidal inlet formation and barrier stretching, which generated the arcuate planform. Shoreline armouring may have slowed the erosional front, helping maintain positional stability. The inlet facilitated tidal exchange, which induced in-place narrowing at Segment 2 and ice-lift shoreline scouring in the northern basin. The tidal inlet, by providing a stable access between the basin and Conception Bay, also facilitated Long Pond's conversion from an agricultural site into a major industrial and recreational port facility in the 1950's. CBS has experienced rapid population growth since WWII. The superimposition of human activity on the barachois has resulted in geomorphic impacts. Port development and subsequent reconfigurations enhanced tidal exchange in the lagoon (enhancing in-place narrowing and shoreline scarping), realigned the littoral cell by isolating either side of the inlet, and generated a sediment sink next to the barrier, which spurred progradation at Segment 1 at the expense of Segment 2, which experienced enhanced in-place narrowing.

A residence was constructed on Burnt Island and an access road was graded across the backbarrier. The forest and island slope may mitigate the residential storm hazard in the short term particularly since terrestrial rollover has occurred more slowly than lagoon-backed barrier overstepping. The beach fronting Burnt Island has narrowed since 1941 however and may be due for an adjustment. A rapid barrier-wide adjustment may also pose a hazard, particularly if rollover onto Burnt Island accelerates as a result.

The access road narrowed the berm and locked the barrier in place. Sluicing overwash occurred in 1976 when the barrier rolled over onto an impermeable glaciofluvial substrate. While the wide littoral apron has dissipated incident storm wave energy and prevented overwashing, the coincident occurrence of a large storm with spring tides does pose an overwash risk. The road will limit barrier responsiveness and will probably facilitate another sluicing overwash. Road construction and maintenance will generate in-place beach narrowing. As the lower low water mark and the berm transgress in response to RSLR, road maintenance will effectively reduce the accommodation space required for normal barrier response. The berm will narrow, as will the entire sub-basin barrier segment. Overwash vulnerability will increase over time, eventually to the point where even moderate storms may be capable of generating overwash events. Access road and residential development have also constrained future management options.

Breach site erosion poses the greatest hazard to barrier integrity. The silt-rich diamict was impermeable and imparted too much stability, generating an unresponsive profile that has proven very erosion-prone. The breach site has continued to erode, manifesting steep scarps and a narrow berm. The 1998 reinforcement borrowed gravel from the littoral apron. This should not be repeated. Sediment flux may quickly replace borrowed gravel under fairweather conditions by preferentially attracting swash to the depleted area and stimulating deposition. However, energetic wave events can influence this coastline at any time and a depleted littoral apron may not effectively dissipate incident wave energy, dramatically increasing the risk of accelerated berm erosion and possibly breaching. The berm texture is generally coarser than the littoral apron texture due to the incident wave power differential. If the borrow area is dominated by relatively small clasts, fine to medium pebbles for example, the combination of low permeability and small average clast size would result in rapid erosion of the breach site during energetic wave events.

Barrier breaching often precedes barrier transgression (Carter *et al.*, 1990) or barrier breakdown (Carter *et al.*, 1989; Carter & Orford, 1993; Orford *et al.*, 1996), especially if cross-shore flow requirements are met, as was the case at Long Pond. During the study period, the barrier was in a state of arrested breakdown. The breaches were artificially repaired, allowing the barrier to retain integrity for longer than may have otherwise been possible. Arrested breakdown cannot persist indefinitely, especially in light of predictions of accelerated sea level rise and increased storm frequency due to regional climate change (cf. Hanson *et al.*, 2004). Segment 2 will eventually break down, causing a large and possibly catastrophic barrier adjustment. As the barrier breaks down, basement geometry determines the potential for barrier reformation (Orford *et al.*, 1996). Segments 1 and 2 will probably disintegrate and not reform, due primarily to the dredged depth of the southern basin. Maintenance of the port facility will require an extensive engineering infrastructure, possibly including a shore parallel breakwater that mimics barrier function.

The barrier may reform across the northern basin although dredging may forestall this as well. The barrier, if it reforms, will probably act as a seepage barrier since the hydraulic head is insufficient to maintain a tidal inlet. The barrier would be anchored by Burnt Island and the northwestern corner of the Long Pond Peninsula. The new barrier would initially be low and the orientation would probably be conducive to cusp development and it may therefore overstep rapidly, rolling over Burnt Island in the process. Burnt Island is composed of unconsolidated glaciofluvial sediments and may erode quickly as the beach transgresses and glaciofluvial sediments are exposed on the beachface. This will also influence the position of the barrier north of Burnt Island.

An event capable of triggering barrier breakdown will certainly overwhelm the sub-basin barrier north of Burnt Island in light of continued sea level rise, the low crest elevation, barrier narrowing by the erosional front and berm narrowing by the access road. The access road will reduce barrier responsiveness and adaptability and will facilitate sluicing overwash, delivering the bulk of the barrier into the lagoon. Barrier breakdown will also put pressure on the access road, particularly if rollover onto Burnt Island is accelerated. This in turn will accelerate bluff erosion between Long Pond and Manuels, possibly stimulating headland erosion and transferring the impact further alongshore.

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Appendix 1: Directional References

Some workers have distinguished the Long Pond basins as the western (smaller) and eastern (larger) basins (cf. Christie, 1966; Delcan, 1995; Public Works of Canada, 1992b; Wells, 1974). This terminology has not been employed for this study. A straight line approximation of the Long Pond shoreline trended southwest to northeast at 045° azimuth, while Conception Bay trended approximately north to south at a 020° azimuth. This had significant implications in terms of wave propagation patterns and incident wave angles. The largest waves were extra-local and propagate from the North Atlantic through the mouth of Conception Bay. These waves exerted a significant morphological control over the southeastern Conception Bay shoreline. In accordance with wave behaviour, fetch parameters and for the sake of simplicity, the mouth of Conception Bay has been referred to as north (to represent the northern quadrant), the head of Conception Bay referred to as south (to represent the southern quadrant) and the opposite side of the bay referred to as west (to represent the western quadrant). Long Pond Lagoon, by this terminology, was oriented north to south. The southern (smaller) basin hosted the tidal inlet (Fig. 1.2). Shore-normal breakwaters have been constructed on either side of the inlet to stabilize the inlet position and minimize sedimentation rates within the port facility (Fig. 1.3). These have been denoted as the northern and southern breakwaters, despite having previously been denoted as the east and west breakwater, respectively (cf. Delcan, 1995; Public Works of Canada, 1992b).

Appendix 2: Port Development at Long Pond

The first recorded attempt to develop a harbour at Long Pond occurred in 1910 (Public Works of Canada reprint, 1910), possibly to support a gravel mining operation. Prior to this, there were no viable harbours along the CBS coastline (Anspach, 1828). The plans were apparently never executed or the project was abandoned due to rapid infilling.

The tidal inlet provided access to the Long Pond basin. The inlet was initially stabilized by a retaining wall between 1948 and 1951 (Plate 1.5). Port development began in earnest circa 1957 or '58 when the Newfoundland Yacht Club was moved from Topsail to Long Pond. Harbour enhancement consisted of several components. The tidal inlet, tidal channel and a portion of each basin were dredged (Public Works of Canada, 1957). A shore-normal breakwater was constructed south of the inlet, the breakwater/retaining wall on the northern side of the inlet was extended, and a government wharf was constructed. Port development occurred over several decades and consisted of a great deal of trial and error (cf. Delcan, 1995; Geotechnical Associates Ltd, 1984; Public Works of Canada, 1957; 1962; 1972; 1984; 1989b; 1992a; 1992b; 1992c).

The inlet stabilization structures have been modified frequently (Plate 7.1). A southern breakwater was constructed by 1962 (Public Works of Canada, 1962), was extended an additional 15 m in 1973 (Public Works of Canada 1972; 1974) and was reinforced with boulder armouring in 1992 (Public Works of Canada, 1992d).

The northern inlet shoreline was armoured by a retaining wall that doubled as a breakwater. The original structure was replaced in 1972 by a shorter structure and reinforced with metal facing (Public Works of Canada, 1972). A shore-normal breakwater was constructed 75 m north of the inlet (Public Works of Canada 1974). The retaining wall was replaced by wooden crib work in 1992 (Public Works of Canada, 1992c). Some gravel has accumulated between the retaining wall and the breakwater.

The government wharf was constructed by 1964 (Public Works of Canada, 1967) and has required frequent repairs (Public Works of Canada, 1975; 1986; 1988; 1995). The wharf serves as a shipping and offloading facility and has been frequented by Coast Guard vessels, freighters and offshore draggers and trawlers (cf. Plate 1.6 d, e). Between 1994 and 1999, the port hosted between 122 and 242 vessels annually (Marine Institute, 2000).

The port has been dredged frequently. Initially, tidal exchange was insufficient to scour the channel, and shoaling occurred. The channel was dredged when shoaling hindered navigability (cf. Public Works of Canada, 1964; 1977; 1989a; 1990). The inlet was first dredged in 1958 to a width of 18 m and a depth of 4 m (Canadian Hydrographic Service (prepared by E. J. Cooper), 1960). The next dredging operation occurred in 1962 (Public Works of Canada, 1962). The inlet was apparently dredged in two year intervals during the 1960's (W. Hamilton, *pers. comm.* 1997; Christie, 1966; Wells, 1974) but was required less frequently after the southern breakwater was extended and the northern breakwater was constructed in 1973. The inlet was widened to 90 m at this time. The inlet and port basin were dredged to 8 m (Canadian Hydrographic Service, 1987) due to the establishment of the pyrophyllite shipment facility and the oil tank farm, both of which required larger draught capability. Dredging operations were occasionally necessary, for example in 1984 (Public Works of Canada, 1984b; 1992b). Soundings were recorded on other occasions (Public Works of Canada, 1982; 1995), but it was unclear whether these preceded dredging or were merely tests to determine whether dredging was necessary. The basin was dredged in 1989 (Public Works of Canada, 1990). From 1989 to 1994, the port was dredged 3 times due to geological instability near the Government Wharf (Taylor, 1994).

The tidal channel was dredged to a depth of 4 m (Canadian Hydrographic Service, 1987). The channel was first dredged circa 1957 (W. Hamilton 1997, *pers. comm.*; Public Works of Canada, 1957). Soundings recorded in 1964 (Public Works of Canada, 1964a; b) may have indicated a dredging operation. Sedimentation prompted dredging in 1989 (Public Works of Canada, 1989a; b) at a cost in excess of $1,000,000 (Taylor, 1994). Dredging also occurred in 1977 (Public Works of Canada, 1977a; b) and 1992 (Public Works of Canada, 1992a) in response to breaches in the barrier that occurred in 1976 and 1992. These events facilitated sediment transport and deposition within the channel. Both breaches occurred at the same location (Fig. 1.2). The barrier was repaired with unsorted dredge spoil from the channel, which consisted of silt, sand, pebbles, cobbles and boulders. Repairs after the 1992 breach cost in excess of $ 40,000 (Taylor, 1994). The present configuration of the stabilization infrastructure appears to have enhanced the tidal prism and maintained navigability within the port facility (at least while the barachois maintained alongshore integrity) although maintenance dredging operations have continued (Transport Canada, 2001; Taylor, 1994).

Appendix 3: Complete Beach Profile Dataset

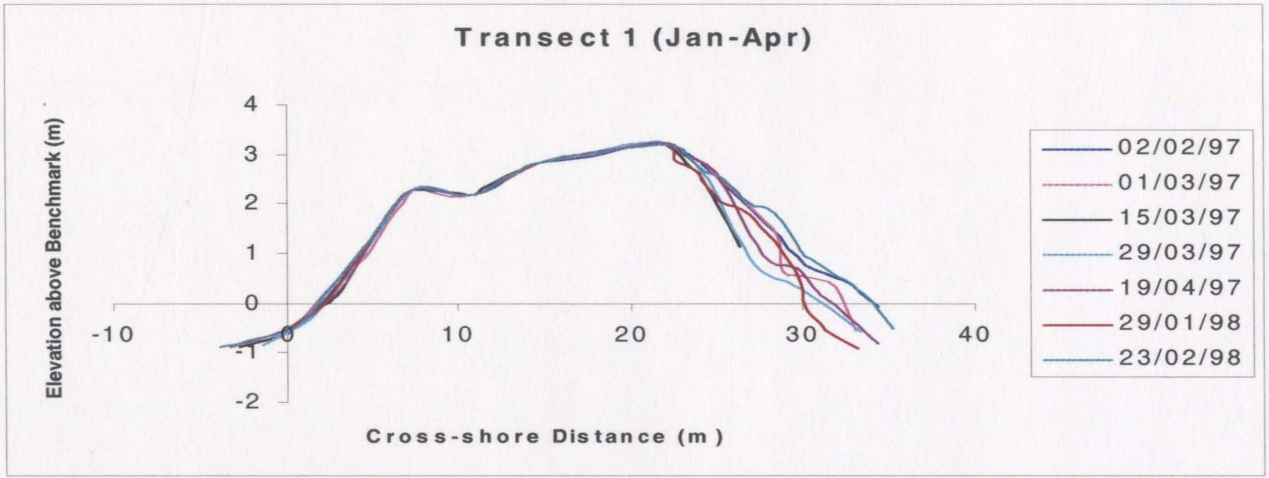

Figure A3.1a. Cross-sectional profile, Transect 1 (Jan. - April). Vertical Exaggeration x2.5.

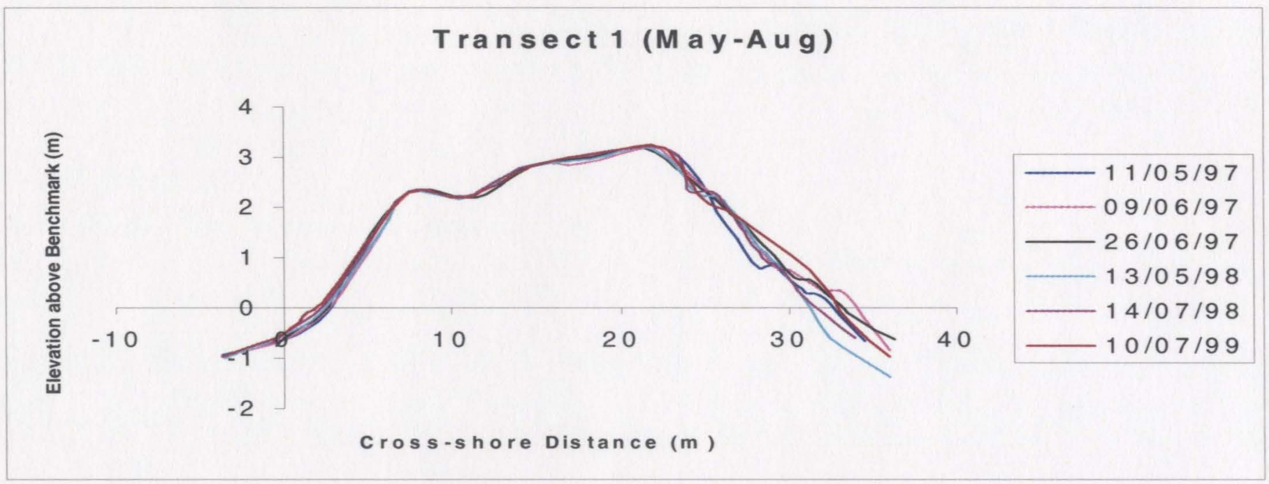

Figure A3.1b. Cross-sectional profile, Transect 1 (May - Aug.). Vertical Exaggeration x2.5.

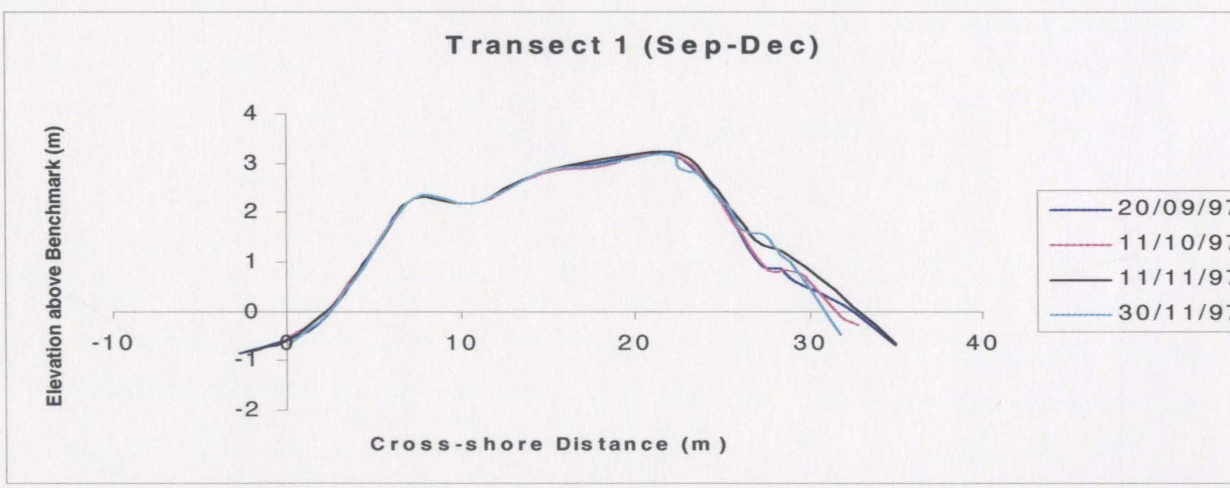

Figure A3.1c. Cross-sectional profile, Transect 1 (Sept. - Dec.). Vertical Exaggeration x2.5.

Table A3.1: Summary of Transect 1.

Littoral Apron	Steep and narrow, volume and texture fluctuated, no evident seasonal pattern; coarse pebbles and cobbles observed most frequently, often poorly sorted, most commonly well rounded discs, blades and equants
Berm	Flat-crested, 15 m wide, steep slopes, composite profile; well-rounded coarse pebbles and fine to medium cobbles, discs and blades most common; 0.2 m increase in crest elevation parallel to backbarrier; inert except bermface
Lagoonal Apron	Moderate to well sorted, fine to medium pebbles, with smaller fractions of coarse pebbles and cobbles; most commonly well rounded discs, blades, and equants, with a small number of rollers; volumetric changes
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, interstitial ice and scarping (up to 0.7 m), icefoot (both sides)
Comments	Prograded and built vertically after 1973, when the modern port configuration was constructed; well developed interstitial ice lasted from January to early March in 1997, not as well developed and shorter-lived in 1998; this area hosted a tern nesting site and ATV's were banned south of Transect 5; surveys were not conducted during the nesting season to avoid stressing the population

Table A3.2: Summary of Transect 2.

Littoral Apron	Steep and narrow, volume and texture fluctuated, no seasonal pattern; cobbles and coarse pebbles observed most frequently, often poorly sorted, most commonly well rounded discs, blades and equants
Berm	Flat-crested, 10 m wide, steep slopes, composite profile; well-rounded coarse pebbles and fine to medium cobbles, most commonly well-rounded discs and blades, with some equants; some subangular clasts, sand and silt in backbarrier slope; inert except bermface
Lagoonal Apron	Apron: spits were oriented nearly parallel with ebb tidal currents; moderate to well sorted fine to medium pebbles with some coarse pebbles and cobbles, well rounded discs, blades, and equants most common with a small number of rollers, often silt-coated; swales often contained sand, volumetric changes Dredge spoil: silt to boulders, silt lenses exposed at base, line of coarse clasts at breakpoint
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, spit and swales (backbarrier), interstitial ice and scarping (0.4 - 0.7 m), icefoot (both sides)
Comments	Marked Inflection Point; congregation area for several species of gulls; grasses and smooth hawksbeard (Crepis capillaris) established on the berm; dredge spoil dated from 1992 breach; wide lagoonal apron predated 1992 but increased in size and volume afterwards; ATV's prohibited

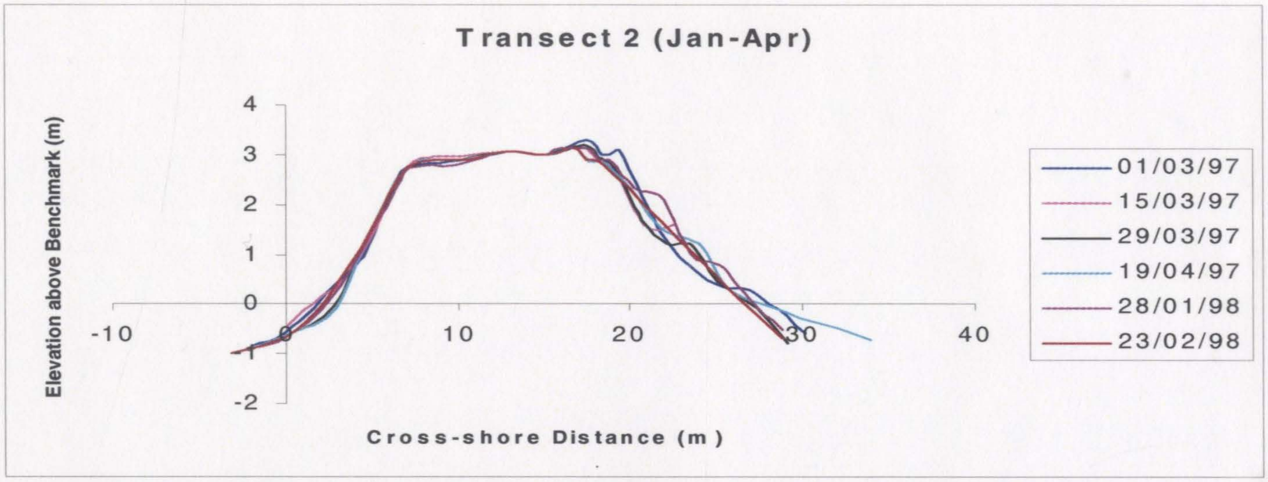

Figure A3.2a. Cross-sectional profile, Transect 2 (Jan. - April). Vertical Exaggeration x2.5.

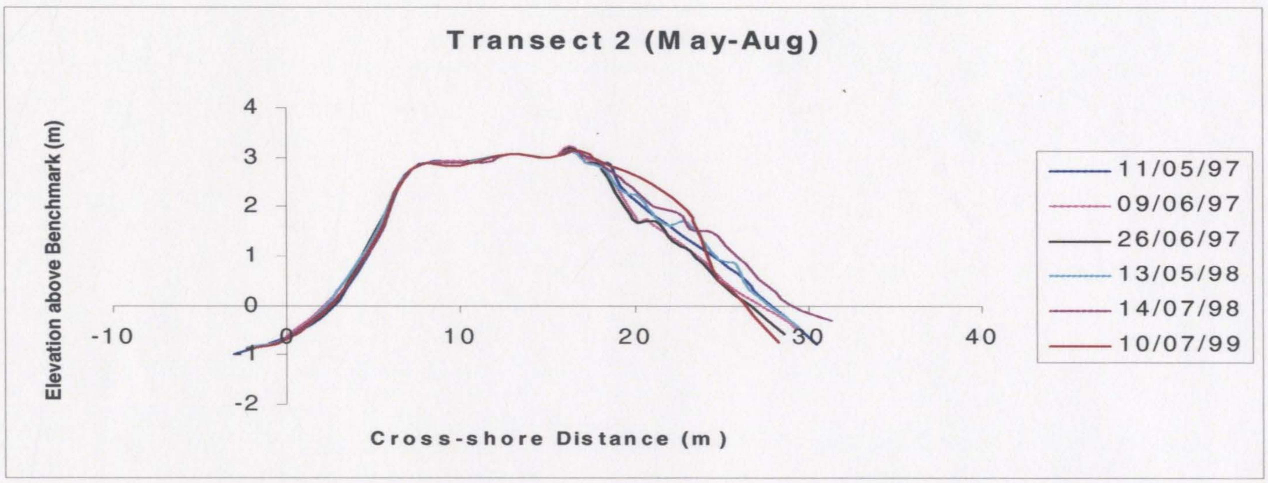

Figure A3.2b. Cross-sectional profile, Transect 2 (May - Aug.). Vertical Exaggeration x2.5.

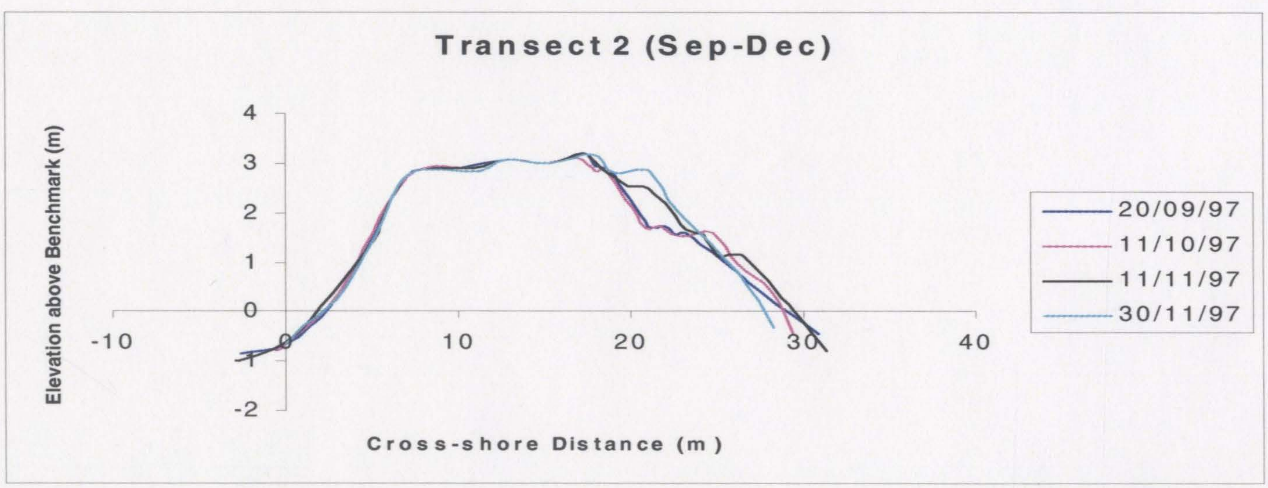

Figure A3.2c.Cross-sectional profile, Transect 2 (Sept. - Dec.). Vertical Exaggeration x2.5.

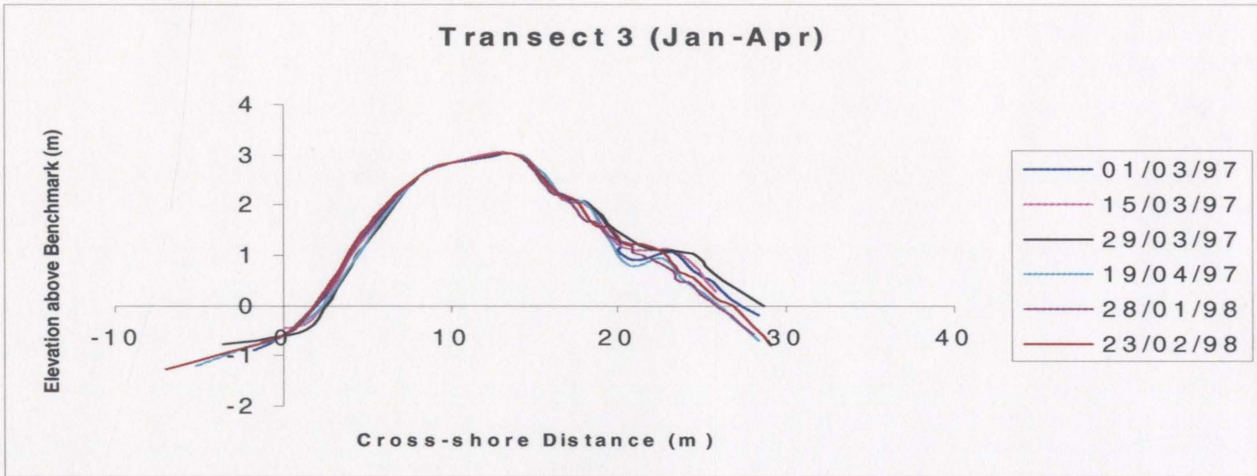

Figure A3.3a. Cross-sectional profile, Transect 3 (Jan. - April). Vertical Exaggeration x2.5.

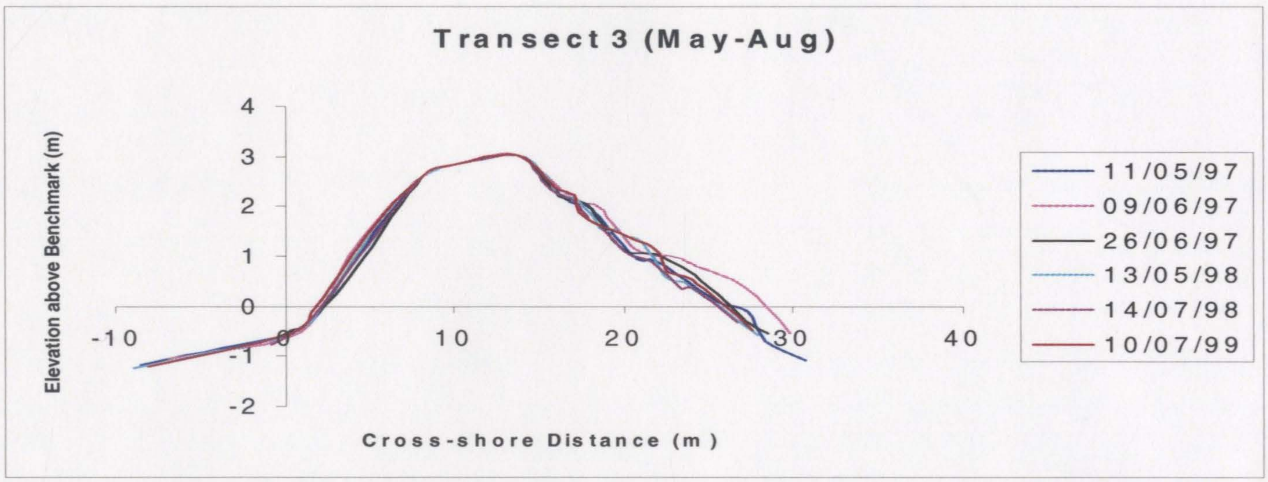

Figure A3.3b. Cross-sectional profile, Transect 3 (May - Aug.). Vertical Exaggeration x2.5.

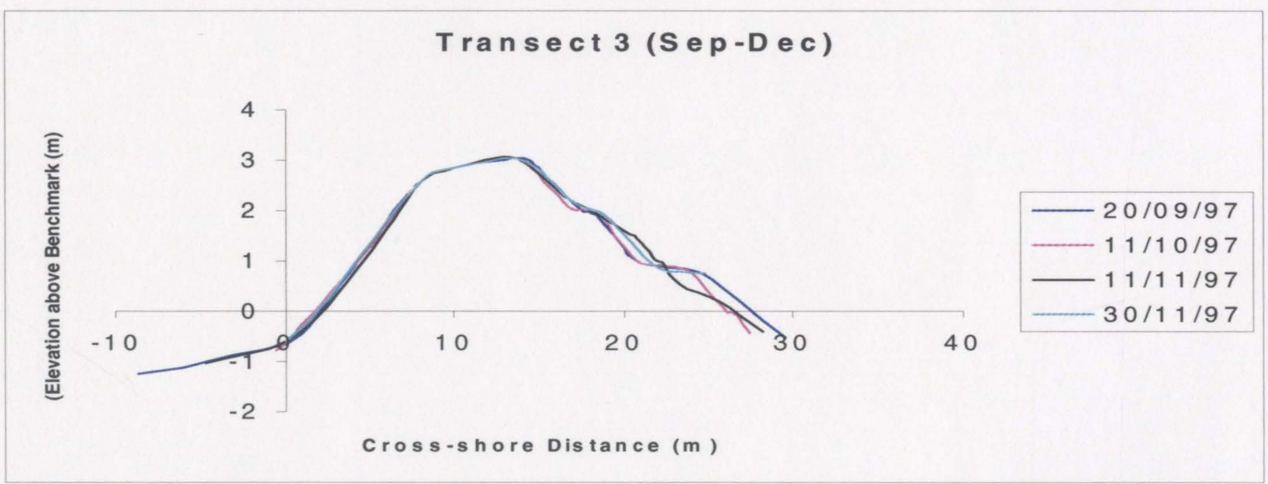

Figure A3.3c. Cross-sectional profile, Transect 3 (Sept. - Dec.). Vertical Exaggeration x2.5.

Table A3.3: Summary of Transect 3.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine pebbles to fine cobbles, often poorly sorted but pockets of sorted clasts often observed, most commonly well rounded blades, discs, and equants
Berm	Flat-crested, 6 m wide, backberm steeper than bermface, composite profile; coarse pebbles and fine to medium cobbles, well rounded discs and blades most common with small spherical equant fraction; inert except for bermface
Lagoonal Apron	Poor to moderately sorted fine to medium pebbles, with some coarse pebbles and cobbles, most commonly rounded discs and blades with some equants and few rollers; particles often silt-covered; volume fluctuated
Sedimentary Structures	Shore parallel swash ridges, apron cusps, minor interstitial ice and scarping, icefoot (both sides)
Comments	Change in the cross-shore morphology of the beach, specifically a narrowing of the crest, a slope decrease in the slope face and backberm and a widening of the littoral apron, northern margin of the dredge spoil; ATV's prohibited

Table A3.4: Summary of Transect 4.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine pebbles to fine cobbles, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded blades, discs, and equants
Berm	Flat crested, 5.5 m wide, backberm steeper than bermface, composite profile; coarse pebbles and fine to medium cobbles, cobbles prevalent on the upper bermface with pebbles commonly at the breakpoint, well-rounded discs and blades most common with some equants; inert except for bermface
Lagoonal Apron	Moderate to well sorted fine to medium pebbles with some coarse pebbles and cobbles, well rounded discs and blades were most common with some equants and a small number of rollers, volume fluctuated
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, minor interstitial ice and scarping (0.2 m), icefoot (both sides)
Comments	Littoral apron has progressively incorporated greater proportion of total barachois width, ATV's prohibited

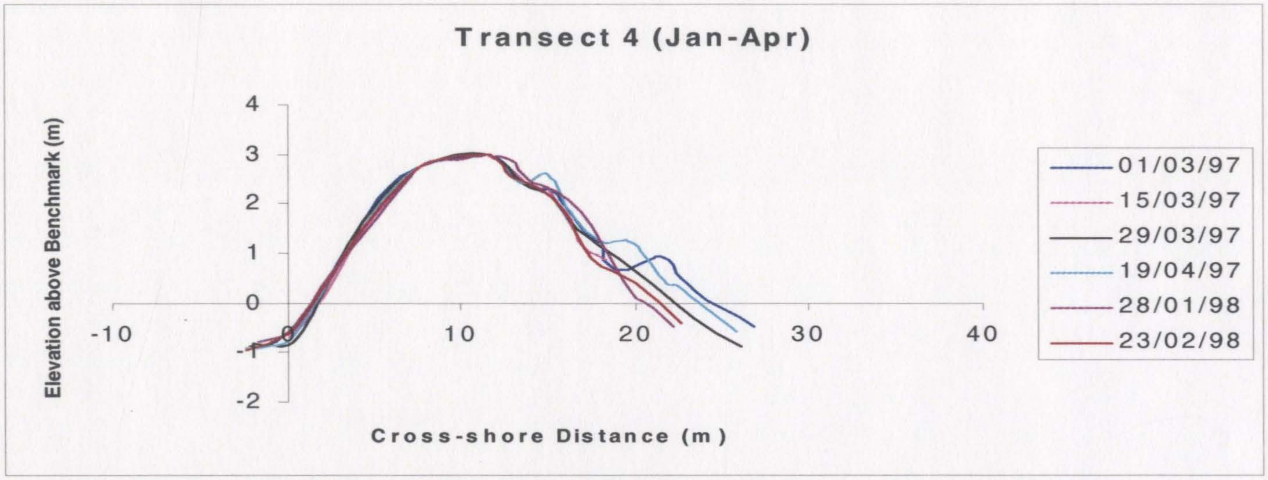

Figure A3.4a. Cross-sectional profile, Transect 4 (Jan. - April). Vertical Exaggeration x2.5.

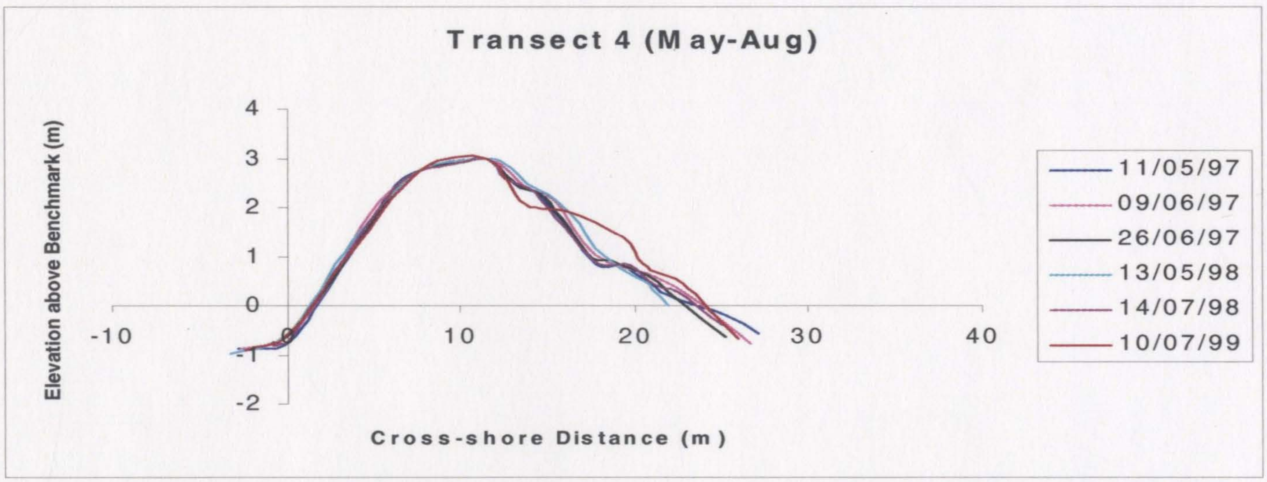

Figure A3.4b. Cross-sectional profile, Transect 4 (May - Aug.). Vertical Exaggeration x2.5.

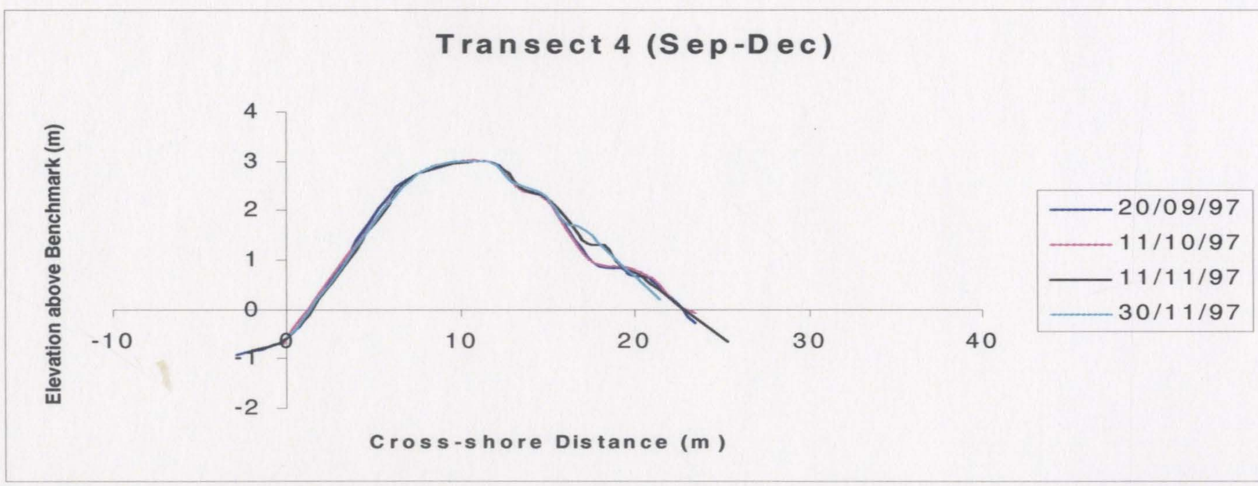

Figure A3.4c. Cross-sectional profile, Transect 4 (Sept. - Dec). Vertical Exaggeration x2.5.

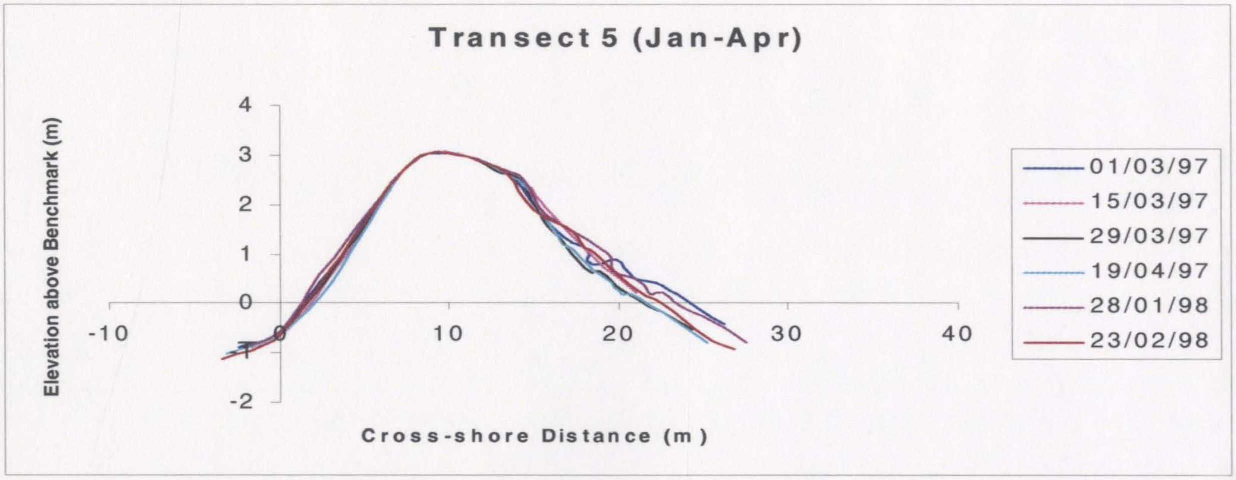

Figure A3.5a. Cross-sectional profile, Transect 5 (Jan. - April). Vertical Exaggeration x2.5.

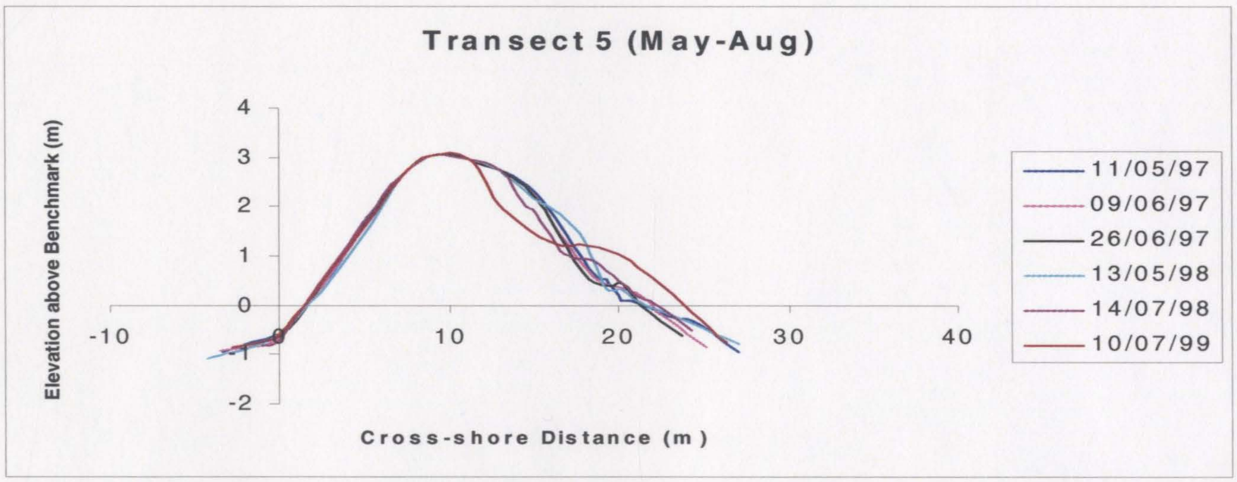

Figure A3.5b. Cross-sectional profile, Transect 5 (May - Aug.). Vertical Exaggeration x2.5.

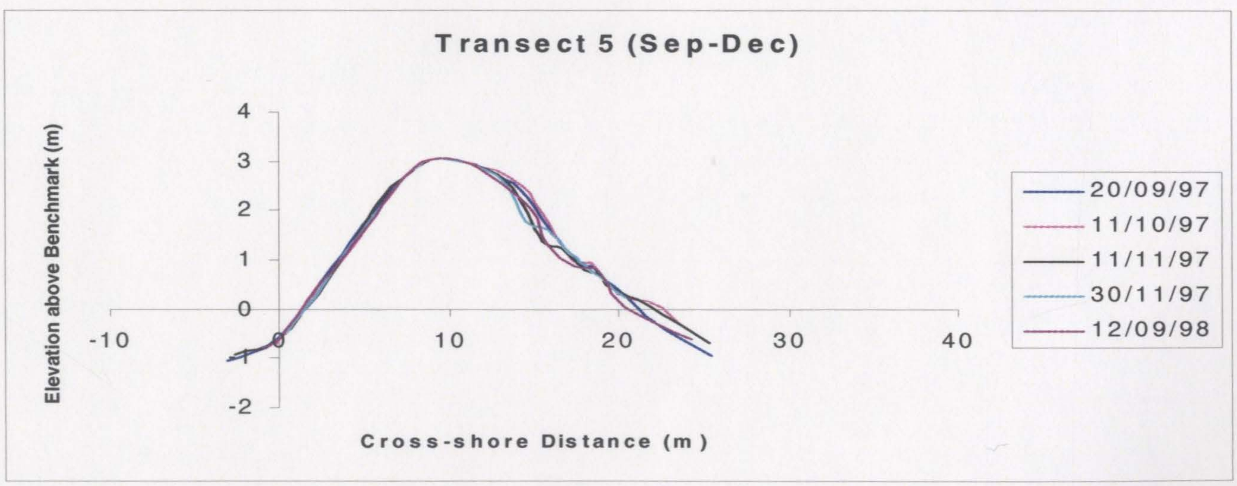

Figure A3.5c. Cross-sectional profile, Transect 5 (Sept. - Dec.). Vertical Exaggeration x2.5.

Table A3.5: Summary of Transect 5.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine pebbles to fine cobbles most common but sand and small boulders observed, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded blades, discs, and equants
Berm	Flat crested, 4 m in width, backberm steeper than bermface, composite profile; coarse pebbles and fine to medium cobbles, well rounded discs and blades most common with some equants; inert except for bermface
Lagoonal Apron	Moderate to well sorted medium pebbles to fine cobbles, well rounded discs and blades were most common, with some equants and a small number of rollers; volume fluctuated
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, minor interstitial ice and scarping (< 0.2 m), icefoot (both sides)
Comments	Southern limit of sand in littoral zone, ATV use prohibited south of transect

Table A3.6: Summary of Transect 6.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine pebbles to fine cobbles most common but sand and small boulders observed, often poorly sorted but pockets of sorted particles observed, most commonly well rounded discs, blades, equant abundance variable
Berm	Pre - reinforcement: crest 1 m wide, steep scarped bermface steep backberm, composite profile; silt to boulders, unsorted except for silt lenses exposed on lower backbarrier, clasts usually well-rounded Post reinforcement: flat crested, 4.8 m in width, elevation reduced 0.3 m, backberm steeper than bermface, composite profile; unsorted but coarsened downslope, clasts usually well-rounded; berm has eroded since the reinforcement and at the end of the survey period, the crest measured 3.1 m wide and the bermface was being scarped
Lagoonal Apron	Poorly sorted coarse pebbles and cobbles with some small boulders and fine pebbles, often well rounded but no predominate clast shape; minor volume fluctuation; boulders and coarse cobbles formed a discontinuous line at the breakpoint
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, icefoot (both sides), scarping prior to reinforcement, silt lenses, coarse clasts at breakpoint
Comments	Southern limit of breach site, reinforced in January, 1998 to reduce breach vulnerability

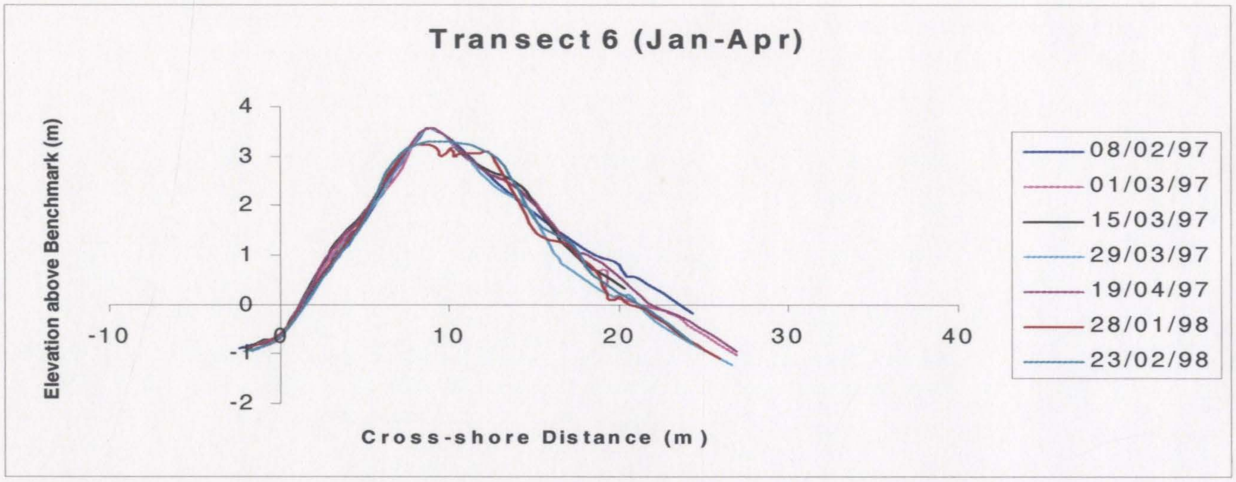

Figure A3.6a. Cross-sectional profile, Transect 6 (Jan. - April). Vertical Exaggeration x2.5.

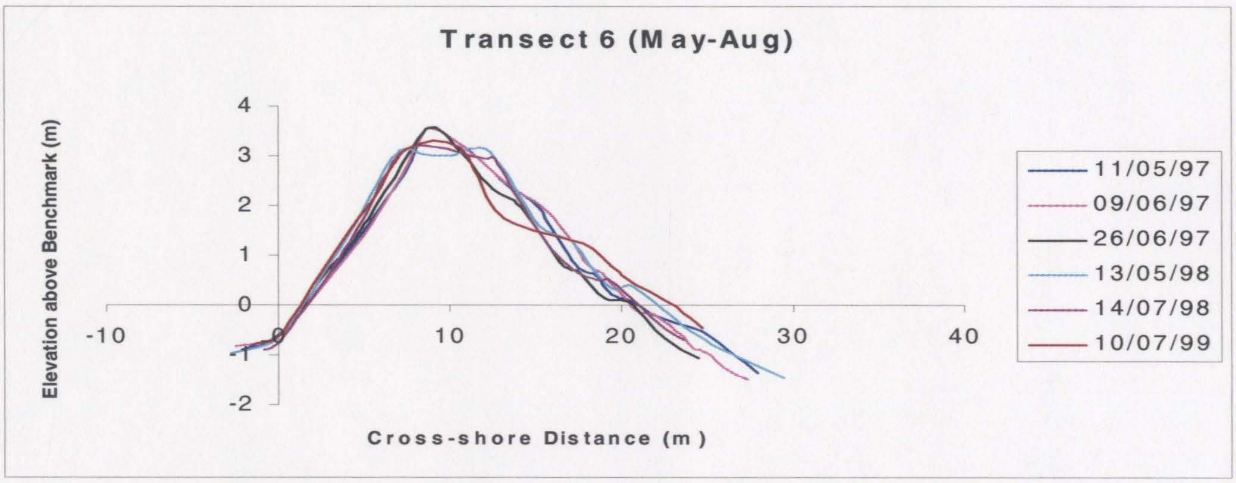

Figure A3.6b. Cross-sectional profile, Transect 6 (May - Aug.). Vertical Exaggeration x2.5.

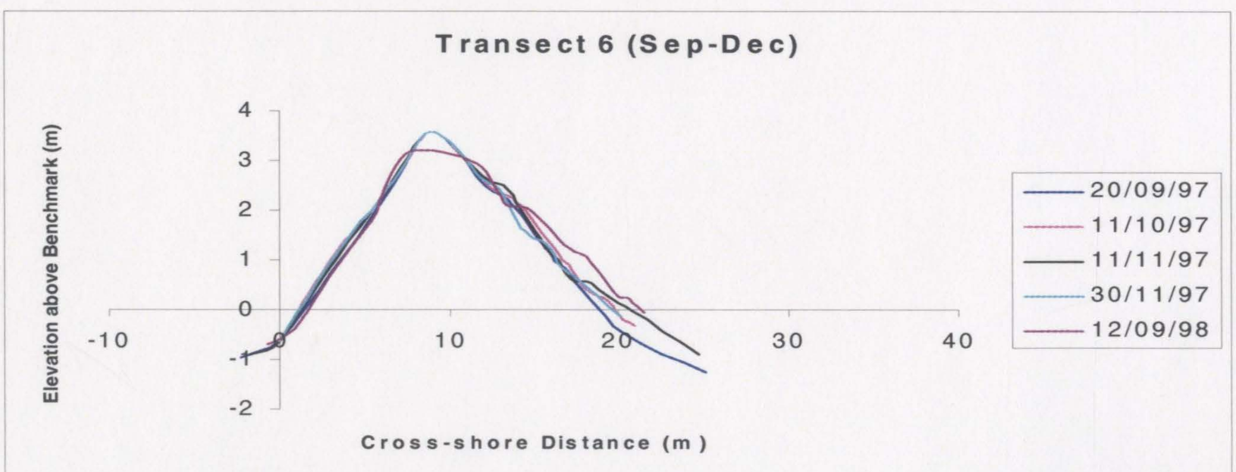

Figure A3.6c. Cross-sectional profile, Transect 6 (Sept. - Dec.). Vertical Exaggeration x2.5.

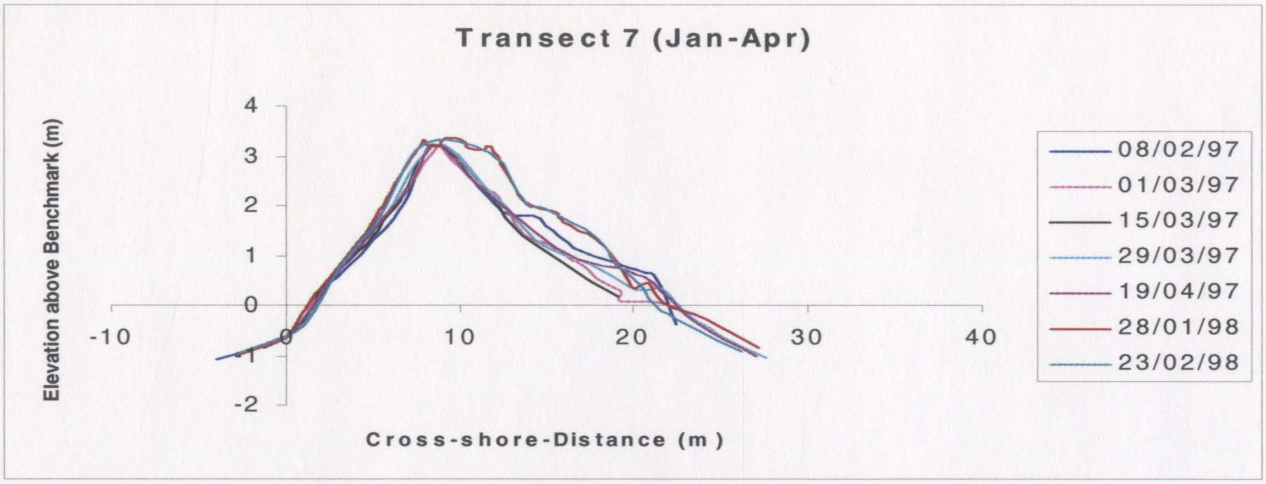

Figure A3.7a. Cross-sectional profile, Transect 7 (Jan. - April). Vertical Exaggeration x2.5.

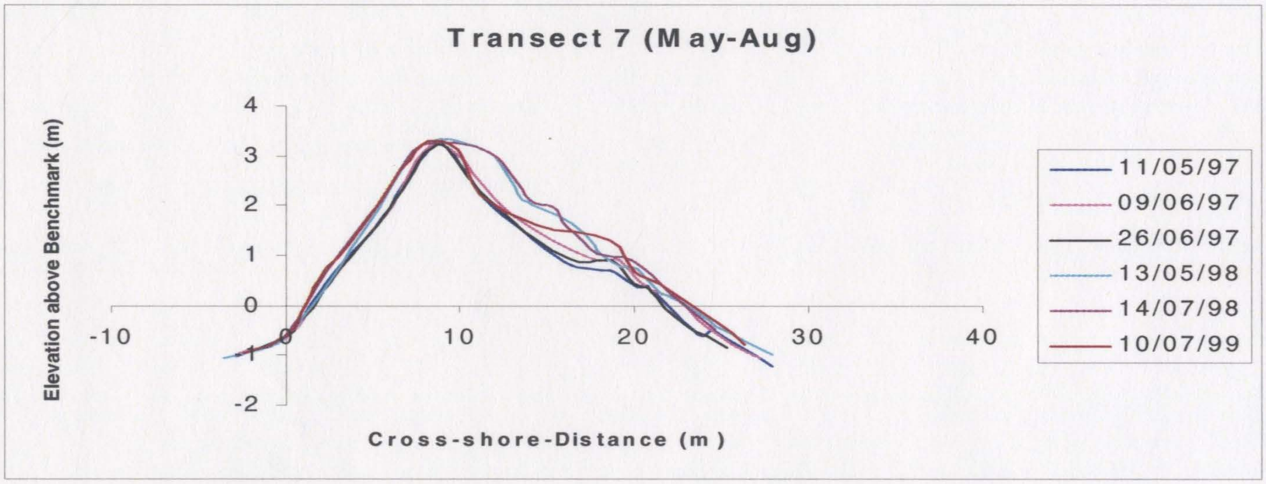

Figure A3.7b. Cross-sectional profile, Transect 7 (May - Aug.). Vertical Exaggeration x2.5.

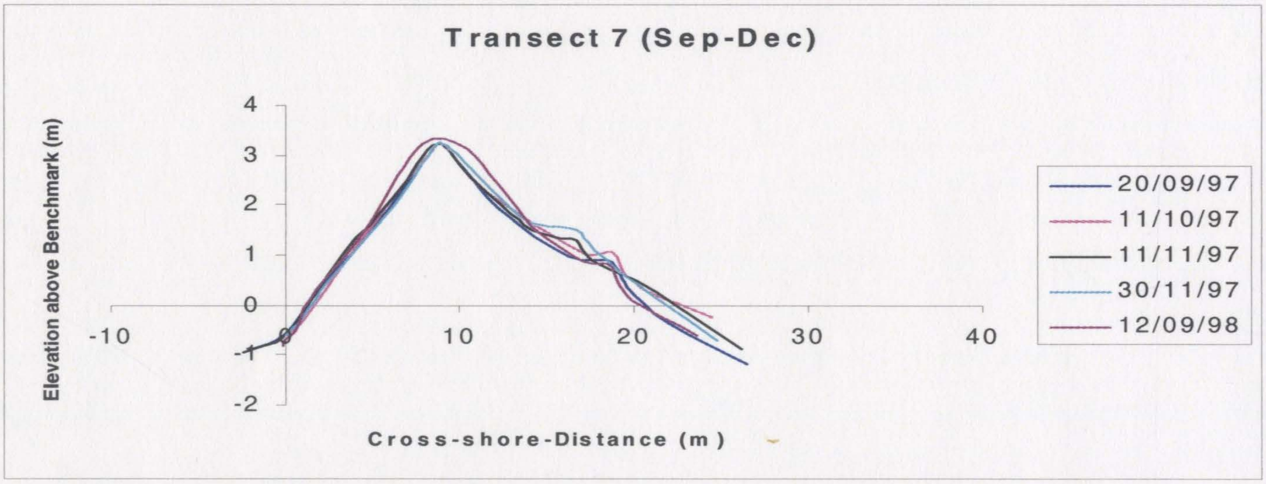

Figure A3.7c. Cross-sectional profile, Transect 7 (Sept. - Dec.). Vertical Exaggeration x2.5.

Table A3.7: Summary of Transect 7.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine pebbles to cobbles common but sand and small boulders observed, often poorly sorted but pockets of sorted particles observed, most commonly well rounded discs, blades, while equant abundance variable
Berm	Pre - reinforcement: crest centimetres wide, scarped arcuate berm, steep backberm, composite profile; silt to boulders, ropes, detritus, silt lenses, Post reinforcement: flat crested, 3.8 m in width, backberm steeper than bermface, composite profile; coarsen downslope, clasts well-rounded; berm eroded since reinforcement and at the end of the survey period, crest measured 3.1 m wide and the bermface was being scarped, berm erosion was detected by September 20, 1998 and arcuate scarping had recurred, within 1 metre north of the pre-backfill erosional maximum
Lagoonal Apron	Poorly sorted fine to coarse pebbles with some cobbles and small boulders, often well rounded but no dominant clast shape; minor volume fluctuation; boulders and coarse cobbles formed a discontinuous line at the breakpoint
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, icefoot (both sides), scarping prior to reinforcement, silt lenses, line of coarse clasts at breakpoint
Comments	Heavy erosion; reinforced in January 1998 to reduce breach vulnerability

Table A3.8: Summary of Transect 8.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine to coarse pebbles most common but sand, cobbles and small boulders observed, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded discs, blades, while equant abundance variable
Berm	Pre - reinforcement: crest 2.9 m wide, not as scarped as remainder of breach, composite profile; fine pebbles to cobbles and boulders, minor silt fraction, clasts well-rounded but no dominant shape Post reinforcement: flat crest, 4.7 m wide, composite profile; fine pebbles to small boulders, clasts well-rounded
Lagoonal Apron	Poorly sorted fine to coarse pebbles, some cobbles and small boulders, often well rounded discs, blades with few equants and rollers; minor volume fluctuation; coarse clasts formed discontinuous line at breakpoint
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, berm cusp, icefoot (both sides), scarping prior to reinforcement, coarse clasts at breakpoint
Comments	Site selected to monitor the northernmost breach area and transition between channel and northern Long Pond basin; several very large, subrounded granite boulders located 15 m north of the transect partially buried in the berm

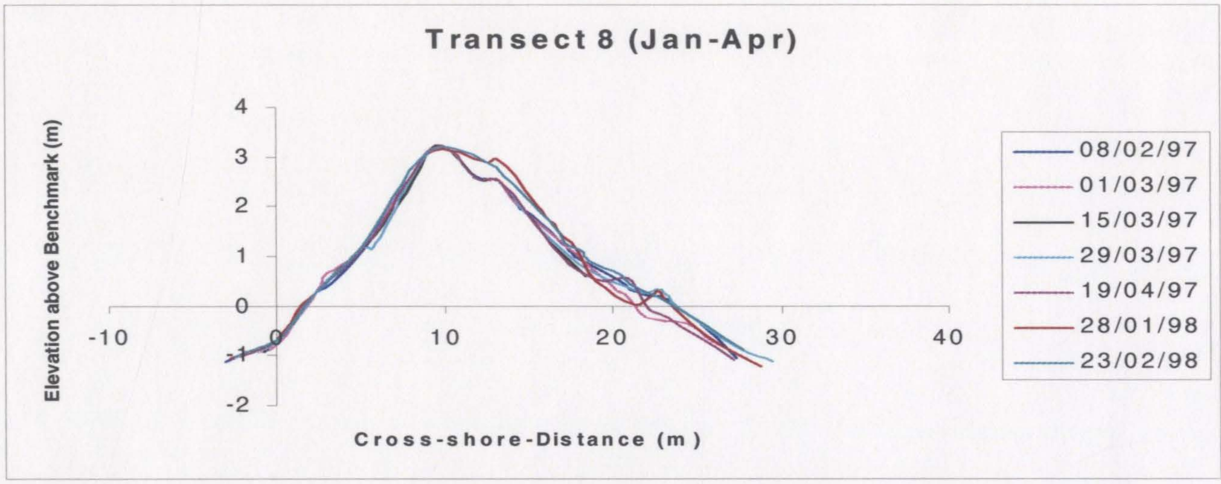

Figure A3.8a. Cross-sectional profile, Transect 8 (Jan. - April). Vertical Exaggeration x2.5.

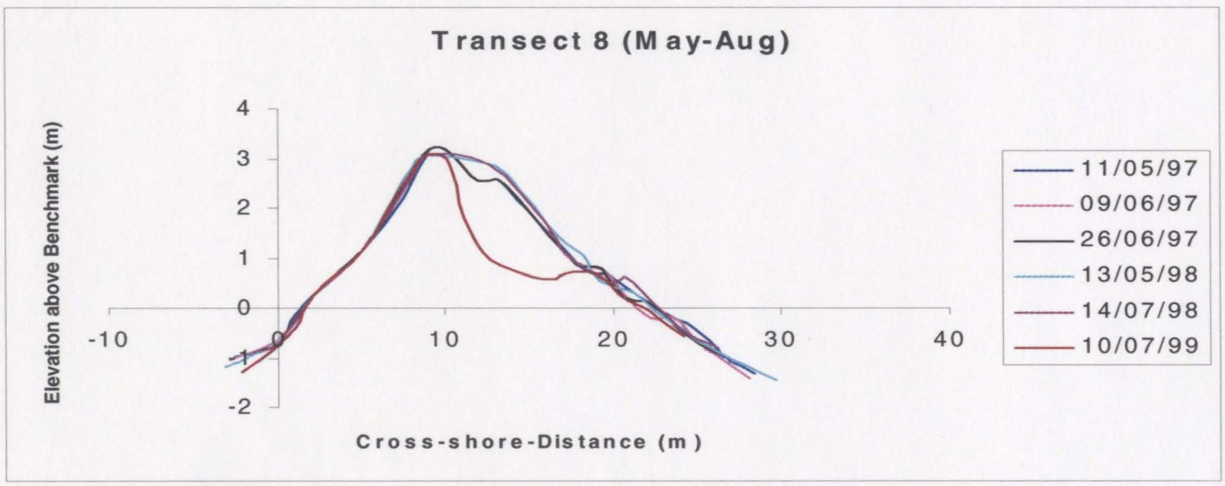

Figure A3.8b. Cross-sectional profile, Transect 8 (May - Aug.). Vertical Exaggeration x2.5.

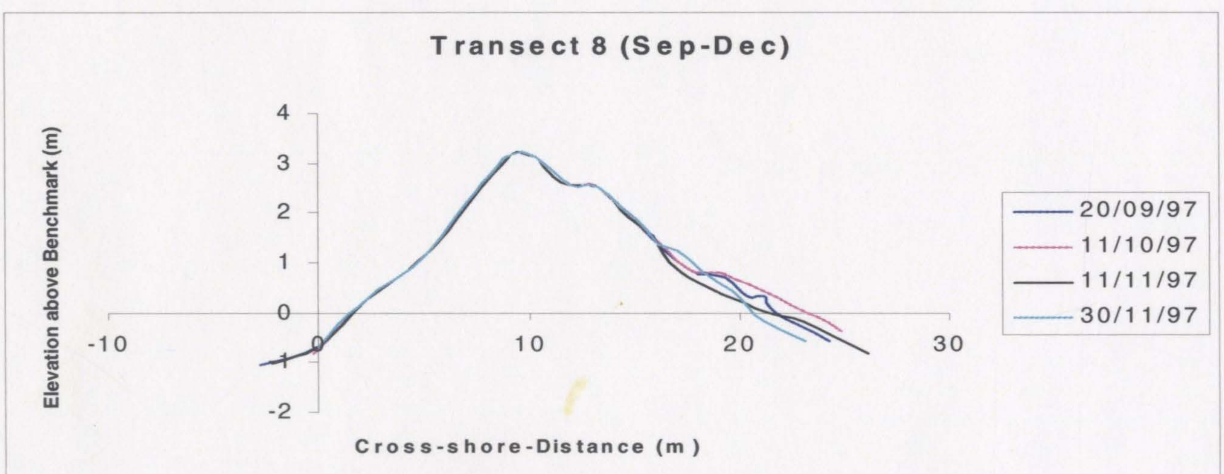

Figure A3.8c. Cross-sectional profile, Transect 8 (Sept. - Dec.). Vertical Exaggeration x2.5.

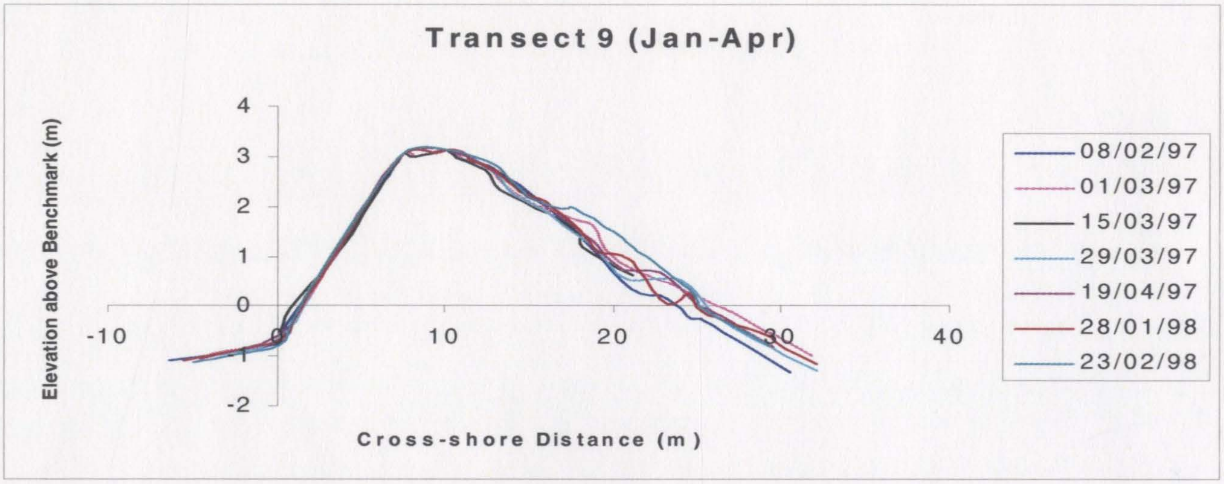

Figure A3.9a. Cross-sectional profile, Transect 9 (Jan. - April). Vertical Exaggeration x2.5.

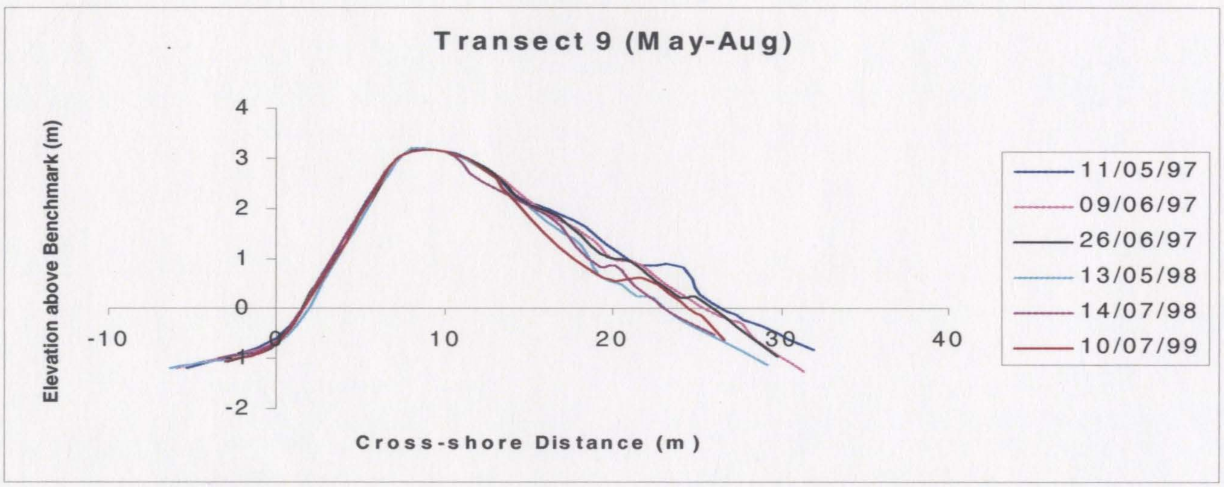

Figure A3.9b. Cross-sectional profile, Transect 9 (May - Aug.). Vertical Exaggeration x2.5.

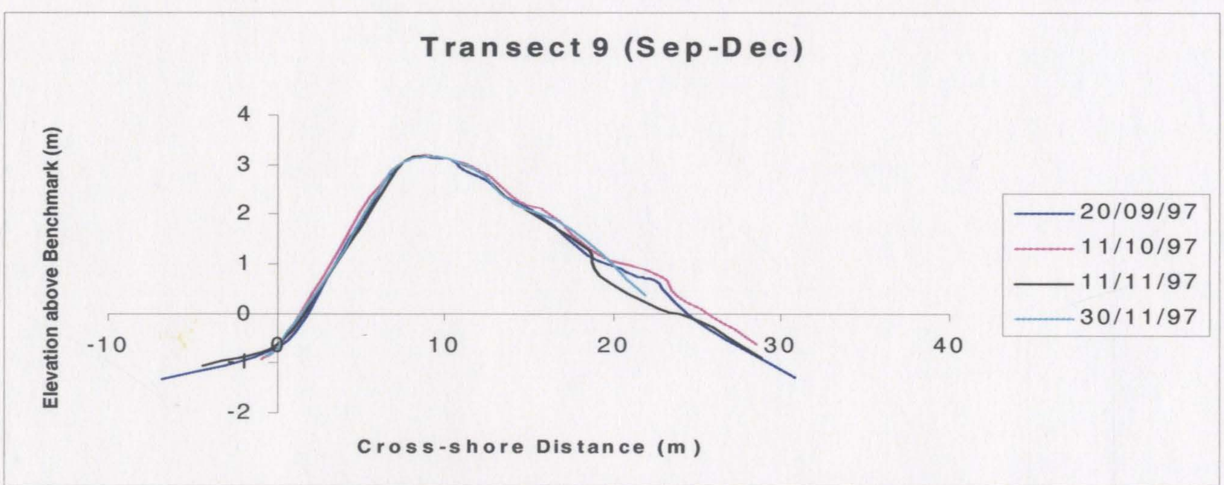

Figure A3.9c. Cross-sectional profile, Transect 9 (Sept. - Dec.). Vertical Exaggeration x2.5.

Table A3.9: Summary of Transect 9.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine pebbles to cobbles, some sand and small boulders, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded discs and blades although frequency of equants variable
Berm	Flat crested, 4.5 m wide, backberm steeper than bermface, composite profile; fine pebbles to cobbles, coarsened downslope, well-rounded discs and blades most common with some equants; inert except for bermface, berm cusps common
Lagoonal Apron	Moderate to well sorted cobbles with some pebbles, well rounded discs and blades were most common with some equants and a small number of rollers, volume fluctuated
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, berm cusps, overwash fans (inactive), icefoot (both sides)
Comments	Southern limit of overwash fan development, fans perched on backbarrier; compact measuring less than 5 m in width and 40 to 60 cm in thickness, predated survey

Table A3.10: Summary of Transect 10.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine to coarse pebbles, some sand, cobbles, and small boulders, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded discs and blades, although the abundance of equants was variable
Berm	Flat crested, 3.5 to 5.5 m wide, backberm steeper than bermface, composite profile; coarse pebbles to cobbles, with some smaller clasts, well-rounded discs and blades most common with some equants; inert except for bermface, berm cusps common
Lagoonal Apron	Moderate to well sorted cobbles with small pebble fraction, well rounded discs and blades were most common with some equants and a small number of rollers, volume fluctuated, shore-fast ice in winter
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, berm cusps, overwash fans (inactive), icefoot (both sides), harbour ice
Comments	Crest width varied with berm cusp presence - absence

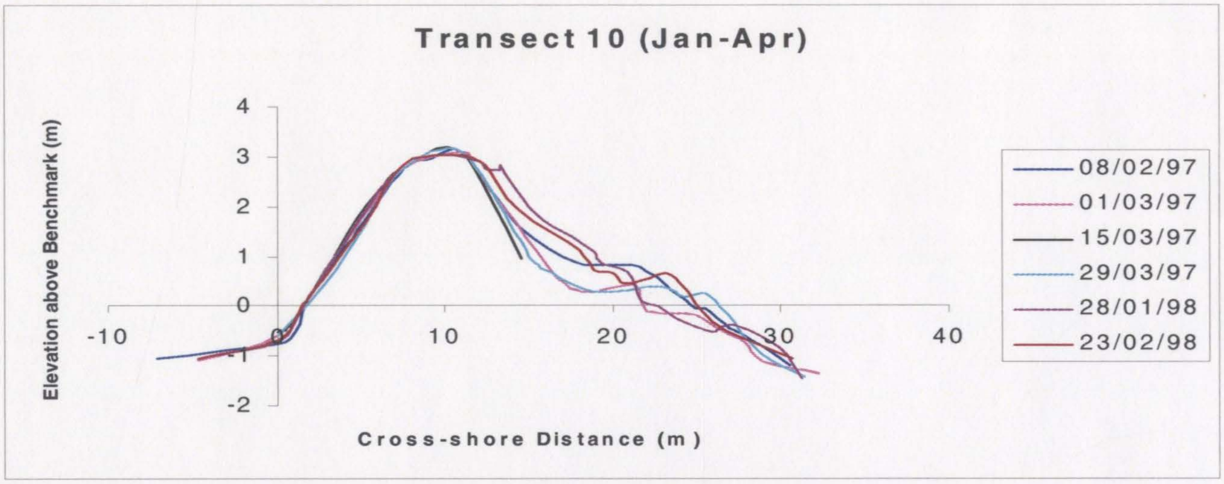

Figure A3.10a. Cross-sectional profile, Transect 10 (Jan. - April). Vertical Exaggeration x2.5.

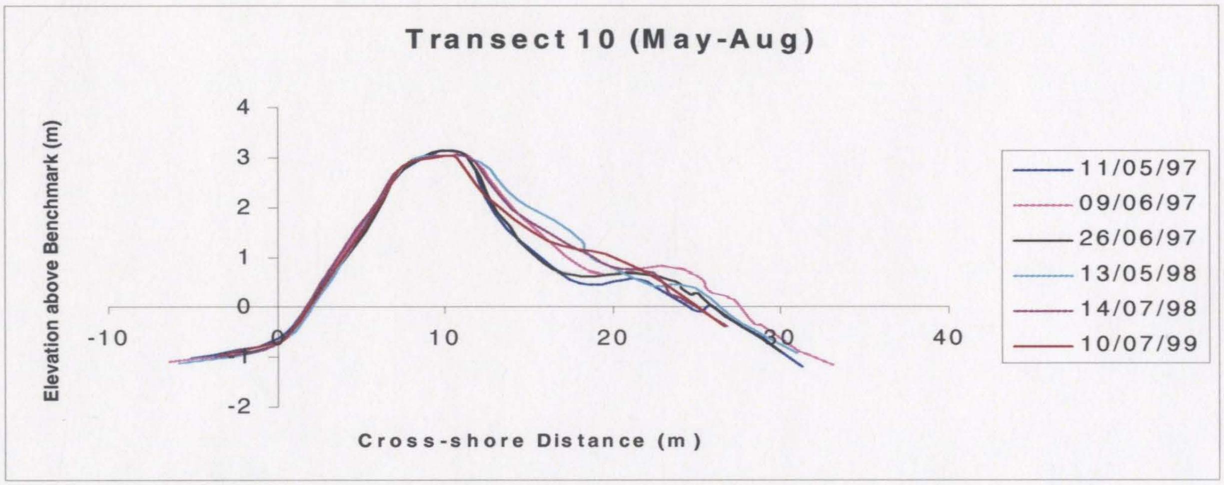

Figure A3.10b. Cross-sectional profile, Transect 10 (May - Aug.). Vertical Exaggeration x2.5.

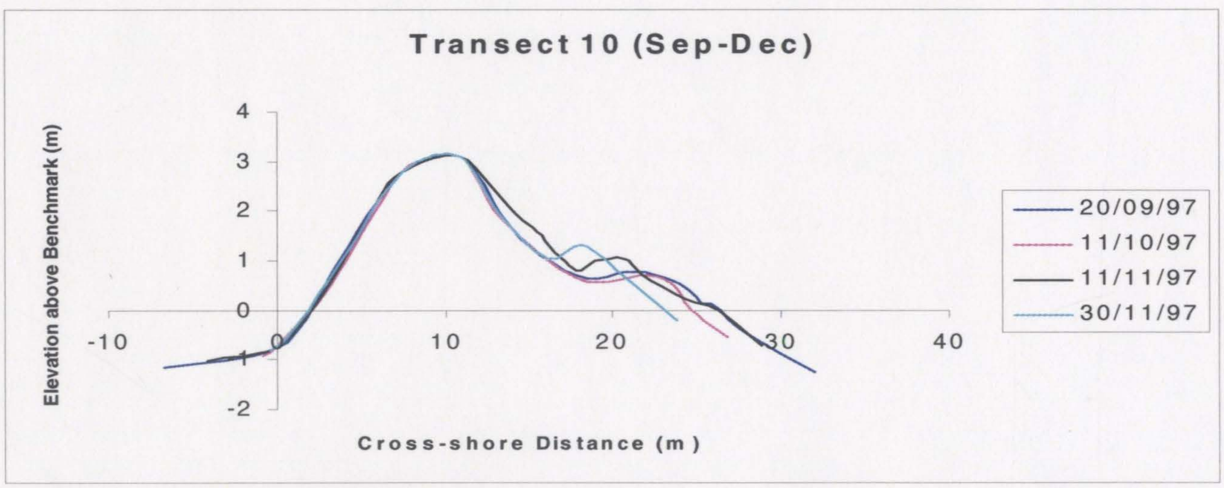

Figure A3.10c. Cross-sectional profile, Transect 10 (Sept. - Dec.). Vertical Exaggeration x2.5.

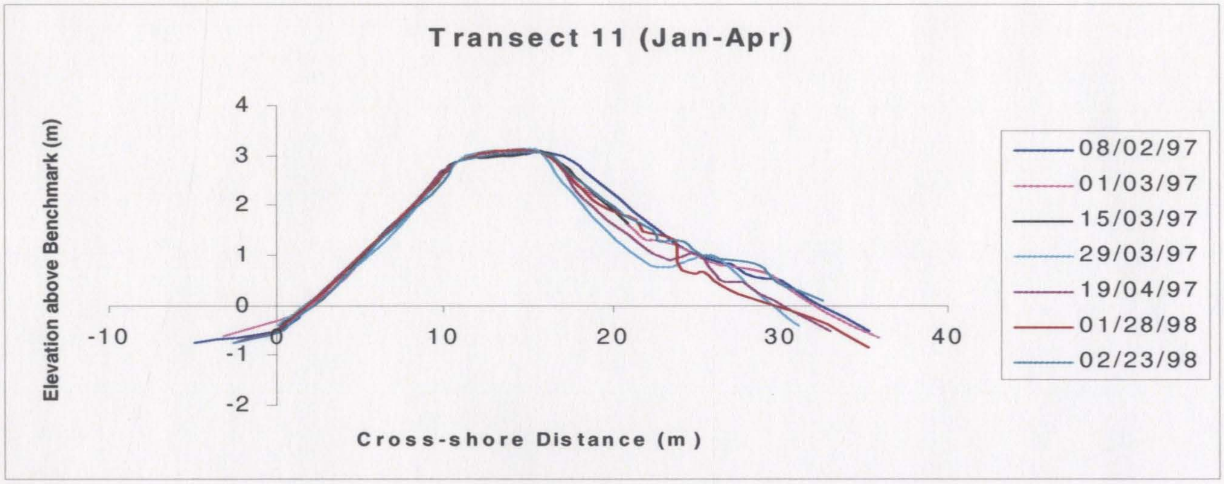

Figure A3.11a. Cross-sectional profile, Transect 11 (Jan. - April). Vertical Exaggeration x2.5.

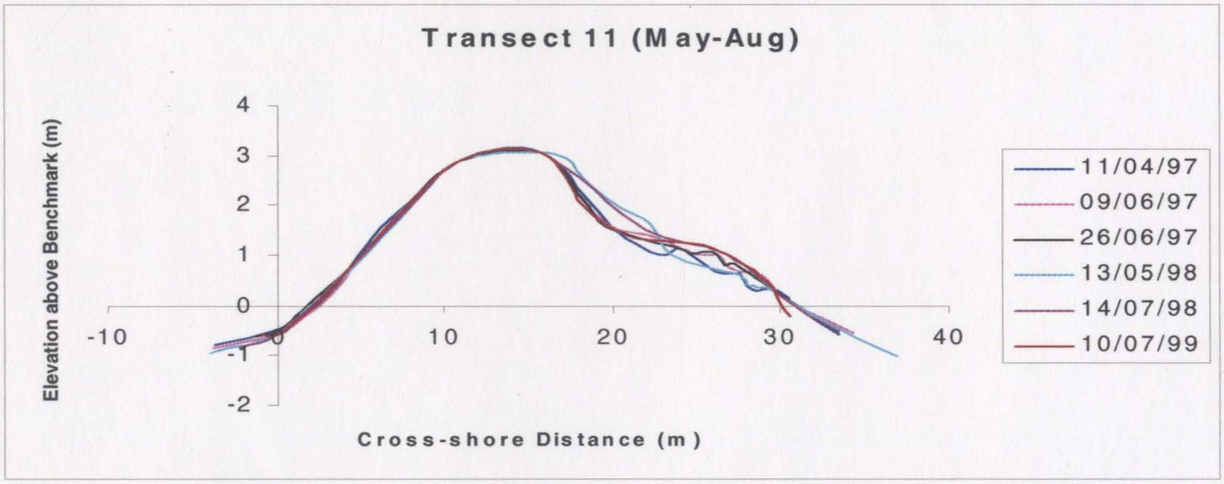

Figure A3.11b. Cross-sectional profile, Transect 11 (May - Aug.). Vertical Exaggeration x2.5.

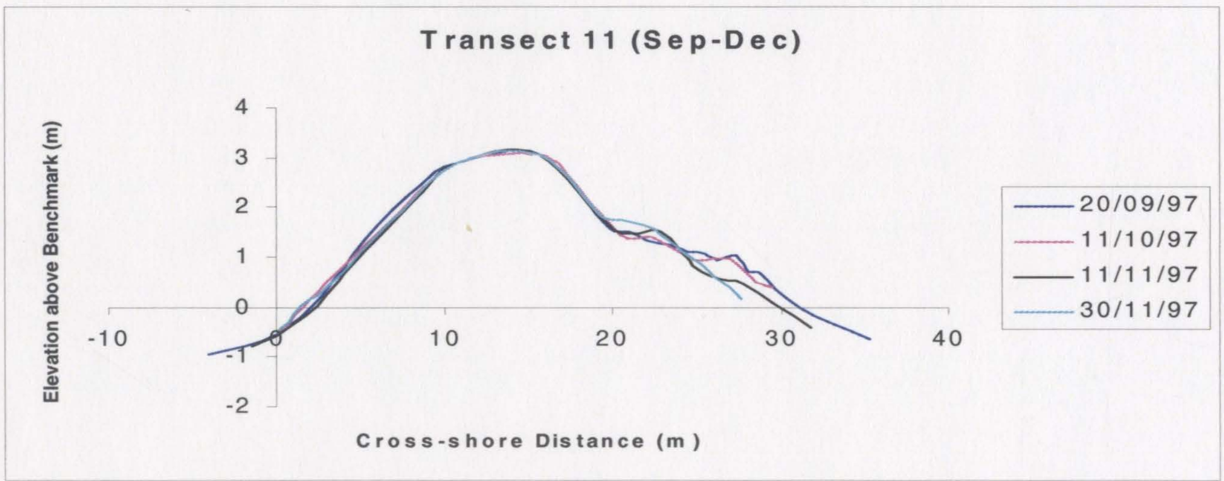

Figure A3.11c. Cross-sectional profile, Transect 11 (Sept. - Dec.). Vertical Exaggeration x2.5.

Table A3.11: Summary of Transect 11.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine to coarse pebbles sand and cobbles sometimes observed, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded blades, discs, and equants
Berm	Crest height rose seaward, 5 m wide, backberm steeper than bermface but slope decreased, composite profile; coarse pebbles to cobbles, well-rounded discs and blades most common with some equants; inert except for bermface, berm cusps common
Lagoonal Apron	Moderate to well sorted medium to coarse pebbles with some cobbles, well rounded blades and discs were most common with some equants and a small number of rollers, volume fluctuated; shore-fast ice
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, berm cusps, overwash fans (inactive), icefoot (both sides), harbour ice, pressure ridging
Comments	NLGS-selected site

Table A3.12: Summary of Transect 12.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine to coarse pebbles, some sand and cobbles and small boulders, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded discs and blades, although abundance of equants was variable
Berm	Flat crest, 6 m wide, backberm steeper than bermface but slope of each gentler than observed further south, composite slope, but transition from littoral apron to berm less abrupt; coarse pebbles to cobbles, well-rounded discs and blades most common with some equants; increase in number of subrounded clasts (still very minor fraction), some asphalt clasts; inert except for bermface, berm cusps common
Lagoonal Apron	Moderate to well sorted fine to medium pebbles with some coarse pebbles and cobbles, well rounded discs and blades were most common with some equants and a small number of rollers, volume fluctuated; shore-fast ice
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, berm cusps, overwash fans (inactive), icefoot (both sides), harbour ice, pressure ridging
Comments	Transition from a high, steep berm to the south to a lower, gentler berm to the north; benchmark lost after 23/02/98

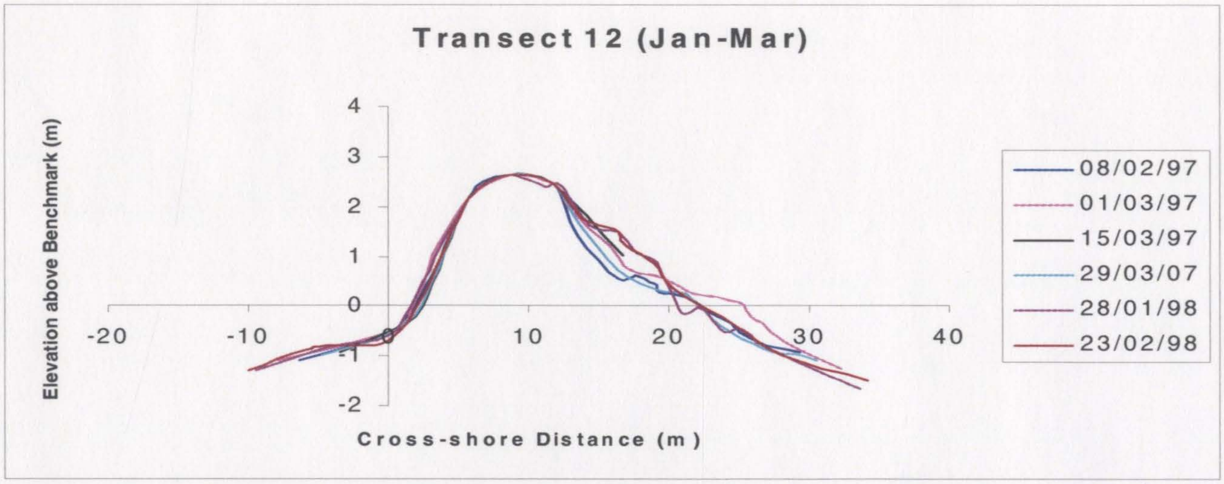

Figure A3.12a. Cross-sectional profile, Transect 12 (Jan. - Mar.). Vertical Exaggeration x2.5.

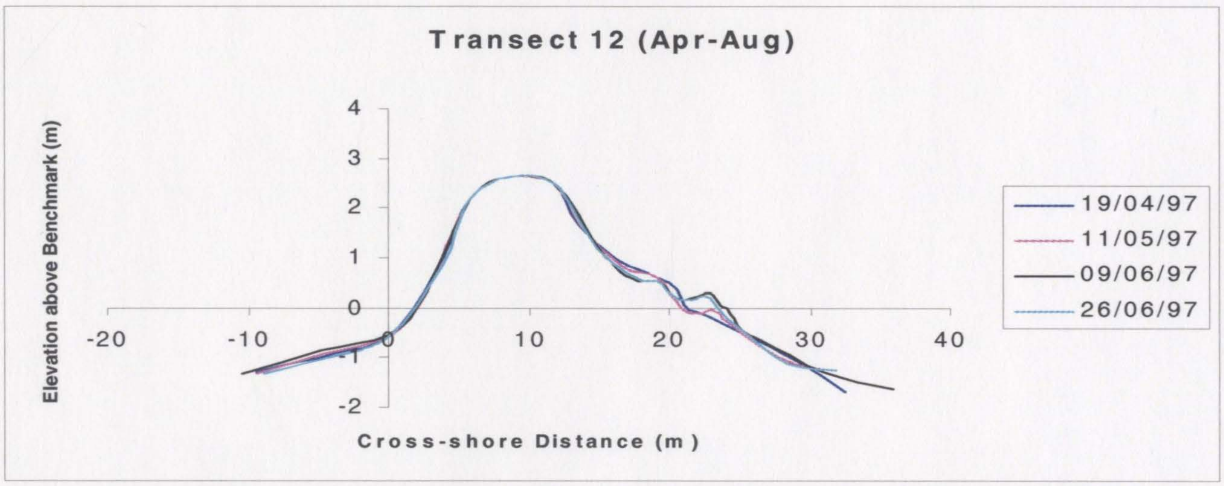

Figure A3.12b. Cross-sectional profile, Transect 12 (Apr. - Aug.). Vertical Exaggeration x2.5.

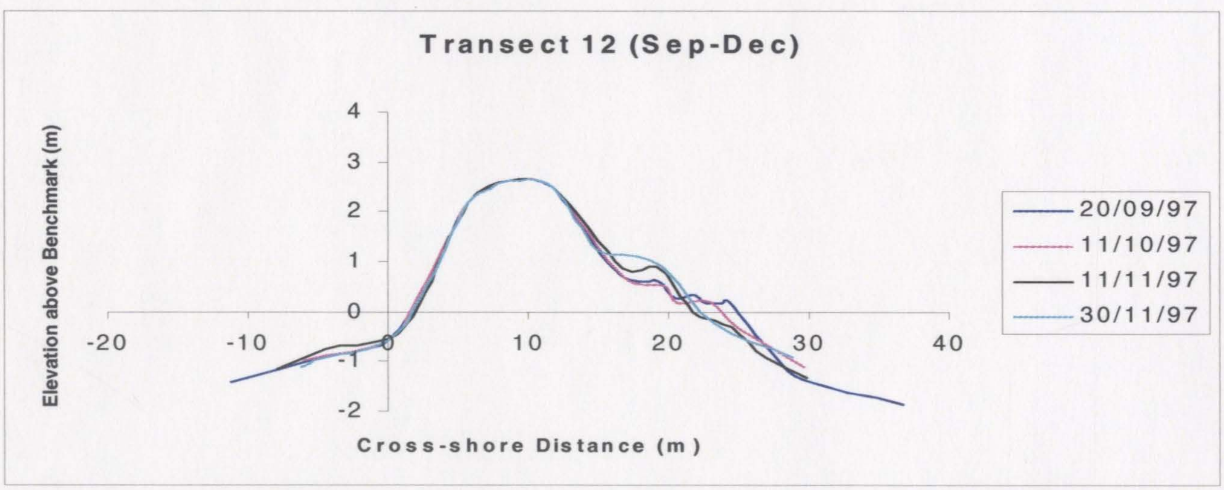

Figure A3.12c. Cross-sectional profile, Transect 12 (Sep. - Dec.). Vertical Exaggeration x2.5.

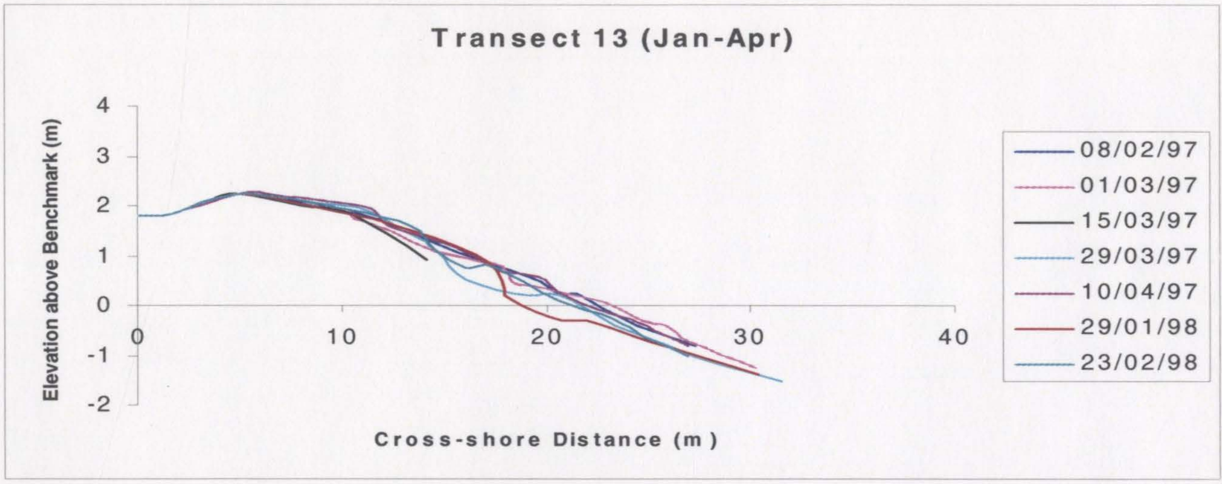

Figure A3.13a. Cross-sectional profile, Transect 13 (Jan. - April). Vertical Exaggeration x2.5.

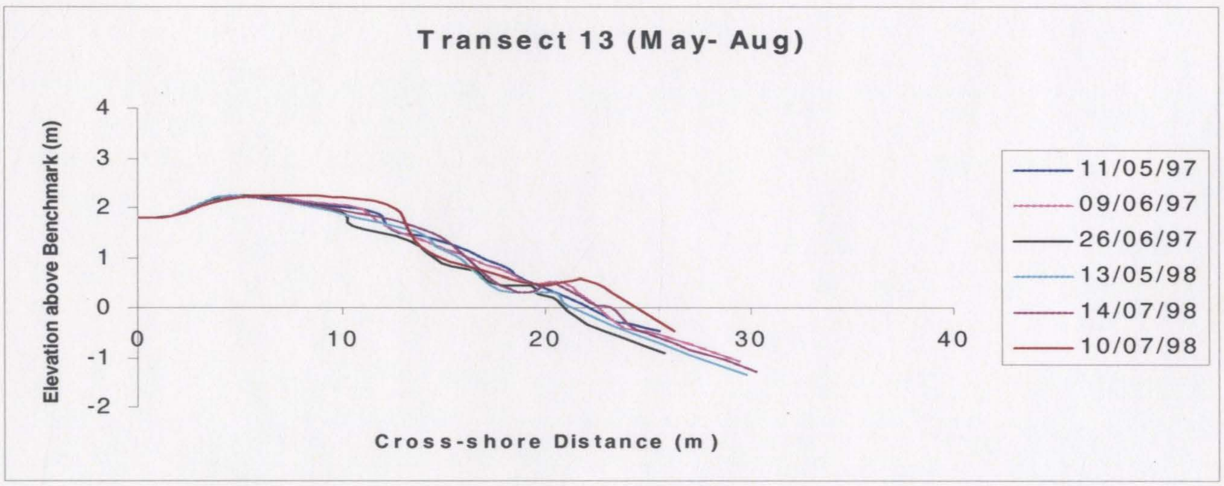

Figure A3.13b. Cross-sectional profile, Transect 13 (May - Aug.). Vertical Exaggeration x2.5.

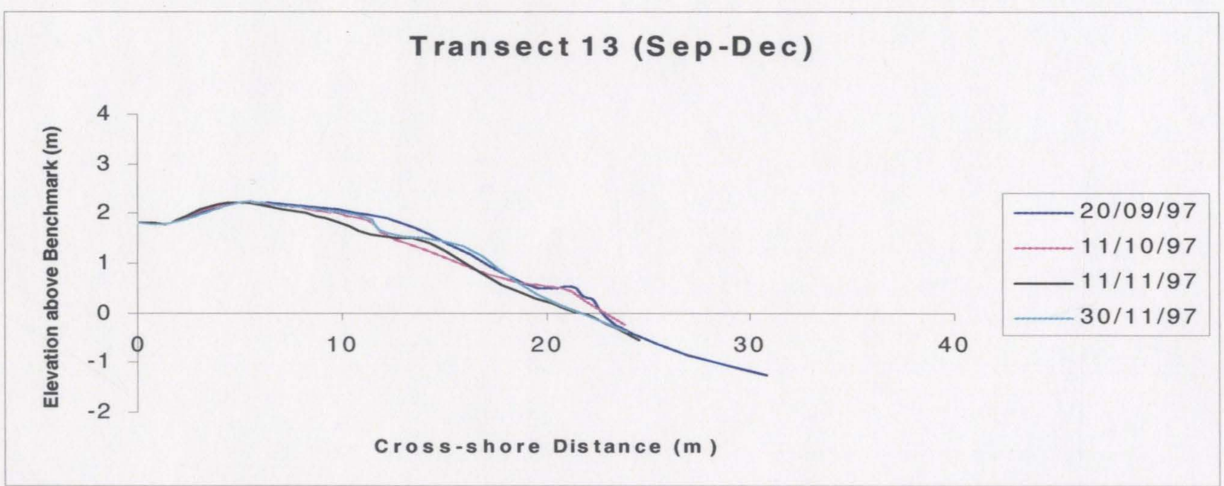

Figure A3.13c. Cross-sectional profile, Transect 13 (Sept. - Dec.). Vertical Exaggeration x2.5.

Table A3.13: Summary of Transect 13.

Littoral Apron	Wide and steep, volume and texture fluctuated but commonly coarse, no seasonal pattern; fine pebbles to fine cobbles, some sand, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded discs and blades, although abundance of equants was variable
Berm	Flat crested, up to 8 m wide, simple slope although breakpoint detectable; coarse pebbles to cobbles, well-rounded discs and blades most common with some equants; subrounded and subangular clasts more common, but still rare, rare asphalt clasts; inert except for bermface, berm cusps common
Lagoonal Apron	N/A
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, berm cusps, gravel swathes within forest cover, icefoot
Comments	Site selected by NLGS, rooted trees and stumps projecting out of gravel, residence constructed after survey period ended

Table A3.14: Summary of Transect 14.

Littoral Apron	Wide and steep, volume and texture fluctuated, no seasonal pattern; fine pebbles to cobbles, some sand, often poorly sorted but pockets of sorted particles sometimes observed, most commonly well rounded blades and discs, although abundance of equants was highly variable
Berm	Flat crested, 6 m wide, backberm steeper than bermface but neither slope steep, simple slope but breakpoint detectable; coarse pebbles to cobbles, well-rounded discs and blades common with equants, subrounded and subangular clasts observed but comprised a very minor component of the berm sediments; berm cusps common; crest truncated by road construction
Lagoonal Apron	Pre-road: moderate to well sorted fine to medium pebbles with some coarse pebbles and cobbles, well rounded discs and blades were most common with some equants and rollers, volume fluctuated; shore-fast ice Post-road: backberm adjacent to the road was scarped 60 to 80°, road flat, impermeable due to addition and compression of fines, revetement on shoreline
Sedimentary Structures	Shore-parallel swash ridges, apron cusps, berm cusps, overwash fans (inactive, obliterated by road construction), seepage pits in lagoon, icefoot (both sides), harbour ice, pressure ridging, impermeable access road, revetement on lagoonal shoreline
Comments	In 1924, barrier had high (~ 4 m), steep, berm; overwash fans larger and less spatially constrained (10 m wide, 0.2 - 0.4 m thick) than those further south; access road constructed on backbarrier during study period

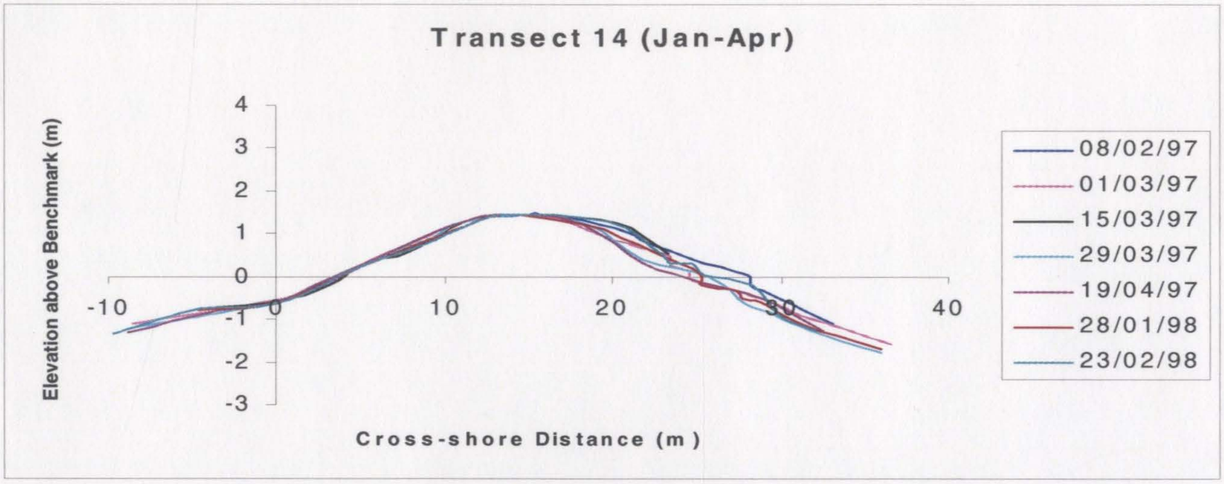

Figure A3.14a. Cross-sectional profile, Transect 14 (Jan. - April). Vertical Exaggeration x2.5.

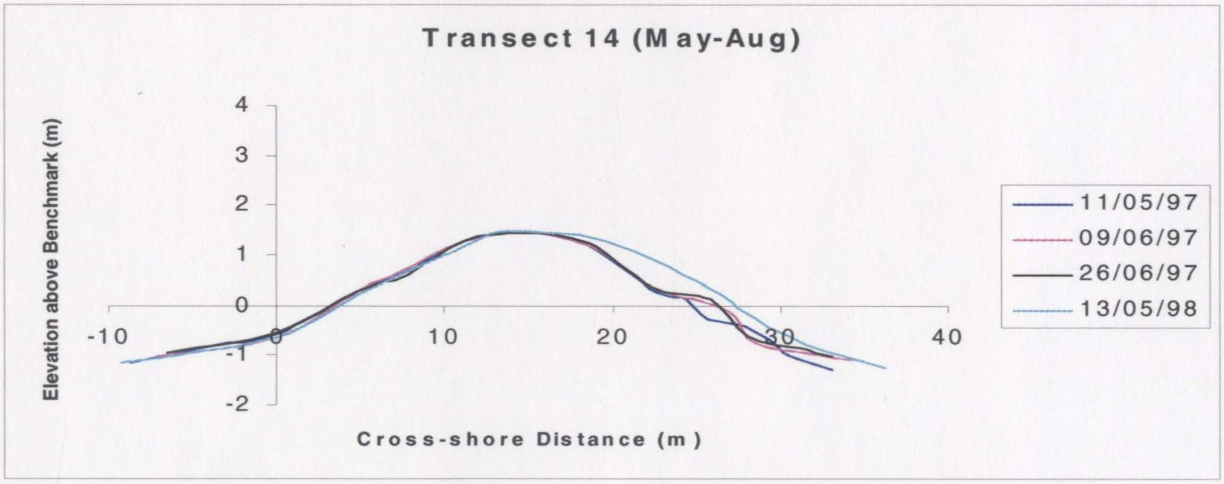

Figure A3.14b. Cross-sectional profile, Transect 14 (May - Aug.). Vertical Exaggeration x2.5.

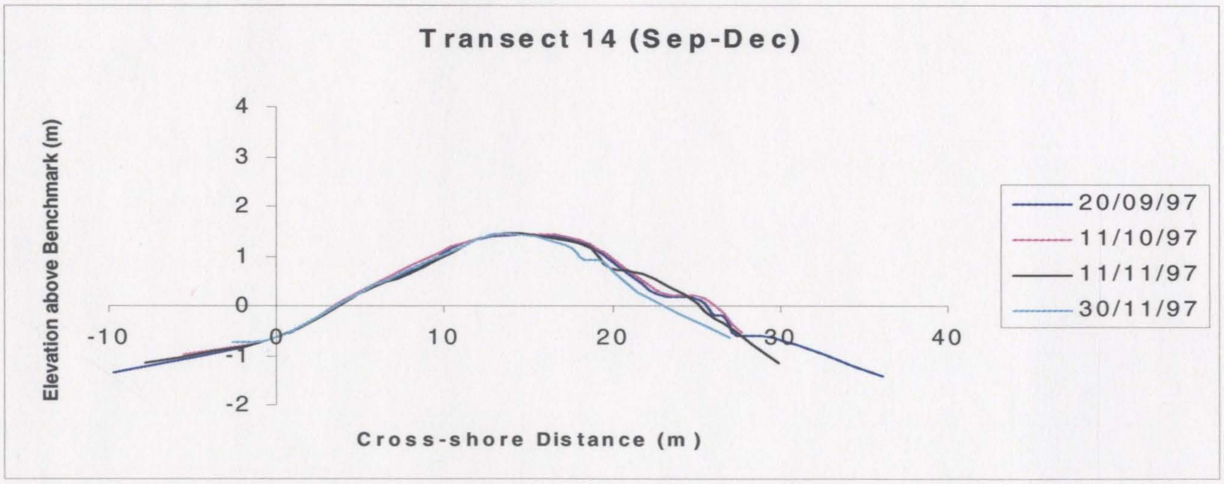

Figure A3.14c. Cross-sectional profile, Transect 14 (Sept. - Dec.). Vertical Exaggeration x2.5.

Appendix 4: Cusp Measurements

Table A4.1: Summary of cusp measurements, 01/03/97.

Type	Berm
Distribution	North of Transect 10
Wavelength	10.6 - 21 m
Swash Length	1 - 3.9 m south of Burnt Island, 5.7 to 7.55 m north of Burnt Island
Depth	0.68 - 1.02, decreased slightly south to north
Skew	Symmetrical near Transect 13, skewed slightly north between Transect 10-12, skewed slightly south between Burnt Island and mainland
Spacing	Groupy with cusp absence zones
Stacking	Transect 10 (Lower cusp truncated upper cusp)
Horns	Development improved from south to north, usually similar slope and texture as berm but some reverse grading evident in northern cusps
Embayments	Some obscured by icy snow; where exposed, texture slightly finer than horns; elevation consistent alongshore where not stacked
Comments	Wavelength decreased north to south within groups

Table A4.2: Summary of cusp measurements, 21/03/97.

Type	Berm
Distribution	North of Transect 10
Wavelength	11.2 - 23.1 m
Swash Length	6.2 - 15.03 m, larger swash lengths associated with larger wavelengths
Depth	1.04 - 3.14, decreased from south to north
Skew	Skewed south, Transect 10-14, northern skew to north, due to horn size
Spacing	Groupy with intervals of no cusp development
Stacking	None
Horns	Strong reverse grading, distinct from berm, upper clasts very coarse
Embayments	Finer than horns but occasionally very coarse in centre; elevation consistent
Comments	Cusps formed by 1.5 - 2 m swells,15/03/97, wave period 14 s

Table A4.3: Summary of cusp measurements, 29/03/97.

Type	Berm
Distribution	North of Transect 8
Wavelength	14.7 - 22.2 m
Swash Length	7.2 - 12 m, longest swash lengths at Transect 10
Depth	1.23 - 2.78, greatest depth at Transect 10
Skew	Symmetrical, except southernmost skewed slightly north
Spacing	Groupy with intervals of no cusp development
Stacking	None
Horns	Poorly developed, usually similar slope and texture as berm
Embayments	Similar to horns; elevation consistent alongshore
Comments	Cusp near Transect 9 contained a triangular structure on the northern side of the bay, 1 m in length and 1.2 m across the base, consisting of fine to medium discose pebbles, structure last observed 20/09/1997 despite some cusp reworking further north on at least one occasion

Table A4.4: Summary of cusp measurements, 26/05/97.

Type	Berm
Distribution	North of Transect 8 (Single cusp measured at Transect 10)
Wavelength	18.7 m
Swash Length	7.24 m
Depth	2.48 m
Skew	Symmetrical
Spacing	Groupy with intervals of no cusp development
Stacking	None
Horns	Poorly developed, similar slope and texture as berm
Embayments	Similar to horn; elevation consistent alongshore
Comments	Similar to previous survey: cusps may have been modified instead of being reworked into new cusps

Table A4.5: Summary of cusp measurements, 20/09/97.

Type	Berm
Distribution	North of Transect 8, reworking limited to north of Transect 10
Wavelength	10.44 - 22.8 m
Swash Length	6.38 - 10.03 m
Depth	1.26 - 2.45, decreasing from south to north
Skew	South, skew a function of differences in horn size.
Spacing	Groupy with intervals of no cusp development
Stacking	None
Horns	Poorly developed, similar slope and texture as berm
Embayments	Similar to horns; elevation consistent alongshore
Comments	Cusps between Transects 8 and 10 did not seem reworked

Table A4.6: Summary of cusp measurements, 11/11/97.

Type	Apron and Berm
Distribution	Apron: Northern breakwater to Transect 2 Berm: North of Transect 8
Wavelength	Apron: 4.6 - 5.1 m Upper berm: 8.5 - 11 m Lower berm: 11.7 -12 m Single: 11 - 15.6 m
Swash Length	Apron: 3.3 - 3.5 m Upper berm: 3- 3.5 m (truncated) Lower berm: 2.3 - 6.5 m (decreased from south to north) Single: 5. - 6.7 m
Amplitude/ Depth	Apron: 0.15 - 0.2 m Upper berm: 0.7 - 1.16 m Lower berm: Depth 0.87 - 1.58 m (decreased from south to north) Single: 1.35 - 2.25 m
Skew	Apron: Symmetrical grading to south, function of horn orientation Upper berm: Symmetrical Lower berm: Symmetrical Single: Symmetrical except slightly south at Transect 10

Spacing	Apron: Rhythmic Berm: Groupy with cusp absence zones, size consistent within groups compared to previous surveys
Stacking	Apron: None Berm: Discontinuous stacking (did not consist of two distinct tiers) , near Transects 9, 11, and 13, lower cusps smaller and truncated upper cusps
Horns	Apron: Well developed, on top of beach plane, indeterminate grading Upper berm: Similar to berm except coarser horns at Transect 13 Lower berm: Similar texture to berm except coarser at Transect 13 Single: North of Transect 10, horns were coarser than the surrounding gravels; those to the south were similar in slope and texture as berm
Embayments	Apron: Finer than horns Upper berm: Little differentiation between horn and bay Lower Berm: Coarser sediment in embayment at Transect 9 Single: Similar to horns; lower stacked and single cusp elevations consistent
Comments	Apron: Cusp size increased from north to south; Berm: Stacking spatially limited, consisting of one or two stacked cusps per occurrence; maximum wavelength recorded north of Transect 8, while the maximum swash length and cusp depth recorded at Transect 10

Table A4.7: Summary of cusp measurements, 30/11/97.

Type	Berm
Distribution	North of Transect 9
Wavelength	12 - 15.5 m
Swash Length	4.1 - 5.3 m
Depth	1.2- 2.6 m
Skew	Mainly south due to horn size; symmetrical at Transect 9 and 11
Spacing	Groupy with intervals of no cusp development
Stacking	Transect 10 (Lower cusp truncated upper cusp)
Horns	Reverse graded south of Transect 11, similar to berm between Transect 11 and 13, coarser than berm north of Transect 13
Embayments	Coarser than horns south of Transect 11, similar to horns, Transect 11 - 13, finer than horn north of Transect 13; elevation consistent alongshore
Comments	No evidence of stacking indicating a great deal of bermface reworking

Table A4.8: Summary of Cusp Measurements, 15/12/97.

Type	Apron and Berm
Distribution	Burnt Island Vicinity (barachois was not completely surveyed)
Wavelength	Apron: 9.25 m (average) Berm 19 m
Swash Length	Apron: 9 m (average) Berm: N/A
Amplitude/ Depth	Apron: 0.2 - 0.3 m Berm: N/A
Skew	Apron: South, due to orientation of horns, may have varied alongshore Berm: Symmetrical
Spacing	Apron: Rhythmic Berm: Indeterminate
Stacking	Consisted of berm cusps positioned above apron cusps north of Transect 8; apparently single tier of cusps on berm
Horns	Apron: well developed, reverse graded, projected above the beach plane Berm: Reverse graded, coarser than berm texture
Embayments	Apron: Finer than horns, some sand evident Berm: Finer than horns, elevation appeared consistent alongshore
Comments	Survey did not extend south of Burnt Island; apron cusps appeared continuous along barachois based upon observed pattern of wave breakage south of Burnt Island; pattern also indicated that these cusps were roughly the same size, but the skew direction had been reversed south of stress point; Only one berm cusp inspected, but the previous survey had not documented berm cusps of this size at this location

Table A4.9: Summary of cusp measurements, 23/02/98.

Type	Apron
Distribution	Entire length of barachois
Wavelength	8.4 - 15.2 m
Swash Length	4.75 - 7.9 m
Amplitude	0.3 - 0.45 m

Skew	Skew varied alongshore, horn size and orientation: south of inflection point, skewed south; between inflection point and stress point, skewed north; near stress point, symmetrical; north of stress point, skewed south but skew angle decreased near Burnt Island, north of Burnt Island, skewed north
Spacing	Rhythmic
Stacking	Berm cusps positioned above apron cusps north of Transect 8
Horns	Coarser than surrounding sediments, weak reverse grading in southern cusps
Embayments	Below beach plane, variable texture, sometimes resembled adjacent littoral apron, but often hosted small amount of sand in centre
Comments	Cusp dimensions varied with littoral apron width and the longest wavelengths and swash lengths occurred near Transects 4 and 10

Table A4.10: Summary of cusp measurements, 13/05/98.

Type	Berm
Distribution	North of Transect 8
Wavelength	8 - 14.2 m, increasing from south to north
Swash Length	2.8 - 5.95 m increasing from south to north
Depth	0.75 - 1.2 m increasing from south to north
Skew	South, due to differences in horn size
Spacing	Not groupy but not truly rhythmic either
Stacking	None
Horns	Poorly developed, similar in texture and slope as berm
Embayments	Similar to horns; elevation consistent alongshore
Comments	Cusp size increased from south to north, cusp spacing irregular but cusp occurrence consistent north of Transect 8