COASTAL GEOMORPHOLOGY OF SOUTHWEST BANKS ISLAND, NWT: HISTORICAL AND RECENT SHORELINE CHANGES AND IMPLICATIONS FOR THE FUTURE

KARISSA D. BELLIVEAU

Your file Votre référence
ISBN: 978-0-494-42079-9
Our file Notre référence
ISBN: 978-0-494-42079-9

COASTAL GEOMORPHOLOGY OF SOUTHWEST BANKS ISLAND, NWT: HISTORICAL AND RECENT SHORELINE CHANGES AND IMPLICATIONS FOR THE FUTURE

by

Karissa D Belliveau

A thesis submitted to the

School of Graduate Studies

in partial fulfillment of the

requirements for the degree of

Master of Science

Department of Environmental Science/Faculty of Science
Memorial University of Newfoundland

Submitted April 2007

St. John's Newfoundland

Abstract

Predicted changes in Arctic climate include decreased sea-ice extent, increased storm frequency, and sea-level rise. The western Canadian Arctic is highly sensitive to sea-level rise and climate change due to, high ground ice concentrations in unlithified sediments, increased storm effectiveness, decreased sea-ice extent, and high erosion rates. The southwest coast of Banks Island has similar climate conditions, substrates and ground ice contents. Publicized community concern about changing coastal conditions led to Sachs Harbour, NWT being chosen as one of the first coastal sites for detailed study as part of an ArcticNet project.

Sachs Harbour and the southwest coastline of Banks Island is dominated by low unlithified coastal bluffs containing segregated ice lenses and ice-rich silty sand horizons. Initial investigations identified three possible mechanisms for coastal erosion: wave activity and storm events, rising sea level and decreasing sea-ice extent, and increased thermal ablation coupled with regional submergence.

Thirty-one coastal surveys, nearshore bathymetric surveys, and sediment samples were used to determine present coastal processes and rates change. Suspended particulate matter before and after a precipitation event were used to determine the effectiveness of runoff. Aerial photographs and satellite images were used to determine historical change along the coastline and within the community. Sea ice and storm records were analysed from the 1950s to present in order to determine the frequency of events and the associated sea-ice conditions.

Coastal bluffs along the southwest coast are undergoing retreat at variable rates, dependant on ice content within sediments. Two main areas of retreat occur, to the west of Martha Point in an area of exposed ground ice with retreat rates of 5.9 m since 2003, and to the southeast of the community where fine grained sediment and narrow beaches leave the bluffs exposed. Within Sachs Harbour, most coastal bluffs are not presently retreating with the exception Line 2 which is retreating approximately 0.40 m/a.

Storm records for Sachs Harbour indicate that event frequency throughout the record varies, with declining storm frequency since 2000. Due to the presence of sea ice in the region during the open-water season, storm events often have limited fetch which minimizes the impact on the southwest coast.

Aerial photograph and satellite image analysis have indicated four major depositional areas, Sachs Spit, Martha Point Spit, Sachs Landing Beach, and Cape Kellett Spit. Areas of erosion include, west of the Martha Point Spit, within the community, and to the southeast of the community. Sediment transport is a complex. There are two major sediment transport cells, a large cell toward the west and a smaller cell moving sediment towards the community.

As thermal erosion is the dominant mechanism of coastal change in Sachs Harbour and throughout the study area, armouring or other anthropogenic measures to prevent erosion within the community will be ineffective. As the community is fronted by a large beach, community expansion on the coastal bluffs is not advisable. With warming conditions in the region, thermal retreat will continue and as sea ice extent decreases, the effectiveness of storm events of eroding this coastline will increase.

Acknowledgements

I would like to acknowledge the hard work and dedication of my supervisor Norm Catto for his assistance both in the field, throughout the writing process and the entire duration of this Master's project. Thanks to my committee members Evan Edinger, Don Forbes, and Kathleen Parewick, for giving advice and keeping a visualization of the scope and context of this project. A special thanks to Dave Frobel, Jon Keogak, Gavin Manson, and Dominque St-Hiliare for their contributions during in the field and to Tracey Novak for her lab assistance with sediment samples. I would also like to acknowledge my funding sources, ArcticNet Network of Excellence, Canadian Climate Impacts and Adaptations Directorate, Natural Resources Canada, and a grant from the Northern Scientific Training Program. Finally I would like to thank my family and friends, especially Tanya Brown, Heather Hickman and Michael Aubie for their constant wisdom and moral support. Also the assistance, generosity, and knowledge of the community of Sachs Harbour, NWT were invaluable to the completion of this project

Table of Contents

List of Tables

List of Figures

List of Appendices

Chapter 1 – Introduction

1.1 – Introduction

Changes in Arctic climate and their impacts are of global importance. Predicted changes include decreased sea-ice extent, increased storm frequency, and sea-level rise (IPCC 2001a; ACIA 2005a; Manson *et al.* 2005b). In the Beaufort Sea, climate warming is expected to cause thawing of permafrost leading to accelerated erosion of the coastline, reduction of sea-ice thickness and extent, and rising sea level (Manson *et al.* 2005b).

Extensive research has been conducted along the Beaufort Sea coast to evaluate and address concerns that coastal erosion is damaging and destroying infrastructure, particularly in Tuktoyaktuk (Johnson *et al.* 2003). High concentrations of ground ice in unlithified sediments and locations exposed to storm events suggest this shoreline is highly susceptible to mechanical and thermal erosion during open-water storms (Harper *et al.* 1985; Solomon 2005). Increased storm events and increased periods of open-water which are predicted from climate scenarios in this region (IPCC 2001a; ACIA 2005a) may increase the effectiveness of storms at eroding this coastline.

The southwest coast of Banks Island has similar substrate types, ground-ice contents, sea-ice conditions, relative sea-level rise patterns and climate conditions to those at Tuktoyaktuk. Prior to this study, there had been relatively little research to determine how the coastline of southwest Banks Island has responded to changing climate. This research will aid in understanding how the coastline will evolve over the coming decades and the resulting impacts on the community of Sachs Harbour.

1.2 – Rationale and Objectives

The southwest coastline of Banks Island has been studied in the past (Harry *et al.*1983) but little work has been completed in the area since the 1980s. Previous studies in this region have suggested this area is highly sensitive to potential climate-change effects (Shaw *et al.* 1998). Residents of the community of Sachs Harbour have also expressed concern about changing coastal conditions in recent years (Ashford and Castleden 2001; Berkes and Jolly 2001; Nichols *et al.* 2004). As a component of the ArcticNet program, a geomorphic study of the southwest coastline of Banks Island was initiated to determine which areas are vulnerable to changing climate conditions and how these changes will affect the community. Once these changes are recognized, the community will then have a better understanding of potential adaptations to minimize adverse effects.

To determine vulnerability of this region to changing climate, this project documents the current coastal geomorphology of southwest Banks Island through fieldwork, assesses previous changes in the coastal region and predicts future changes. Specific objectives of the study were to:

1. Determine the present coastal morphology and processes through measurement of rates and patterns of erosion, alongshore sediment dynamics and the effectiveness of wave action during the open-water season;
2. Incorporate and correlate previous studies, aerial photographs and satellite images to assess coastal changes;

3. Determine open-water conditions during storm event using long term sea-ice records;
4. Analyse the frequency of storms the region has experienced using meteorological records;
5. Assess the vulnerability of the southwest coastline of Banks Island to changing climate conditions; and
6. Suggest potential adaptations or changes in planning the community of Sachs Harbour can implement to minimize adverse impacts.

1.3 – Study Site: Southwest Coastline of Banks Island

1.3.1 – Location

The community of Sachs Harbour (71°59' N, 125°14' W) is located on the southwest coast of Banks Island, Northwest Territories, 523 km northeast of Inuvik. Banks Island (60,165 km^2) was originally named Banksland in 1820, after Sir Joseph Banks, during the British exploration of the North West Passage (The Community of Sachs Harbour *et al.* 2000). Banks Island is at the southwest edge of the Canadian Arctic Archipelago, separated from the mainland Northwest Territories in the south by Amundsen Gulf; from Victoria Island in the east by Prince of Wales Strait; from Melville and Prince Patrick Islands in the north by M'Clure Strait; and is bordered in the west by the Beaufort Sea (Figure 1.1).

Sachs Harbour is the only permanent community on Banks Island and had a population of 117 in 2003 though has declined to approximately 100 people in 2005

(Indian and Northern Affairs 2005; K. Parewick 2006, personal communication). The community was named after the ship "Mary Sachs" which visited the southwest portion of the island during the Canadian Arctic Expedition in 1913. Sachs Harbour was established as a permanent community in 1929 and gained Hamlet status in 1986 (Usher 1970; Indian and Northern Affairs 2005). The traditional name of this community is 'Ikaahuk' meaning 'where to go across to', named for the annual migration of hunters and trappers to the community from Victoria Island (Indian and Northern Affairs 2005). The study area on the southwest coastline of Banks Island is approximately 33 km in length, from the mouth of the Sachs River to the tip of Cape Kellett on the southwest edge of the island.

1.3.2 – Climate

Sachs Harbour is considered to be in the Mid-Arctic Climate zone, characterized by periods of constant darkness during the winter with extremely low temperatures, a short period of constant light and temperatures slightly above freezing for 2-3 months in the summer, continuous permafrost and little precipitation (French 1996). A weather station has been recording data in this community since 1955-1956 with continuous records from 1956 until present, with data recorded a minimum of six hours daily as the station is not autonomous (Environment Canada 2006a).

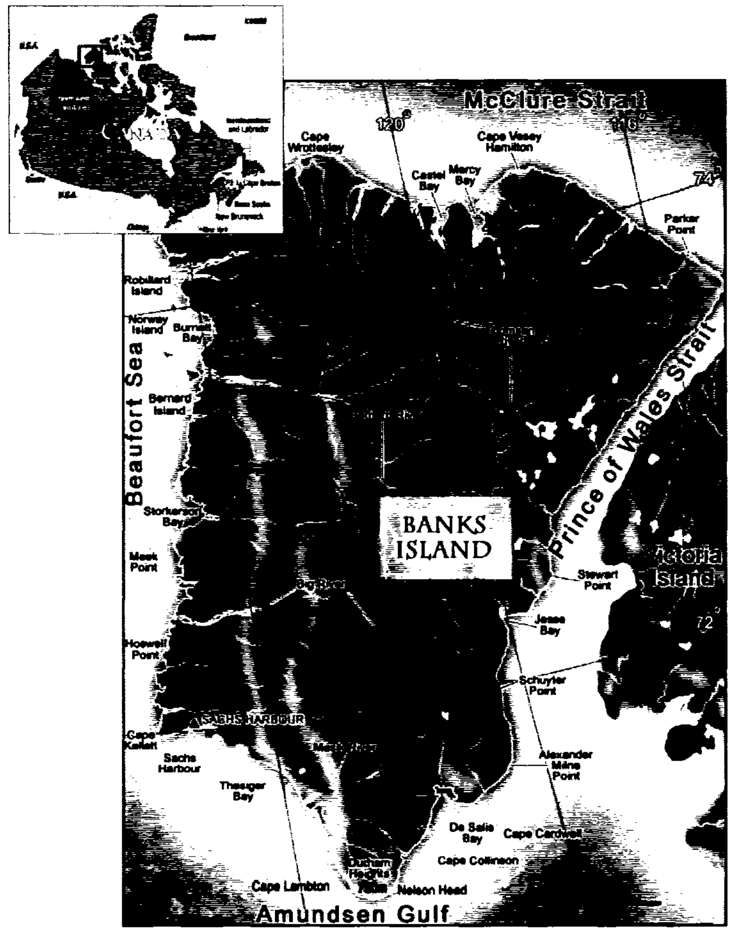


Figure 1.1: Location of Banks Island and Sachs Harbour (which is located on the south coast near the southwest corner of the island) Northwest Territories (modified from Herbert PDN 2002).

Mean annual temperatures (taken from 1971-2000 climate normals for Sachs Harbour) are -13.3 °C, with mean January temperatures of -29.3 ± 4.1 °C, and mean July temperatures of 6.8 ± 1.9 °C (Environment Canada 2004). Total precipitation in this region is low, with an annual mean of 128 mm (Data from Environment Canada 2006c, 1956-2005), with mean snowfall of 760 mm and 44 mm of rainfall (Environment Canada 2004). Increased precipitation during the summer and fall months has been suggested by community members causing increasing difficulty in travel outside the community

(Berkes and Jolly 2001). An increase in precipitation from 1956 to 2005 has been recorded, with average annual precipitation of 74.1 mm/a in 1956, and 177.3 mm/a in 2005; though averages vary throughout the record (Environment Canada 2006c).

Weather records from 1971 – 1977 indicate that prevailing wind directions in Sachs Harbour during the open-water season (June-September) are from the southeast, with winds from the north and northwest forming a subordinate component (Harry *et al.* 1983). Climate data for Sachs Harbour from 1971 – 2000 indicate maximum wind speeds occurring in the late fall and winter with the maximum hourly speed of 97 km/hr which occurred in February, originating from a northerly direction (Environment Canada 2004). Recorded storm events (classified as wind speeds > 10 m/s for a minimum duration of six hours) in the region suggest that storms increase in frequency and intensity later in the open-water season in this region (during August and September) with over 25% of storms occurring in the month of October and between twenty and 25% in September (Atkinson 2005; Manson *et al.* 2005b). There is no conclusive trend of increasing storm activity affecting this community between 1956 and 2005, with storms occurring most years throughout the duration of the record (Manson *et al.* 2005b).

The southwest coast of Banks Island is ice covered for approximately 8-9 months of the year, with annual break-up occurring in early July and freeze-up in the second half of October (Canadian Ice Service 2002; Manson *et al.* 2005b). Multi-year ice from the Arctic ice pack continuously circulating in the Arctic Ocean penetrates into the northeastern Beaufort Sea; however, the Amundsen Gulf is predominantly first year ice (Hudson 1987; Parkinson *et al.* 1987). First-year ice is present beyond the extent of shorefast ice (extending from the land) and is quite mobile compared to multi-year ice (Canadian Ice Service 2002). During break-up in the spring, northwest winds begin to die off, and winds from the east and southeast become predominant, creating thaw leads near the coast of Banks Island (Smith and Rigby 1981) and a polynya, an area of open-water, occurs at the southwest edge of the Amundsen Gulf, known as the Cape Bathurst Polynya (Canadian Ice Service 2002). The Cape Bathurst Polynya is a recurrent polynya as the flaw leads occur in the region annually, and extensive pack ice is often mobile in the polynya while the region is ice covered (Barber and Hanesiak 2004). Melting begins in coastal areas in late June and the entire Amundsen Gulf is generally cleared of ice by the beginning of August (Canadian Ice Service 2002). Freeze-up in the fall begins along the southern edges of the Arctic ice pack with new ice forming along the multi-year ice, and spreading southwards and seawards, while landfast ice begins to form in coastal regions (forms at air temperatures below -2 ℃) as air temperatures drop below zero in October (Canadian Ice Service 2002).

1.3.3 – Vegetation

Vegetation on southwest Banks Island is relatively sparse with both low and high Arctic tundra species prevalent, as this region lies in the continuous permafrost zone (Vincent 1983; Pielou 1994). This area of Banks Island is considered to be in the Low Arctic zone with over 200 species of vascular plants, with high Arctic plants present (Vincent 1983). High Arctic tundra plants are commonly, species of willow (*Salix*), and members of the berry-bearing heath family (*Ericaceae*) (Aiken *et al.* 1999 onwards). Low Arctic species include: sedges (*Carex*), grasses, (*Dryas)* Arctic Dryad, (*Campanula*) (*uniflora*) Arctic Harebell, (*Papaver radicatum*) Arctic Poppy, (*Silene*) Moss Campion, and several types of lichens and mosses (Aiken *et al.* 1999 onwards; Ballard and Pullen 2004). Tundra is dominated by grasses and low dwarf willows due to the short growing season and low temperatures (Bailey 1998). These species survive because they are generally short and closer to the warmer soil during the spring and summer months, are slow growing and are completely dormant during the winter months (Pielou 1994). Species composition and distribution are dependent on the short growing season (typically 8 weeks), soils poor in nutrients, minimal water supply and windy conditions (Pielou 1994). During melt or wetter conditions, water percolates into the upper soil layer which becomes saturated, providing moisture for shallow rooting plants (Ballard and Pullen 2004). The most adaptable plants colonize bare, frost heaved soils and form long roots which bind and stabilize the soil (Pielou 1994). The root depth depends on the depth of the active layer (layer of seasonally thawed ground) during the growing season, as water and plants roots do not penetrate into the underlying permafrost (Canadell *et al.* 1996). These deeper rooting plants may act as a stabilizer, preventing active layer erosion in shallow sloping coastal bluffs.

1.4– Physical Setting

1.4.1 – Pre-Quaternary Bedrock Geology

Geology varies with the topographic area on Banks Island. The southwest coastline is dominated by Quaternary sediments, although pre-Quaternary geological units form the substrate of these sediments (Figure 1.2). The geology of the southwest coastline of Banks Island will be summarized emphasizing units which contribute to sediments and topography. Pre-Quaternary units include the: Glenelg, Christopher, Isachsen, Kanguk, Eureka Sound, Beaufort and Worth Point Formations (Vincent 1982; Lane and Dietrich 1996). Banks Island lies in the Arctic Platform geological province (Douglas 1969; Wheeler *et al.* 1997).

The Late Proterozoic Glenelg Formation is exposed at the southern tip of Banks Island, near Nelson Head and has two members (Figure 1.1). The upper member is dominated by fine to medium grained sandstones and siltstones deposited in a fluvial or deltaic environment. The lower member is dominated by cherty dolomites with stromatolites and basaltic sills dated 635 – 640 Ma and were deposited in a shallow marine environment (Miall 1976).

The lower Cretaceous Christopher and Isachsen Formations are exposed along the southeastern portion of Banks Island north of Nelson Head. The Isachsen Formation is composed of two units. The lower unit consists of medium to very coarse grained, pale quartzose sand, containing pebble and gravel beds, while the upper unit consists of fine grained sands, silty sand, and some carbonaceous beds, with small scale ripples common (Miall 1974; Miall 1975). Both the lower and upper members of the Isachsen Formation consist of deltaic sediments (Miall 1974; Miall 1975). The Christopher Formation is also lower Cretaceous and is composed of (predominantly) unlithified fine grained marine clays, silts and sands. The upper Cretaceous Kanguk Formation is composed of unlithified and poorly lithified sand units in this region (Miall 1979; Vincent 1983; Vincent *et al.* 1983). This formation, which is approximately 40 m thick at an exposure in the Duck Hawk bluffs directly west of Sachs Harbour, represents a tidal marine sand bar depositional environment (Miall 1975).

The Paleogene Eureka Sound Formation is composed of cyclic successions of sand, shale, interlaminated sand and shale, soil zones and thin lignitic coals (Miall 1974; Miall 1975). The sand units are unconsolidated quartzose sand containing silicified wood while the shales are soft, dark brown-grey and micaceous. The soils are sandy and iron stained, with roots and rootlets, while the lignitic coal is discontinuous with shales in most locations (Miall 1974; Miall 1975). These units indicate a continental depositional environment, likely a progradational delta, indicated by the cyclical succession of the units (Miall 1974; Miall 1975).

The Miocene Beaufort Formation is composed of horizontally and cross-bedded fluvial sand, with lithic clasts dominated by quartzites, multicoloured cherts, and quartzitic sandstones and with gravel clasts with sandstones, dolomites, and siltstones present (Vincent 1990). Dating of floral and faunal fossils within the Beaufort Formation indicates an early Miocene age for the lower unit and late Miocene age for the upper unit (Vincent 1990).

Between the Beaufort Formation units and glacial units deposited on Banks Island, a formation of colluvial material derived from the underlying units combined with organic peat mats and other organic materials is known as the Worth Point Formation (Table 1.1) (Vincent 1990). The lower unit of the Worth Point Formation is composed of lacustrine and fluvial beds and the upper unit of aeolian deposits (Vincent 1990). This unit has only been observed in two locations on Banks Island with an exposure in the

Duck Hawk Bluffs between five and 16 m in thickness (Vincent 1990). Flora and fauna, such as conifers, identified within the unit indicate warmer conditions than at present and also indicate that this unit predates the last three continental glaciations (Vincent 1990).

1.4.2 – Quaternary History

Several glacial and interglacial periods are recorded in sediments on Banks Island. Because of its location on the northwest margin of North America, where continental ice sheets reached their maximum extent, it is thought that Banks Island may provide one of the longest Quaternary records in Canada (Vincent 1982). Three major glaciations have been described on Banks Island: the Banks, Thomsen and Amundsen Glaciations (Table 1.1) (Vincent 1983). Three major marine sequences and two major interglacials (aside from the present interglacial) have also been recorded (Table 1.1) (Vincent 1982).

Table 1.1: Summary of Quaternary events and corresponding units present on the southwest coastline of Banks Island (Modified from Vincent 1982; Vincent 1990). Oxygen Isotope stages are indicated for each event (OI Stage).

<table>
<tr><th colspan="2">Chrono - stratigraphy</th><th colspan="2">Geological Event</th><th>Lithostratigraphy</th></tr>
<tr><td colspan="2">Holocene
OI Stage 1</td><td colspan="2">Postglacial</td><td>Organic, aeolian, alluvial, marine and colluvial</td></tr>
<tr><td rowspan="3">Late Pleistocene</td><td>OI Stage 2</td><td rowspan="2">Amundsen Glaciation</td><td>Russel Stade</td><td>Carpenter Till (Sandhills Readvance)</td></tr>
<tr><td>OI Stage 4</td><td>M'Clure Stade</td><td>Sachs Till (Thesiger Lobe)</td></tr>
<tr><td>OI Stage 5</td><td colspan="2">Cape Collinson Interglaciation</td><td>Organic Bearing Sediments</td></tr>
<tr><td>Mid Pleistocene</td><td>OI Stage 18</td><td colspan="2">Thomsen Glaciation</td><td>Big Sea Sediments
Kellett Till</td></tr>
<tr><td rowspan="3">Early Pleistocene</td><td>OI Stage 19</td><td colspan="2">Morgan Bluffs Interglaciation</td><td>Cape Collinson Formation</td></tr>
<tr><td>OI Stage 20</td><td colspan="2">Banks Glaciation</td><td>Post Banks Sea
Bernard Till and Durham Heights Till
Pre Banks Sea Sediments</td></tr>
<tr><td>OI Stage 21</td><td colspan="2">Preglacial</td><td>Worth Point Formation</td></tr>
</table>

The Banks Glaciation, the earliest known glaciation (believed to be approximately Oxygen Isotope (OI) Stage 20) was the most widespread with ice extending over the entire island except for the north-western corner (Vincent 1983). The Banks Glacier originated from the mainland ice sheet southeast of Banks Island and flowed northwestward on the island flowing over Cretaceous (Christopher, Isachsen and Kanguk Formations) and Paleogene (Beaufort Formation) sediments until it reached the north-west part of the island (Vincent 1982). The Banks Glacier retreated towards the south-east (Vincent 1982).

The Bernard and Durham Heights Tills were deposited in southwest Banks Island, near the coastline (Figure 1.2) (Table 1.1) (Vincent 1982). The Bernard is characterized as a black till with low carbonate and high smectite clay contents with few stones and is of variable thickness of up to 20 m (Vincent 1982). The Bernard Till covered the Beaufort, Christopher, Kanguk and Eureka Sound Formations (Vincent 1983). The Durham Heights Till found only at the southern tip of the island in the Durham Heights region, is characterized by its dark colour and fine grained matrix (Vincent 1983). This till covered the Kanguk, Christopher and Glenelg Formations (Vincent 1983).

In the Duck Hawk Bluffs, marine sediments (Post-Banks Sea sediments) are found above Banks Glacial sediments indicating a marine transgression and regression following the retreat of the Banks Glacier, known as the Post-Banks Sea (Table 1.1) (Vincent 1982). Following the marine phase, overlying organic-rich sediments along the southwest coastline in the Duck Hawk Bluffs indicate an interglacial period known as the Morgan Bluffs Interglaciation, with floral and faunal assemblages indicating warmer climate conditions than at present (OI Stage 19) (Table 1.1) (Vincent 1983; Vincent 1990).

The Thomsen Glacier flowed from an ice sheet centred to the southeast of the island, towards the north-west over the southern and eastern portions of the island, depositing the Kellett Till on the southern part of the island (OI Stage 18) (Table 1.1) (Vincent 1982; Vincent 1990). The southwest coastline of the island was not ice covered during the Thomsen Glaciation as it was submerged by a marine transgression, known as the Big Sea. This sea submerged the lowland areas of Banks Island up to 215 m in elevation (Vincent 1982).

The Kellett Till overlies the Durham Heights and Bernard Tills as well as the Christopher, Kanguk, Eureka Sound and Beaufort Formations (Figure 1.3) (Table 1.1) (Vincent 1983). This till is light coloured with a sandy matrix, dominantly derived from the Beaufort Formation and is of variable thickness (Vincent 1983). The larger clasts of the Kellett Till are dominated by cherts and carbonates (Vincent 1983). During the Big Sea and glacial retreat, sediments along the southwest coastline were washed and organic sediments were deposited during the Cape Collin son Interglaciation, with floral and faunal assemblages indicating warmer than present conditions (Table 1.1) (Vincent 1982; Vincent 1990).

The Amundsen Glaciation was the most recent, involving two advances on the island during the M'Clure Stade (OI Stage 4) and later during the Russell Stade (OI Stage 2) (Vincent 1982). During the McClure Stade, lobes of ice situated to the south advanced onto Banks Island. The Thesiger Lobe flowed over Thesiger Bay and the Prince of Wales

Strait from the Amundsen Gulf covering the southwest edge of the island and depositing the Sachs Till (Vincent 1982). The northwestern limit of the Thesiger lobe is the Duck Hawk Bluffs (Vincent 1982). The southwesterly retreat of the Thesiger Lobe is marked by a series of end moraines and an extensive delta, which forms the Sachs Harbour Lowlands southeast of Sachs Harbour. The Sachs Till is light-coloured, sometimes pinkish, with a sandy matrix and variable thickness averaging one to two metres (Figure 1.3) (Table 1.1) (Vincent 1983). Chert and carbonate clasts indicate that the parent material for this till originates from the Kanguk, Christopher and Beaufort Formations (Vincent 1983).

The lowland area southeast of the Sachs River was affected by a readvance of this lobe, known as the Sandhills Readvance (Vincent 1983). The Sandhills moraine extends 25 km between Thesiger Bay and the Sachs River, and is composed of ice-contact deposits and the Carpenter Till, younger in age and overlapping the Sachs Till (Vincent 1982). The Carpenter Till is very sandy with a similar lithology to the Sachs Till (Figure 1.3) (Table 1.1) (Vincent 1983). This till overlies older complex marine sediments thought to be deposited during the Big Sea and the complex moraine sequence is intercut with kettle lakes throughout (Vincent 1983). A marine transgression following retreat of the Thesiger Lobe, called the Meek Point Sea, covered the southwest coastline (Vincent 1982).

Although only relative ages exist for these three glaciations and their corresponding interglaciations, it has been proposed that glacial ice did extend onto Banks Island during the limit glacial maximum (LGM) of Late Wisconsinan age (Dyke

1987). Dyke (1987) also proposed that the M'Clure stade most likely corresponds with OI Stage 2, with the Sandhills moraine representing glacial retreat after the last glacial maximum (LGM).

Following this retreat after the LGM (OI Stage 2), landforms that developed along the southwest coastline represent a periglacial landscape (Gurney and Worsley 1997). Geomorphic features and landforms found within the region include patterned ground, thermokarst lakes, pingos, patterned ground, and ground ice (French 1996). Permafrost in the region is 400-500 m deep (Gurney and Worsley 1997), indicating a long period of growth when the region was free of glacial ice. Development of kettle lakes (formed from the melting of partially buried glacial ice), thermokarst lakes and pingos (formed from ice segregation associated with freezing of taliks under drained lakes) within the region all suggest to a newer set of geomorphic processes following ice retreat (Gurney and Worsley 1997). The absence of marine features of OIS 2 age or younger above modern sea level on the landscape indicates that no post-OIS 2 transgression occurred. Studies of the mainland Beaufort Sea have indicated that during OI Stage 2 (LGM) the marine lowstand was approximately 70 m below present (Forbes 1980; Hill *et al.* 1993; Hequette *et al.* 1995). Sea level is currently rising in the Tuktoyaktuk region at approximately 3.6 mm/a (Manson *et al.* 2005b).

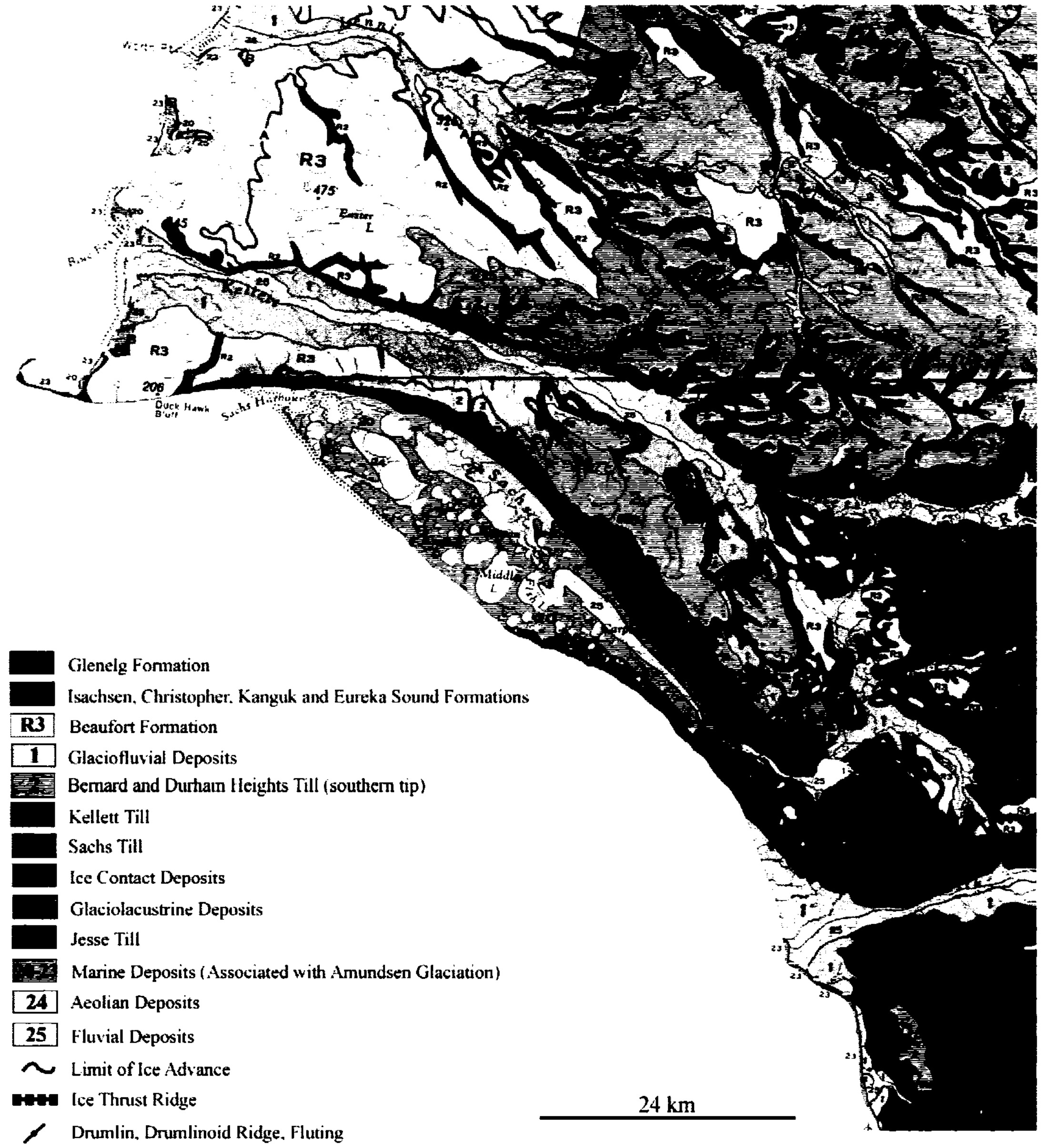


Figure 1.2: Surficial geology of the southwest coast of Banks Island including limits of glacial advance (Modified from Vincent 1983).

1.4.4 – Topography

Banks Island is divided into three main topographic regions. These are the northern uplands, the southern uplands, and a central lowland region (Vincent 1982). The highest elevation on the island lies in the upland areas in the north at 675 m above sea level (asl). Sachs Harbour lies within the lowland region (Vincent 1982). The area surrounding Sachs Harbour is dominated by an undulating ridge between 60 and 80 m asl, which extends along and behind the southern coastline of the island (French 1975). This morainal ridge acts as a drainage divide between the Sachs River to the southeast and the Kellett River to the north (French 1975). The ridge slopes are sparsely vegetated gravely and boulder-strewn, with gelifluction stripes composed of medium- to coarse-grained sands with angular pebbles and scattered larger clasts, and are sparsely vegetated (French 1974). The gelifluction stripes have shown rates of movement of 20 mm/yr (French 1975).

Lying in the continuous permafrost zone, permafrost is present in all localities on Banks Island except for local thawed zones (taliks) which occur under lakes and river channels (French 1996). South and southeast of Sachs Harbour is the low lying coastal plain of the Sachs River (referred to as the Sachs Lowlands), composed mainly of sands and gravels and containing many thermokarst lakes (Manson *et al.* 2005b).

This coastal system is considered to be low energy and microtidal (0.2-0.4 m) environment (Department of Fisheries and Oceans Canada 2006). In the community of Sachs Harbour, the beach front is narrow in most locations. The widest beach, a small sand and gravel foreland used as a landing beach (Sachs Landing Beach), is gently sloping and appears to be prograding and migrating eastward (Manson *et al.* 2005a). To the south of the community is the Sachs Spit (Figure 1.3). The harbour developed through breaching, merging and marine flooding of thermokarst lakes behind the growing spit (Manson *et al.* 2005b). Previous studies indicate that erosional processes along this coastline include a combination of various thermokarst (thaw failure and consolidation) effects combined with wave undercutting and removal of sediment (Forbes *et al.* 2004).

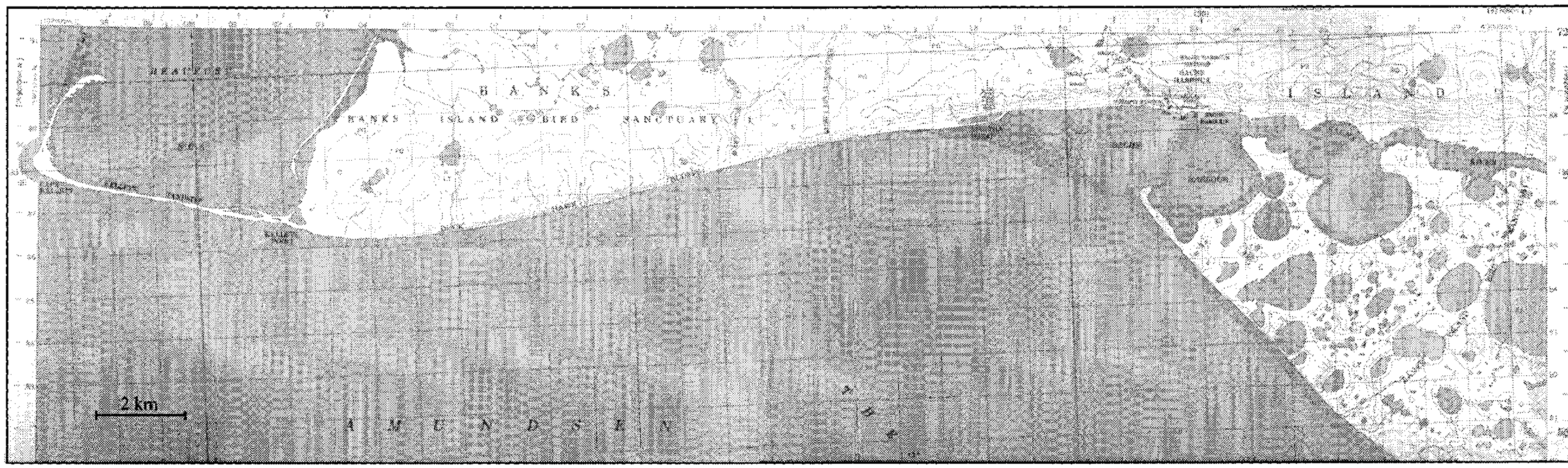


Figure 1.3: 1/50,000 topographic map of the southwest coast of Banks Island. Note that the bluffs of the area do not exceed 50 m in height within the study area (Adapted from the 1/50,000 NTS# 097G15 provided by Natural Resources Canada 2005).

Chapter 2: Climate Change, Holocene History and Coastal Processes

2.1 – Changing Climate Conditions in the Arctic

2.1.1 – Air Temperatures

In most areas of the Arctic surface temperatures have increased from 1966 to 2003, with warming trends exceeding 1-2°C per decade in northwestern North America (ACIA 2005a). Temperature increases, north of 60 degrees, exceed those of southern latitudes with mean increases of 0.04°C/a over the past 40 years (ACIA 2005a). Thermal infrared satellite data for the circumpolar Arctic from 1981 to 2001 shows a 1.09 ± 0.22°C/decade warming with a 95% confidence interval between 0.65 and 1.53°C /decade over North America and analyses indicate that the Western Arctic has a high positive trend in surface temperatures (Comiso 2003). Spring, summer and autumn temperatures particularly show warming trends when the impact on frozen surfaces such as sea ice and permafrost is most critical, while winter trends are variable (Comiso 2003). Consensus of emission model scenarios project increases in temperature between 1.4 and 5.8°C globally over the next century (IPCC 2001a).

The effects of increased temperatures are expected to be amplified in the Arctic. Increased temperatures will lead to decreases in sea-ice cover, increased thermal melting and erosion processes, increased freshwater discharge from melting sea ice and glaciers and subsequent effects on ecosystems and terrestrial and marine fauna (ACIA 2005a).

2.1.2 – Sea Ice

Sea ice is a dominant control on exchanges of heat, moisture and salinity with the atmosphere. It also affects light penetration and albedo, habitat for floral and faunal species and provides protection to Arctic coastlines from storm events and erosion (ACIA 2005b; NSIDC 2005a). Two primary forms of sea ice are seasonal and perennial, first year and multi year ice respectively (Canadian Ice Service 2002). First year ice is in its first winter of growth or first summer of melt and ranges from a few tenths m to 2.5 m in the High Arctic (Wadhams 2000; Canadian Ice Service 2002). First year ice that survives the summer melt becomes multi year ice, with a hummocky (lumpy) appearance (Wadhams 2000). Multi year ice floes can be up to 3 m of thickness before forming ridges (Wadhams 2000; Canadian Ice Service 2002).

The seasonal growth and decay of sea ice during the spring and fall in the circumpolar Arctic has a maximum extent of 14-15 million km^2 in March, and a minimum of 6-7 million km^2 in September (Parkinson *et al.* 1999; ACIA 2005b). Historical records and satellite observations from 1978 – 2003 have indicated a decline in sea-ice extent during the summer months, with first year ice decreasing 3% per decade (Cavaleri *et al.* 1997) and multi-year ice decreasing 7% per decade (Johannessen *et al.* 1999). In September 2002, circumpolar Arctic sea ice reached a record minimum, with low ice conditions remaining over the next two years (Serreze *et al.* 2003; Stroeve *et al.* 2005). In 2005 a new sea ice minimum was recorded of 5.32 million km^2, the lowest since the beginning of the satellite record (NSIDC 2005a). Combined with increased summer melt, decreased winter sea-ice recovery leaves sea ice more susceptible to summer melt and overall decline (NSIDC 2005b). With overall decline, models predict a nearly-ice free Arctic Ocean during the summer by the end of the century (Johannessen *et al.* 2004).

Off the Alaskan coast of the Beaufort Sea, winter changes in sea ice in a 23 year study (1972-1994) indicate a less than 3% reduction in sea ice and a close to 20% decrease in sea ice during July, August and October. Overall, during this 23 year study of the region, a 6% reduction in sea-ice concentration was observed in the Southern Beaufort Sea. These observed changes in the Beaufort Sea are in agreement with changes observed in other Arctic and Sub-Arctic regions (Wendler *et al.* 2002).

Decreases in sea ice extent during the summer melt season led to an increase in the number of open-water days. Satellite data has indicated a trend in increasing open-water days from 1981-2001 with an increase in open-water days of 17 ± 6 days in the coastal North American Arctic (Comiso 2003). The coastlines of the Beaufort Sea are highly susceptible to erosion and storm surges during the open-water season (Manson *et al.* 2005b) and decreased sea ice in the region would lead increased effectiveness of these storms on eroding the coastline as sea ice is known to suppress wave development and propagation (Squire *et al.* 1995).

2.1.3 – Permafrost

Distinct and unique processes occur in cold environments associated with freezing and sub-freezing temperatures (French 1976b). As the southwest coast has an average annual temperature of -13.3°C, it is necessary to discuss periglacial processes; processes occurring in cold, non-glacial environments (French 1976b; Washburn 1980; Clark 1988; Williams and Smith 1989). Periglacial processes are reliant on the seasonal or perennial thawing of frozen ground (permafrost) (French 1976b; Washburn 1980; Clark 1988; Williams and Smith 1989). Permafrost, ground that has remained below 0°C for two or more consecutive years, underlies most areas of the Arctic in zones of either continuous or discontinuous permafrost (French 1996; ACIA 2005c). The southern limit of the continuous permafrost zone is coincident with a mean annual air temperature of -8°C (Brown 1960; Pewe 1966; Brown 1967). Extensive permafrost (continuous and discontinuous) underlies 50% of landmass in Canada or 5.7 million km^2 (French 1996; Smith and Burgess 2006a).

Commonly associated with permafrost in unconsolidated sediments is ground ice, or ice within sediments (usually expressed by percentage volume), found in various forms (Harry 1988). Ground ice is often recognized as pore ice, segregated ice and wedge ice, which are most significant in the volume near the surface of permafrost features such as ice wedges (Harry 1988). Ground ice in the various forms, is common in the region as revealed by ice wedges in the coastal cliffs and by the existence of pingos (French *et al.* 1982; Gurney and Worsley 1997). Ice wedges form from downward movement and freezing of meltwater infiltrating thermal-contraction cracks in poorly drained permafrost during the early spring (French 1996). These wedges can spread out laterally and join with other wedges to form ice wedge polygons (French 1996). Massive ground ice or ice up to tens of metres in thickness exists in coastal lowlands in the Western Canadian Arctic and has been exposed in coastal cliffs (Burn *et al.* 1986; French *et al.* 1982; Rampton 1982). The Quaternary history of the area has allowed for prolonged aggradation of permafrost in cool conditions, and the ice has segregated from sediment, although in some regions massive bodies may be buried glacial ice (French and Harry 1988; French and Harry 1990; Dallimore and Wolfe 1988). Massive ice that is segregated in origin is often interbedded with sediment (Mackay 1989). The southwest coastline of Banks Island is dominated by eroding bluffs composed of interbedded silty sand, fine sand, and gravel between 6-20 m in height, and containing between 40% and 95% ice with 25% excess ice and ice lenses (French 1976a; French *et al.* 1982; Manson *et al.* 2005b). Massive ice has been observed along the southwest coast (Harry *et al.* 1983; Worsley 2000) and to the southeast of the community, at least 2 m in thickness (French and Harry 1988; French and Harry 1990).

Formation and growth of permafrost are dependant on climate conditions and permafrost thaw can lead to subsidence of ground surfaces (in areas with high concentrations of ground ice), increased carbon fluxes, increased runoff and instability in structures built on permafrost (ACIA 2005c; Romanovsky 2006; Smith and Burgess 2006a). Distribution, temperature and thickness are affected by natural environmental change and anthropogenic disturbances, such as changes in air temperature, precipitation, surface disturbances such as clearing of vegetation or organic layer, forest fires, shoreline erosion, and river channel migration (Smith and Burgess 2006a).

The active layer depth can range to 100 mm in the High Arctic, and varies yearly based on temperature, precipitation, soil type, vegetation, snow cover and water content (French 1996). Increasing surface temperatures can lead to increasing active layer depth or lead to active layer detachments and exposure of ground ice (slumping of material between the active layer and permafrost boundary) (Kokelj *et al.* 2002; Huscroft *et al.* 2004). Changing surface temperatures are moderated within the active layer and there is a variable time lag between changing surface temperatures and changing permafrost temperatures (Smith and Burgess 2006a).

Increasing soil temperatures in permafrost have been observed in Canada, Russia, and Alaska over recent decades (ACIA 2005c). Studies from northwestern Canada (Northwest Territories) have indicated that temperatures in the upper 30 m of permafrost have increased by up to 2°C in the past 20 years (studies conducted from 1985 to 2000, and 1990 to 2000) or approximately 0.1°C/a (Couture *et al.* 2003; Romanovsky 2006). Other areas of the circumpolar Arctic show increasing permafrost temperatures in both continuous and discontinuous permafrost (ACIA 2005c). In areas of discontinuous permafrost, ground temperatures are within 1-2°C of melting, and increasing surface temperatures will likely cause permafrost in these areas to disappear (Smith and Burgess 2006a).

Studies of permafrost in the Northwestern Canadian Arctic have indicated that the southern mainland Beaufort Sea, Herschel Island, and Banks Island are highly susceptible to increasing temperatures due to high ground ice contents in unlithified sediments, shallow rooting vegetation cover, and susceptibility to erosion (Kokelj *et al.* 2002). Current low permafrost temperatures (less than -5°C), however, decrease the potential for thaw (Smith and Burgess 2006b). In areas where ground ice is exposed, such as along erosional coasts, the potential for thaw is much greater, leading to subsidence and infrastructure loss (Smith and Burgess 2006b).

2.2 – Holocene History and Sea-Level Rise in Western Canadian Arctic

2.2.1 – Sea-level History in the Beaufort Sea

During the Last Glacial Maximum (LGM) in OI Stage 2, ice did not cover Banks Island but was present to the south, near the mainland Beaufort Sea coastline (Vincent 1990; Hill *et al.* 1993). The lowstand in the Canadian Beaufort Sea was determined through seismic evidence along the Beaufort Sea shelf and radiocarbon dating and was approximately 70 m lower than at present in the region (Hill *et al.* 1985; Vincent 1990; Hill *et al.* 1993). A sea-level curve completed for the region using radiocarbon dating of thirty-six samples including freshwater peats, marine fauna, plant material, wood fragments and charcoal from archaeological sites, was spread over a large geographic area and indicates that sea level has been rising for the past 15,000 years (Forbes 1980; Hill *et al.* 1993; Hequette *et al.* 1995). The curve for the region indicates a rising sea level at rates of between 4 and 5 mm/a in the early Holocene (ca. 9000 years BP), a rapid rise with an approximate mean of between 7 and 14 mm/a during the middle of the Holocene (ca 5000 years BP) and a flattening of the curve (a mean rate of less than 3 mm/a) in the past 3000 years (Hill *et al.* 1993; Hequette *et al.* 1995). This sea-level curve was developed using data from a large geographical area in the southern Beaufort Sea, and effects such as consolidation, basin subsidence, postglacial isostatic rebound, and forebulge collapse are variable across the region (Hill *et al.* 1993).

Sea-level rise in the region results from a combination of eustatic sea-level rise with glacio-isostatic effects and/or sediment loading (Forbes 1980). Eustatic sea-level changes are based on fluctuations in the volume of water in ocean basins (Bird 1969). Glacio-isostatic effects result from crustal depression due to loading by an ice sheet, associated forebulge development around the margins, and land uplift and forebulge collapse and migration following deglaciation (Quinlan and Beaumont 1981; Liverman 1994; Lambeck 1995). During LGM, many areas of the Beaufort Sea and Banks Island were in proximity to the ice sheet and were subsequently influenced by forebulge migration during deglaciation (Dyke 1987).

No sea-level curve has been completed for southwest Banks Island. However, there is no evidence of marine transgression since the LGM and sea level is believed to have been rising throughout the late Holocene (Gurney and Worsley 1997). This picture is compatible with the regional sea-level investigations elsewhere in the southern Beaufort Sea.

2.2.2 – Recent Records of Sea-Level Change

Warming climate conditions globally are anticipated to cause warming ocean conditions and melting of glaciers and ice caps (Shaw *et al.* 1998). Thermal expansion in oceans combined with increased meltwater input will lead to rising sea-levels globally (IPCC 2001a). Predictions for the next century indicate a rise in the global sea level of 0.09-0.88 m (IPCC 2001a). Sea-level rise from thermal expansion and melting glaciers combined with glacio-isostatic effects will likely lead to amplified relative sea-level rise in parts of the Western Arctic.

Long term Global Positioning System (GPS) monitoring stations were established in six locations in the Western Arctic (in 2001) to determine postglacial relative sea-level change (Forbes *et al.* 2004). Determination of relative sea-level change could allow a separation of eustatic and glacio-isostatic signals within the region, and determination of the location of the zero isobase (the area of no vertical crustal motion) (Andrews and Peltier 1989; Peltier 1994; Forbes *et al.* 2004). Continuous GPS stations designed to monitor direct vertical crustal motion were installed in Sachs Harbour (although this became inactive in late 2005), Tuktoyaktuk, Inuvik, Holman, Alert and Resolute with epoch GPS stations (installed only during field seasons annually) in northern Banks Island (Mercy Bay) (Forbes *et al.* 2004).

GPS monitoring in the community of Sachs Harbour indicates that along with rising sea level in the Beaufort Sea region, Banks Island is experiencing subsidence (Manson *et al.* 2005b). Banks Island was believed to be located over the forebulge during the most recent glaciation, and is now actively subsiding. The rate of crustal subsidence has been suggested at 2.50 mm/a in Sachs Harbour and Tuktoyaktuk from modelling (Andrews and Peltier 1989; Peltier 1994). Other evidence of subsidence on Banks Island comes from airborne and satellite imagery as well as ground surveying (Forbes *et al.* 2004).

The rate of eustatic sea-level rise is not known for the Arctic Ocean and Beaufort Sea region. However, global sea-level rise, as indicated from observation and modelling, is estimated at 1.8 ± 0.3 mm/a (Church *et al.* 2004). Approximately 3.6 mm/a relative sea level rise is believed to be occurring in Tuktoyaktuk from modelling and preliminary and continuous GPS stations, which is in agreement with tide gauge data, indicating 3.5 mm/a ± 0.1 relative sea level rise (Manson *et al.* 2005b). Similar rates of relative sea level rise (3.6 mm/a) are expected in Sachs Harbour due to similar rates of crustal subsidence and eustatic sea-level rise between the two areas (Manson *et al.* 2005b).

2.2.3 – Sensitivity to Sea-Level Rise

Concerns about rising sea levels due to thermal expansion and melting glaciers and ice caps have led to studies examining sensitivity of coastlines to anticipated sea-level rise. A study of the sensitivity to sea-level rise in all coastal regions of Canada was conducted by (Shaw *et al.* 1998), using seven parameters from 1:50,000 scale NTS (National Topographic System) maps. The seven criteria examined were: relief, geology, coastal landforms, sea-level tendency, shoreline displacement, tidal range, and wave height (Shaw *et al.* 1998). Each parameter was given a scoring to find an overall average sensitivity index (SI) per map sheet, and this provided the basis for a coastal sensitivity map of Canada (Shaw *et al.* 1998).

Geographic variation in coastal environments leads to potential problems in assessing individual map sheets, as scores are averaged based on elevation, shoreline displacement, wave energy and erosion rates (Shaw *et al.* 1998). Individual map sheet areas with a large variation in elevation may create an unrepresentative average elevation. Coastlines may include areas with high erosion rates adjacent to areas of progradation, leading to unrepresentative mean erosion rates. Areas of the Canadian Arctic are particularly difficult to assess. Erosion occurs during the three to four month open-water season, and causes the average annual erosion rates to be misleading. Determining the effects of wave energy could also be misleading in the area due to sea ice, and varying lengths of the open-water season (Shaw *et al.* 1998). While this method of determining sensitivity to sea-level rise indicates broad regional sensitivity, finer detail is needed within individual areas.

The mainland Beaufort Sea, including the Tuktoyaktuk Peninsula, show moderate to high sensitivity to sea-level rise (Figure 2.1) (Shaw *et al.* 1998). The Tuktoyaktuk Peninsula and Richards Island areas were considered highly sensitive, due to their low lying barriers, spits and breached-lake embayments and coastal deposits composed of unlithified ice-rich sediments with varying rates of coastline recession (Solomon 2005). Although this coastline has a small tidal range, storm surges of and rising sea level have lead to a high sensitivity index for the two areas (Shaw *et al.* 1998). The Beaufort Sea coast to the east (east of Cape Bathurst) and west (Herschel Island and Yukon Coast) are considered to be moderately sensitive, due to higher elevations and lower rates of coastal retreat (Figure 2.1) (Shaw *et al.* 1998).

The southwest coastline of Banks Island is also considered to be highly sensitive to sea-level rise (Shaw *et al.* 1998) (Figure 2.1). The southwest coastline is dominated by ice-rich unlithified Quaternary sediments, low-lying coastal cliffs, believed to have erosion rates similar to the mainland Beaufort Sea, is currently experiencing relative sea-level rise of 3.6 mm/a, and is considered susceptible to coastal storms during the open-water season (Harry *et al.* 1983; Shaw *et al.* 1998; Manson *et al.* 2005b).

Predicted coastal impacts for highly sensitive areas on the mainland Beaufort Sea coastline, such as Tuktoyaktuk, include: flooding, increased thermal and mechanical erosion rates, beach migration, increased rates of freshwater lake breaching and destabilization of sediments in the coastal zone (Shaw *et al.* 1998). The southwest coastline of Banks Island is expected to undergo similar changes based on its high sensitivity and similarities in coastal processes and substrates (Shaw *et al.* 1998).

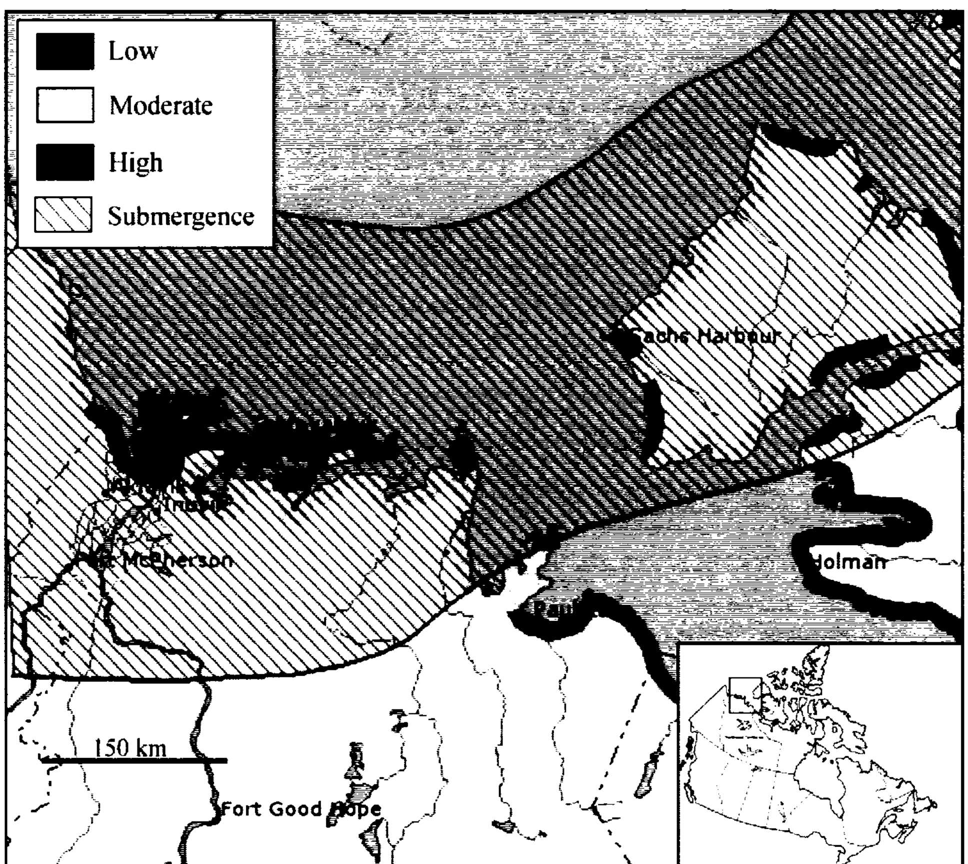


Figure 2.1: Coastal sensitivity to sea-level rise in the Canadian Western Arctic. The southwest coast of Banks Island is highly sensitive to sea-level rise and is currently submerging (Modified from Shaw et al. 1998). Sachs Harbour and Tuktoyaktuk are indicated.

2.2.4 – The Mainland Beaufort Sea Coast

In the Beaufort Sea, ice covers the region nine months of the year, limiting the open-water season to three months from mid-July to mid-October (Harper 1990). Although the open-water season is limited to three months the effects of storm surges and coastal erosion along the south coast of the Beaufort Sea are substantial with continuous permafrost layers underlying both coastal and inland sediments (Harper 1990). Areas of the Beaufort Sea experience storm surges between 2-3 m along the coastline in areas with a small tidal range of 0.7 m or less (Forbes 2000). In some areas of the Beaufort Sea coastal erosion rates vary between 0.6 and 22.5 m annually (MacKay 1963; Forbes and Frobel 1985; Harper 1990; Solomon 2005). In a single storm event more than 10 m of cliff erosion can occur (Solomon 2005).

2.2.5 – Tuktoyaktuk and Richards Island

The coastline near the community of Tuktoyaktuk has been intensively studied since the 1970s due to concerns about coastal erosion disrupting community infrastructure. Tuktoyaktuk lies on the coastal plain of the Beaufort Sea, in an area of low elevation with many lakes, coastal bays and other permafrost related depressions (Rampton 1988; Johnson *et al.* 2003). The Tuktoyaktuk region is dominated by thick layers of sand with interspersed layers of silt and pebbly coarse grained sands containing large volumes of excess ice (Rampton 1975, Rampton 1988; Johnson *et al.* 2003). The excess ice is found in several forms in this region, as massive ice bodies, ice lenses, pore ice, wedge ice, and pingo ice (Bouchard *et al.* 1972; Couture *et al.* 2002; Manson *et al.*

2005b). The community of Tuktoyaktuk has a population of approximately 930 (Census of Canada 2001 data) and has developed along a narrow peninsula into the Beaufort Sea open to the sea on the western side and forming a protective harbour on the eastern side (Wolfe *et al.* 1998; Johnson *et al.* 2003). Although offshore ice cover in the region lasts most of the year, Tuktoyaktuk is vulnerable during the open-water season (mid-June to mid-October) to storms coming from the west and north-west with open-water fetch of more than 300 km (Johnson *et al.* 2003). A maximum storm surge of 2.5 m above mean water level was recorded in this area in the mid 1980s (Harper *et al.* 1988; Johnson *et al.* 2003). Due to unlithified Quaternary sediments along this coastline, coastal erosion rates are 1-2 m per year, with higher short term rates of 7-10 m in a single event (Solomon 2005). With sea level rising in this region, the low-lying topography in the community is susceptible to erosion as well as inundation (Harper *et al.* 1988; Johnson *et al.* 2003).

Historically the narrow Tuktoyaktuk peninsula has been eroding, feeding sediment to the spits both north and south of the community (Johnson *et al.* 2003; Manson *et al.* 2005b). Since the 1980s, coastal protection has been employed to slow the rates of coastal retreat along the peninsula, using concrete slabs, sandbags, beach nourishment, and rip rap (Aveco 1986; Johnson *et al.* 2003). This protection has been ineffective during storm events and has even led to a loss in sediment supply to the northern spit, which can flood at high tide (Manson *et al.* 2005b). Community infrastructure has already been affected in this area since the 1980s, with the destruction of a curling rink and the closure of a school (Wolfe *et al.* 1998). Shoreline retreat in Tuktoyaktuk will continue to occur, impacting more than a dozen buildings in the community with some areas of the community completely flooded during large storm events (Johnson *et al.* 2003). Currently there is ongoing debate in the community over the need to erect more coastal protection along the peninsula, or to redevelop the community in nearby areas of higher ground, abandoning the low-lying areas of the peninsula.

Coastal retreat is also a concern in other areas of the mainland Beaufort Sea coast. Richards Island, east of the Tuktoyaktuk peninsula, is similar to the Tuktoyaktuk in geology, dominated by low-lying Quaternary sediments (fluvial and aeolian sands, glacial till, and glaciofluvial sands), sea-level history and periglacial features (dominated by shallow lakes, drained lake basins, extensive permafrost up to 700 m in thickness) (Rampton 1988; Dallimore 1996; Solomon 2005). Coastal landforms on Richards Island include tundra slopes, deltas, tidal flats, marshes, beaches and barriers, lagoons and other embayments (Hequette *et al.* 1991; Hill and Solomon 1999; Solomon 2005). Cliffs range between stable vegetated slopes to nearly vertical wave washed cliffs between < 2 m and > 30 m in elevation (Hill and Solomon 1999; Solomon 2005). Erosion along this coast is dominated by thermally induced melt in fine grained cliffs with excess ice, and icy bodies combined with mechanical erosion during storm events where storm surges allow waves to break at the cliff face leading to stripping of thawed and slumped material, wave undercutting, and block failure (Dallimore *et al.* 1996; Hill and Solomon 1999; Solomon 2005). Coastal retreat rates vary between 0.2 and 1.7 m/a, with localized retreat rates of about 23 m/a (Solomon 2005). The outer delta areas of Richards Island exposed to open-water storms while the eastern and western sides of Richards Island are protected from events, with retreat rates averaging between 0.2-0.5 m/a (Solomon 2005).

2.2.6 –Yukon Coast

As other areas of the mainland Canadian Beaufort Sea coast, the Yukon coast morphology varies from long gravel barriers, enclosed shallow lagoons, and deltas, with relief less than 3 m, to high coastal cliffs with narrow beaches up to 30 m in elevation (MacDonald and Lewis 1973; Lewis and Forbes 1974; Lewis and Forbes 1975; Harper 1990). This region is part of the Yukon Coastal Plain physiographic region, composed of an eroded bedrock surface covered by marine, fluvial and glacial deposits (Lantuit and Pollard 2005). Similar to other areas of the mainland coast, this area is underlain by extensive permafrost and widespread massive ground ice (Pollard 1990; Lantuit and Pollard 2005). Previous studies of coastal retreat in the region have indicated lower retreat rates than eastern areas of the mainland coast although, recent measurements in the region have suggested that retreat rates have increased over the past 50 years, from 0.67 m/a in 1954 to 1.03 m/a in 2000 in exposed unlithified cliffs near Herschel Island (Lantuit and Pollard 2004).

2.3 – Coastal Processes

Ninety per cent of Canada's coastline is affected by seasonal or multiyear sea ice (Forbes and Taylor 1994). Cold coasts have unique characteristics that are attributed to perennial or seasonal sea ice, permafrost, ground ice, frost action, glacial history, and isostasy (Forbes and Taylor 1994). The central role of ice is a common factor on Arctic beaches; however, there are considerable differences between beach regimes and beach types across the North American Arctic. These are related to the length of the open-water season, local wind fetch directions, and differences in tidal range (McCann 1973). In parts of the western Canadian Arctic (mainland Beaufort Sea), the coast is dominated by unlithified, ice-rich Quaternary sediments, susceptible to high erosion rates by storm events in the open-water season.

2.3.1 – Sea Ice

The presence of sea ice near a coastline limits the open-water fetch, while ice in the coastal zone absorbs wave energy, reducing the effectiveness of wave action (Forbes and Taylor 1994). In the western Canadian Arctic sea ice dominates the region for approximately eight months of the year (October – June) (Solomon 2005). In mid to late October the shoreline freeze-up occurs and an icefoot develops with freezing of swash, spray and interstitial water (Taylor and McCann 1983; Forbes and Taylor 1994). Ice floes become stranded, ice slush begins to accumulate on the shoreline, and occasionally areas of alternating layers of ice and beach sediment form from frozen swash (Taylor and McCann 1983). During the late fall, early winter fast ice completely covers the littoral zone and offshore areas until break-up in late June (Taylor and McCann 1983). During break-up melting snow cover and rapid melting leads to dirty fractured ice in the intertidal zone with a break between the icefoot and offshore ice. During the open-water season sediments are reworked by waves with ice features, such as ice scour, ridges, (kettle shaped) pit marks, and ice rafting, preserved or still being formed by nearshore ice present throughout the season (Taylor and McCann 1983; Forbes and Taylor 1994).

2.3.2 – Ground Ice and Erosional Features

Onshore ice (ground ice) and low-temperature periglacial phenomena such as frost action and the presence of permafrost are associated with distinctive processes that facilitate sediment delivery to the coastal zone and are susceptible to changing climate. In areas composed of unlithified materials and ice-rich sediments, rapid and dramatic coastal retreat is often associated with melting and release of excess ice (Mackay 1963).

In coastal cliffs composed of sands and gravels, beaches form and protect bluffs from direct wave action, so retreat is dominated by thermal mediated erosion of sediment (erosion induced by thawing of permafrost and ground ice and associated consolidation) (Are 1988; Solomon 2005). This is transported to the waterline by solifluction (slow movement of water saturated sediment downslope) and rainwash (overland flow) (Are 1988; Solomon 2005). Fine-grained sediments are transported along the coast and removed from the source area, leaving coarser materials as beach gravel (McCann and Owens 1969). In bluffs with finer sediments (silts and clays), beaches typically do not form and the bluffs are left exposed to wave action. This leads to undercutting of bluffs (development of thermal niches), exposure of ground ice, block failure, bluff collapse, and loss of sediment by suspension. In areas of finer grained sediments, rapid coastal retreat can occur (Mackay 1963; Dallimore *et al.* 1996).

Retrogressive thaw failures can also influence coastal features. Retrogressive thaw failures are short-lived, rapidly developing features and represent the most rapid erosive process (Mackay 1962; Mackay 1966; deKrom 1990; Wolfe *et al.* 2001). These failures occur when rapid movement of thawed material in the active layer occurs along a scarp face or area of permafrost occur in areas underlain by massive icy bodies, or silts with high ice contents along relatively steep slopes (MacKay 1962; MacKay 1966; de Krom 1990; Wolfe *et al.* 2001). These features are characterized by a steep headwall with exposed ice rich permafrost or ground ice and a gently sloping floor (Murton 2001). Further thawing causes the headwall to retreat and slumped material and sediments flow downslope through slides, falls and debris flows and result in amphitheatre shaped basins with associated mudflows transporting sediment downslope (Murton 2001; Solomon 2005). In many locations material from the failure slump onto the coastline to be removed by wave action or becomes additional beach sediment (Lantuit and Pollard 2005). Retrogressive thaw failures tend to be cyclical in development with stabilization and reactivation on time scales of about 10 years (Forbes and Frobel 1985).

2.3.3 – Arctic Coastal Environments and Depositional Features

Due to the short open-water season in the Western Canadian Arctic, waves are unable to move material over long distances, and coastal sediments for beaches are generally derived from local rock or unlithified sediment (Pollard *et al.* 2002). Due to the presence of ice both onshore and offshore for most of the year, arctic beaches are generally low energy environments in which normal wave action and coastal processes are limited (McCann and Owens 1969; McCann 1973). Beaches are often narrow and poorly developed, consisting of poorly sorted, angular coarse sands and cobbles produced by periglacial processes such as permafrost degradation and melting ground ice (MacKay 1963). In areas of moving pack ice throughout the year, such as areas of the Beaufort Sea, ice driven onshore creates push ridges and mounds in the intertidal and supratidal zones (Forbes and Taylor 1994).

Although low energy environments dominate in parts of the Arctic that remain ice congested throughout most of the summer, rapid erosion and dynamic growth of depositional features are common in the western Arctic where extensive open-water is common (French 1996). Depositional features such as recurved gravel spits, winged headlands, barrier beaches and barrier islands occur in areas that have abundant sediment supply (McCann 1983; Harper 1990; Hequette and Ruz 1991). Sediment supply for these depositional features is derived locally by sediment slumping and thermo-erosion of bluffs combined with wave action during storm events (Hequette and Ruz 1991). Incoming waves at an angle produce longshore drift of sediment in the direction determined by the wave approach angle. Long-term net longshore drift can lead to growth of spits and barriers (Gulliver 1899). Longshore drift creates an accumulation of sediment and debris out into a bay or area of open water, creating a narrow area of land which lengthens quickly by deposition of sediment in shallow water building up to the surface (Johnson 1965). As a spit begins to grow, sediment reaching the spit terminus may be deflected landward by wind and wave action, causing the spit to deflect landward, creating a hooked or recurved spit (Johnson 1965). Spit growth can be seen by successive ridges along the seaward side of a spit (Bird 1969). The western coastline of Banks Island contains many depositional features such as winged headlands, barrier beaches, curved spits, and the recurved coarse spit of Cape Kellett (Taylor and McCann 1983).

2.3.4 – Coastal Storms and Storm Surges

Coastal regions are highly susceptible to high magnitude storm events, often associated with high wind speeds, precipitation and associated increased wave action and surges (Harper *et al.* 1988; Solomon *et al.* 1994; Atkinson 2005). Wind-driven waves remove sediment, vegetation, and infrastructure in low-lying areas (Reimnitz and Maurer 1979; Harper *et al.* 1988; Solomon *et al.* 1994; Atkinson 2005). Storm events are generally classified by wind speed and duration, often defined as wind speeds exceeding 37 km/hr for at least six hours (Solomon *et al.* 1994; Atkinson 2005). Storm surges are also associated with storm events, or surges in water level as the result of low atmospheric pressure combined with strong wind stress on the water surface creating a displacement of water, either a rise (positive surge) or fall (negative surge) (Harper *et al.* 1988). Storm surges are accentuated in shallow water, where they may inundate low coastal areas which are normally above the level of wave runup (Harper *et al.* 1988; Solomon *et al.* 1994; Atkinson 2005). Storm surges and associated large waves allow increased wave energy near the coast can have significant impact on coastlines, damaging or removing infrastructure, removing large quantities of sediment and vegetation, and strongly impacting ecosystems (destroying vegetation due to high salt contents) (Reimnitz and Maurer 1979; Atkinson 2005).

In the Canadian Arctic, the presence of seasonal or perennial sea ice decreases the distance of open-water fetch, limiting wave and storm-surge impacts (Squire *et al.* 1995; Atkinson 2005; Manson *et al.* 2005b). However, wind and wave interaction with sea ice can create direct impacts by increasing ice scour on the sea floor (grounding of pressure ridge keels and ice wallow), increasing sediment in suspension, and ride-up and pile-up onshore (Reimnitz and Maurer 1979; Reimnitz *et al.* 1990; Forbes and Taylor 1994; Atkinson 2005). Storm events in the Western Canadian Arctic are effective at eroding coastlines and removing sediment, as most substrate in the region is unlithified and ice rich (Manson *et al.* 2005b). In an ice-rich zone, storm events with relatively warm water or air causes melting and loss of volume, and can increase various types of coastal mass wasting (Vasiliev *et al.* 2003; Are *et al.* 2004; Atkinson 2005). On the mainland Beaufort Sea coast, storm surges can reach elevations of 2-3 m, inundating low-lying coastal regions (Harper *et al.* 1988).

2.4 – Previous Work: Coastal Processes, Banks Island

Studies conducted on Banks Island from the 1970s through the 1990s documented and mapped the geological and glacial history of the island. Along the southwest coastline, in the Sachs lowlands drainage basin of the Sachs River, several studies were conducted on kettle lakes and pingo ice (French 1975; Gurney and Worsley 1997).

Harry *et al.* (1983) investigated coastal processes along the southwest coastline of Banks Island. Processes studied included wind speed and direction, fetch distance, sea-ice conditions, coastal surveying, local circulation patterns and the migration patterns of the Sachs Spit. Wind direction by quadrant, storm wind by quadrant, potential fetch distance, and sea-ice extent were determined for the open-water season (July through September) from 1971 through 1977. Winds from the south-southeast, southeast, and south have the longest ice free fetch directions, as well as the highest occurrences of onshore storm winds during the open-water season (Harry *et al.* 1983).

Harry *et al.* (1983) also completed nine coastal surveys, seven west of the community of Sachs Harbour and two surveys on the Sachs Spit. Cliffs were typically between six and eight metres in height with low slope angles. Cliff morphology was closely related to lithology in the region, with frequent slumps and flows in ice-rich silty cliffs. Sand-dominated and wider beaches showed less change (Harry *et al.* 1983). Aerial surveys of other areas along the coastline, such as Martha's Point and Sachs Spit, showed progradation. The Sachs Spit was suggested to have prograded 400 m between 1950 and 1979 (Harry *et al.* 1983).

Current circulation and sediment transport were examined using drifters, which showed three major drift directions along the coastline (Harry *et al.* 1983). Rates and patterns of change were due to the duration of open-water, the frequency and magnitude of storm conditions, and the unlithified and ice-rich nature of shore materials. Southwest Banks Island was considered intermediate between southern storm-wave environments and High Arctic ice-dominated environments (Harry *et al.* 1983).

More recent studies of coastal processes on Banks Island have focused on remote measurements of coastal change using satellite images and aerial photography (Manson *et al.* 2005a). This study utilized aerial photographs from 1961 and 1985 combined with satellite images from 2003, giving two periods of potential change: 1961-1985 and 1985-2003. This study indicated that cliffs on the western side of the community, west of the Sachs Landing Beach have been retreating while the Sachs Landing Beach has been prograding and migrating eastward since 1961 (Manson *et al.* 2005a). West of Sachs Harbour, the Martha Point Spit was also studied for longer-term changes. The Martha Point Spit has shown patterns of retreat and accretion from 1961-2003, with erosion occurring on the western side of Martha Point as cliffs have been exposed to wave attack as the spit migrated towards the east (Manson *et al.* 2005a). Although patterns of retreat and accretion were visible in this study, erosion and accretion rates declined in the 1985-2003 period compared to rates seen from 1961-1985, with retreat rates of 0.5 m/a for Martha Point between 1961-1985, and rates approaching zero between 1985-2003 (Manson *et al.* 2005a). It was suggested that coastal change in this area is dominated by localized cliff retreat and beach progradation, with longshore drift exposing cliffs to wave attack in some areas and protecting cliffs in others (Manson *et al.* 2005a).

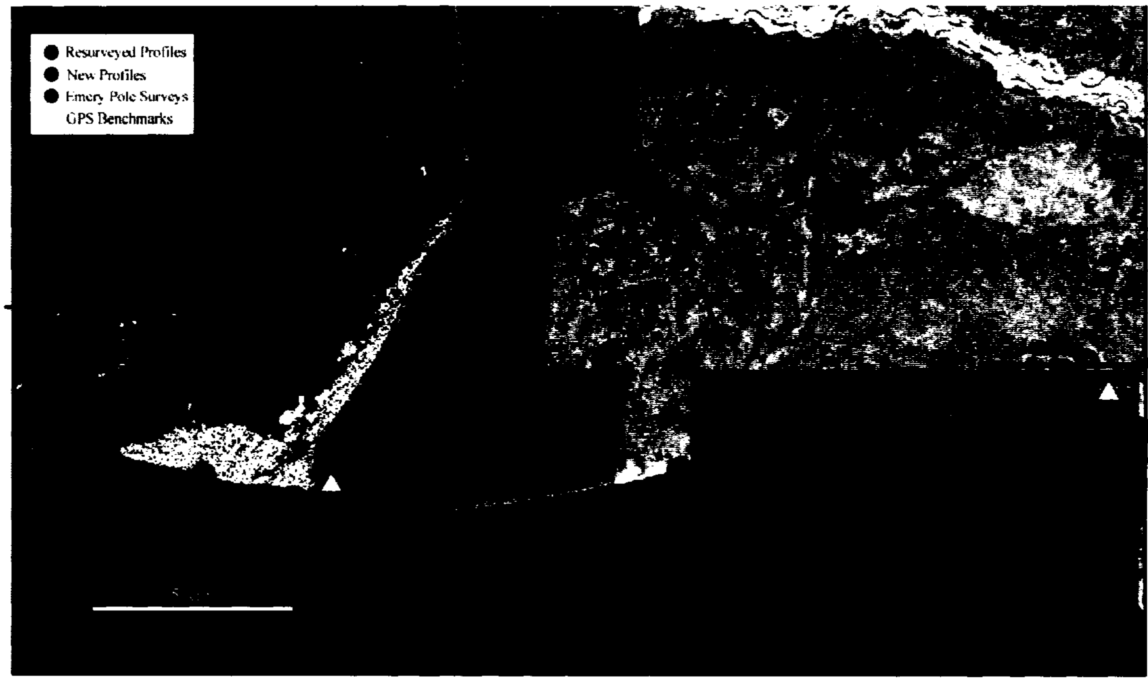
Other studies of Sachs Harbour include a summary of coastal change in communities in the Western Canadian Arctic which provided valuable background on substrate in Sachs Harbour, sea-level change, coastal storms and sea-ice conditions and were the basis of the current study.

Chapter 3 – Methodology

3.1 – Field Methods

3.1.1 – Coastal Surveys

Twenty-seven surveys oriented approximately shoreline normal were surveyed along the southwest coastline of Banks Island. Twenty-three surveys were completed using a real-time kinematic (RTK) GPS survey system. The RTK system is preferred for coastal surveying because it gives location and elevation with a precision of 50 mm, allowing determination of coastal change within the centimetre range (Magellan Corporation 1999). Emery poles (Emery 1961) were used for coastal surveys when the RTK system was unavailable. This system has a lower precision but still allows determination of coastal change on a decimetre scale (Liverman *et al.* 1994; Krause 2004). RTK surveys completed included repetitive surveys in fifteen locations previously studied, allowing comparison over time. Twelve new survey lines could be resurveyed in the future to look at longer term coastal change (Figure 3.1). Eight coastal surveys were resurveyed within the Sachs Harbour community boundaries. Thirteen lines were surveyed at locations from the western edge of the community to Cape Kellett. One line was completed to the east of Sachs Harbour, and three surveys completed on the spit south of the community (Figure 3.1).



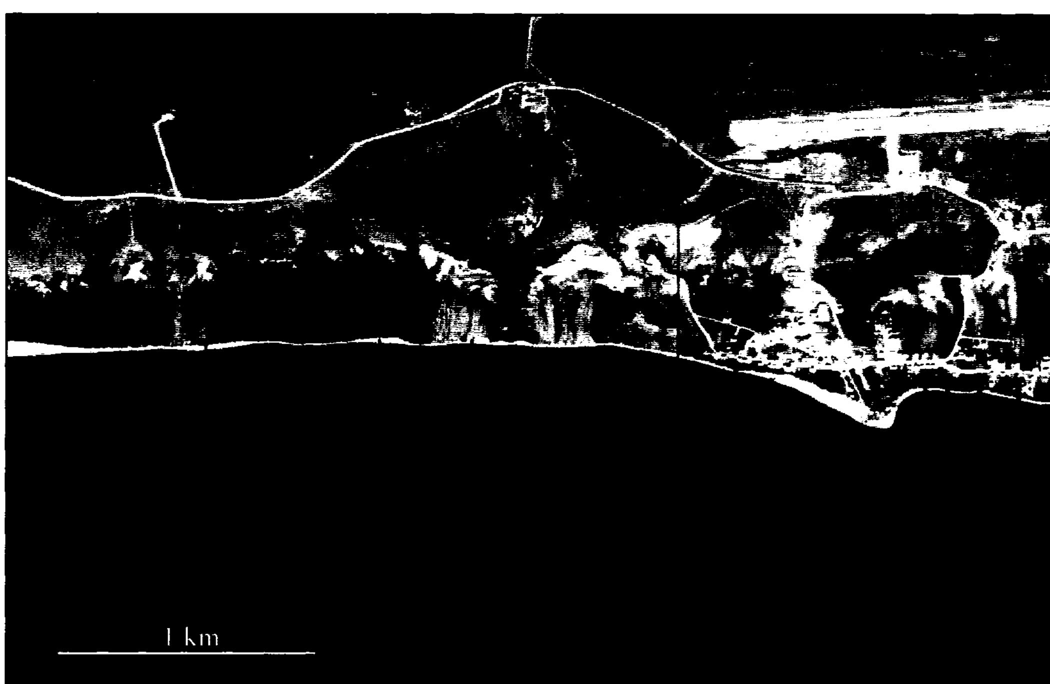


Figure 3.1: Twenty-seven coastal surveys were completed along the southwest coastline of Banks Island in 2005 (a). The blue box indicates surveys completed in or near the community of Sachs Harbour, with the community shown in the blue box (b). Bathymetric surveys were completed shore normal near the waterline of each line (modified from imagery © Digital Globe 2005).

To complete an RTK survey, a base station was positioned in an area no greater than 20 km away from the survey, at a benchmark survey marker with precise known coordinates. A GPS receiver and radio were set up at the benchmark location to receive satellite information and transmit to the rover receiver, which was mobile and used to collect data points by the surveyors. Once the base station was receiving satellite data, the rover unit was then taken to the survey site locations. The rover received data from the GPS satellites and from the base station via radio to allow for real time recording of location and elevation data (Magellan Corporation 1999). Along each survey line, an inland position was chosen in an area not susceptible to erosion in the short term and marked using GPS to establish the landward endpoint marker of the survey. From the endpoint, GPS positions were recorded along the survey marking changes in slope and/or substrate, breaks in slope, and the configuration of the coastal zone extending to the water line. The length of the surveys ranged from approximately 30 to 500 m. The time at the water line position was noted for subsequent consultation of the tide tables to determine exact tide height at the time of surveying. At each GPS position recorded, the elevation was recorded with a short description of the substrate. The elevations were later plotted to create surveys of each survey location, allowing comparison with surveys taken in previous years.

Surveys using Emery poles followed the method outlined by Emery (1961) and Liverman *et al.* (1994). A line was chosen and measured extending from above the break in slope to the water line. At each change in slope and/or substrate the measured horizontal distance and the change in vertical distance was recorded using the horizon, a tape measure, and poles of known incremental heights. The starting location for each survey, the break in slope, the seaward edge of the slope and the water line were recorded using a handheld Garmin ETrex GPS unit. The time was recorded at the water line measurement to determine exact height. From this data, surveys were plotted for all three locations (Figure 3.1a).

Beach and cliff slope were calculated along the beach and cliff widths respectively. Waterline height during 2005 surveying (present as a black line on all diagrams) is indicated, as tidal corrections were not available for all past survey years. However, the region is microtidal (average 0.5 m), and thus tidal position cannot account for major differences between surveys. A 2x vertical exaggeration was used for all surveys along the southwest coast with the exception of the Sachs Spit Lines 2 and 3 and the Cape Kellett Lines, which used a 25x vertical exaggeration.

3.1.2 – Nearshore Bathymetric Surveys

Nearshore bathymetric surveys were recorded offshore of the 27 coastal survey locations, using either a Simrad EQ30 Singlebeam echosounder coupled with Garmin GPS 76 handheld GPS coupled to a CdGPS differential GPS antenna, or a Garmin Map176s GPS-echosounder. Bathymetric surveys were conducted by navigating a small boat to the waterline of each coastal survey, using a Garmin 72 GPS unit and then navigating seaward on a shore-normal course. Continuous soundings were taken with the Garmin Map176s sounder unit, recording location, temperature, and depth every second to approximately 1 km offshore. The Garmin Map176s sounder unit was also used to continuously record data every five seconds while moving between survey locations. The Simrad EQ30 Singlebeam with Garmin GPS 76 sounder unit was utilized between coastal surveys to complete a bathymetric map of the nearshore zone, and continuously recorded data. Sounder data was downloaded to the Garmin Mapsource and Waypoint Manager program, placed in an Excel format and mapped using the ESRI ArcMap program. No bathymetric surveys were completed at Cape Kellett Lines 3 and 4 surveys because of accessibility and ice conditions during the survey period. Bathymetric surveys were at maximum one km in length. A 2x vertical exaggeration was used for all bathymetric profiles.

3.1.3 – Sediment Sampling

Sediments were sampled in both shoreline and shallow nearshore environments along surveys to determine grain size, composition, sediment source and transport direction. Onshore sediment samples were collected from within the cliff or slope, generally from at least 400 mm depth to avoid sampling slumped material which may originate further upslope; from near the slope base, and from near the water line. Sediment samples were air or oven dried. Pebbles and cobbles were noted, measured, and removed from measured samples. Sediment samples were not collected within the community of Sachs Harbour because the shoreline is highly disturbed by ATV traffic, extraction of sediment, and waste disposal. These shoreline modifications have produced sediment assemblages which may not be representative of the original substrate.

In the shallow nearshore environment sediment samples were collected at approximately 20 m and 100 m offshore using a Petit Ponar grab sampler. A GPS position and depth (when possible) were recorded for each site using a Garmin GPS72 and samples were placed in 100 ml plastic sample jars, and subsequently air or oven dried. In offshore locations where samples could not be obtained, the substrate type was noted by visual inspection by investigators in the shallow areas and an underwater video system. Near the community sediment samples were only taken at 100 m offshore as the nearshore areas showed anthropogenic disturbance from boat anchoring and fishing.

3.1.4 – Suspended Particulate Matter

With potentially high erosion rates on the coastal cliffs in the region, high concentrations of suspended sediment may occur in the nearshore environment. In order to determine the amount of sediment suspended in the water column during calm periods, suspended particulate matter (SPM) samples were taken. Initially, due to water clarity, these samples were taken at approximately 100 m offshore. After a minor rain/wind event occurred on August 8-9, SPM samples were collected at both 20 and 100 m offshore to assess any resultant increased sedimentation and re-suspension. To complete an SPM sample, a surface water sample was taken with a plastic 1-l Nalgene bottle at each site. The water sample was manually pumped through a 47 mm diameter 0.45 micrometre (μm) pore size glass fibre filter (An 80 μm filter was also used) into a vacuum flask until the 1-l sample had passed through the filter. The filter was then removed and placed in a sterile plastic Petri dish for analysis. The filters were oven dried, and the mass of the used filter was determined and compared to the average mass of a clean and sterile filter. The difference in mass was the amount of suspended particulate matter present.

3.2 – Laboratory Methods

3.2.1 – Grain Size Analysis

Grain size distributions were determined for shallow nearshore and coastal sediment samples using the modified Udden-Wentworth grade scale (Krumbein 1934). Dried sediment samples with grain sizes ranging from granules (between 2-4 mm) to coarse silt (0.031 mm) were analysed, using sample masses of 100 g or 50 g depending on the grain size. Sieving followed the procedure outlined in Catto *et al.* (1989). The samples were placed in a combined series of sieves in a stack arranged from sieve mesh size -5 to + 4.00 (in descending mesh size) with a pan underneath. Samples were placed in the top sieve, and the stack mechanically shaken for approximately 10 minutes. The mass of sediment retained in each sieve was then weighed and recorded allowing calculation of the percentage of each size proportion within the overall sample (Anderson 2004).

After sieving, sediment samples were examined under a binocular microscope and photographed to determine mineralogic composition and clast roundness. Sediment samples were photographed prior to sieving as well as post-sieving to determine specific sediment composition in each size range of sediments. Analysis of dry sieving determined sorting of each sediment sample to allow comparison of mean grain size and sorting between samples. Mean grain size (M) and sorting (D) were calculated using the cumulative probability of the sample and the grain size in phi scale (Folk and Ward 1957; Folk, 1966). These calculations allowed comparison between sediment samples by grain size and sorting. Values of mean grain size (M) and mean sorting (D) were compared to range values based on the phi scale.

3.2.2 – Aerial Photograph Analysis

Aerial photographs of the study area from 1950 – 1985 were scanned at 1200 dots per inch (dpi) and saved as high resolution tagged image file format (TIFF) files. These files were loaded into the ESRI ArcMap program to be georeferenced. Digital base maps, primarily a 1/50,000 digital topographic map, a 2003 Quickbird satellite image of the study area, and a 15 m resolution Landsat image of southwest Banks Island from 2000 were used to locate known coordinates. Once imported into ArcMap, these photographs were overlain over the digital maps and, at minimum, twenty-five control points were employed for each photograph.

Control points are used in georeferencing to find specific locations on a photograph and matching them with locations on the digital basemaps (ESRI 2004). Examples of control points used were landforms, road intersections, and the corner of buildings (ESRI 2004). As control points are added, the aerial photograph is digitally adjusted to fit with the corrected basemap.

Approximately 25 control points were created and the pixel size and root mean square (RMS) errors were examined. The RMS error is the residual error from calculating and comparing the actual location on the basemap and the transformed position on the photograph (ESRI 2004). A low RMS is desired, because it assesses the accuracy of the transformation (ESRI 2004). At a 600 dpi scanning resolution resulting pixel sizes for the photographs were 0.85 m (1950), 0.25 m (1964), 0.17 m (1972), 2.9 m (1975), 4.1 m (1979) and 0.13 m (1985). Average RMS values for the air photo series were: 11.3 m for 1950 photos, 3.9 m for 1964, 4.2 m for 1972, 5.3 m for 1979 and 3.6 m for 1985. Once the RMS was calculated and determined to be small the aerial photograph was rectified in ArcMap. Rectification is transformation of a raster (aerial photograph in this case) to a new file which is spatially georeferenced (ESRI 2004).

Once georeferenced and rectified these aerial photographs were used to compare the coastline of the study area over decadal scales. The coastline was defined as the water line for each series of digital aerial photographs. Although this is variable with tides and storm surges, the tidal range is small and photographs are assumed to have been taken at times of fine weather when there would be limited surge activity. The shoreline differences between survey years were used to determine quantitative changes in coastal features in the study area.

3.3 – Historical Climate Data

Monthly data for wind speed and direction for the community of Sachs Harbour were downloaded and recorded for the time interval 1978 – 2005 (data obtained from Environment Canada 2006a) and then converted from 10's of degrees to quadrants

(Appendix E). As a previous study examined wind data for 1971 – 1977 from the months July to September (Harry *et al.* 1983), the 1978 – 2005 data were chosen to be examined in detail, with storm frequencies calculated using the entire record from 1956 - 2005.

To calculate storm winds, hourly wind speed values were examined for records from the open-water season records. Storm winds were identified based on two main parameters, event threshold wind speed and duration threshold (Atkinson 2005). The event threshold was taken to be sustained winds of 10 m/s or greater, with a duration threshold of six hours (Atkinson 2005). Lulls in wind speeds and shoulder events were also considered, with lulls defined as a single wind speed observation no less than 7 m/s and with threshold events immediately prior to and following the lull (Atkinson 2005). Shoulder events were defined as involving a wind speed occurring immediately before the first or after the last event threshold which was no less than 7 m/s and therefore likely associated with the event. Once wind speeds were recorded as a storm event, the fetch direction was used to determine the effect of this storm on the coastal and nearshore zones, and the sea ice concentrations offshore during the event.

Sea ice records for the region between June and November for each year were examined to determine the longest open-water fetch direction possible and correlated to each storm event (data obtained from Canadian Ice Service, Environment Canada 2006b). Sea-ice conditions in the western Arctic have been determined, based on observations and satellite/submarine observations, since 1968 and recorded in sea ice charts (Environment Canada 2006b). Sea ice charts were downloaded and examined to determine timing of the open-water season and ice conditions during storm events in

Sachs Harbour. Open-water fetch was defined as the distance over which the wind could effectively generate waves and was limited by sea-ice extent. Storm events with long open-water fetch and coastal survey data were graphed separately and will be discussed as individual events. Storm events without survey data were included in the overall storm frequency for Sachs Harbour.

Chapter 4 – Results: Coastal Surveys and Bathymetric Surveys

Coastal surveys were differentiated between new locations and locations surveyed in previous years. Bathymetric surveys and both onshore and offshore sediment samples have been included with survey descriptions. Survey lines completed using RTK surveying had accuracy of ± 5 cm and Emery pole surveys had decimetre-scale accuracy. No sediment samples were collected for Sachs Harbour survey lines 1-8 due to anthropogenic disturbance of sediment. Beach and cliff slope were calculated along the beach and cliff widths respectively. Waterline height during 2005 surveying (present as a black line on all diagrams) is indicated, as tidal corrections were not available for all past survey years. However, the region is microtidal (average 0.5 m), and thus tidal position cannot account for major differences between surveys.

4.1 – New Survey Locations

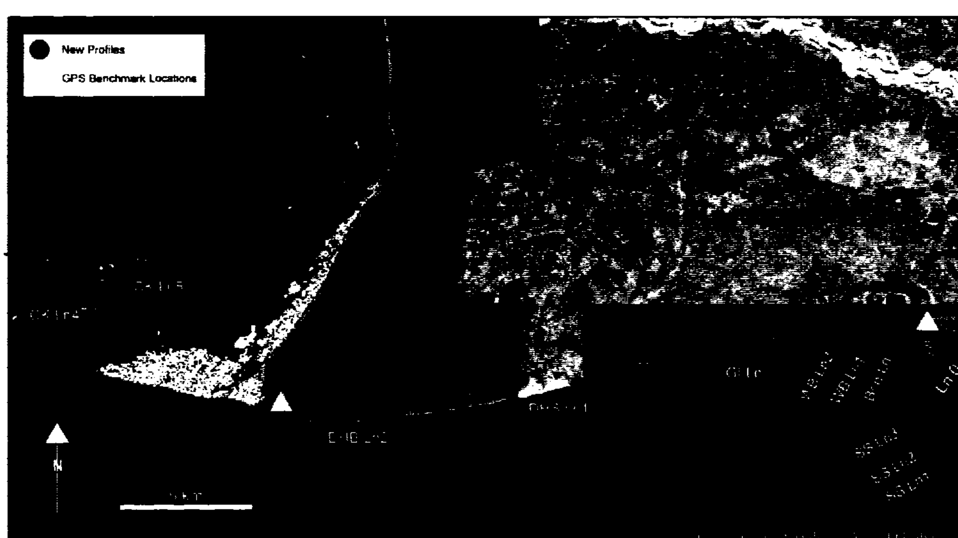


Figure 4.1: Location of new surveys completed in 2005. New surveys were positioned in areas not effectively covered by previous surveys. Bathymetric surveys were completed shore normal from each survey line (modified from imagery © Digital Globe).

Table 4.1: Summary of new survey lines including: end point coordinates, distance to cliff top, distance to cliff base, beach width and beach slope (over the beach width). All elevation data was calculated above water level and beach widths were calculated from the cliff base to the water line (Figure 4.2).

Line	Location (WGS 84)	Distance to cliff top (m)	Distance to cliff base (m)	Beach width (m)	Beach slope (degrees)	Cliff slope (degrees)
Ln 0	423982 E 7988465 N	12.9	18.3	18.8	6.3	38.4
Bcn Ln	421072 E 7988784 N	27.9	36.7	18.7	7.8	35.8
WB Ln1	420713 E 7988786 N	5.0	7.8	28.0	4.0	18.3
WB Ln2	420039 E 7988767 N	10.6	14.4	24.9	3.3	34.2
***GI Ln**	417012 E 7988505 N	31.6	38.1	5.0	4.1	25.9
***DHB Ln1**	411494 E 7987556 N	31.6	36.5	28.9	6.5	55.1
***DHB Ln2**	404473 E 7986394 N	15.2	23.9	43.7	5.2	34.04
CK Ln4	396739 E 7989567 N	no cliff edge	no cliff base	61.7	variable	no cliff slope
CK Ln5	397974 E 7990337 N	no cliff edge	no cliff base	170.9	variable	no cliff slope
SS Ln1	422536 E 7985351 N	5.9	35.6	8.8	7.5	44.2
SS Ln2	422292 E 7985651 N	no cliff edge	no cliff base	71.2	0.3	no cliff slope
SS Ln3	421806 E 7986313 N	no cliff edge	no cliff base	130.2	0.3	no cliff slope

Survey lines completed using the emery pole technique

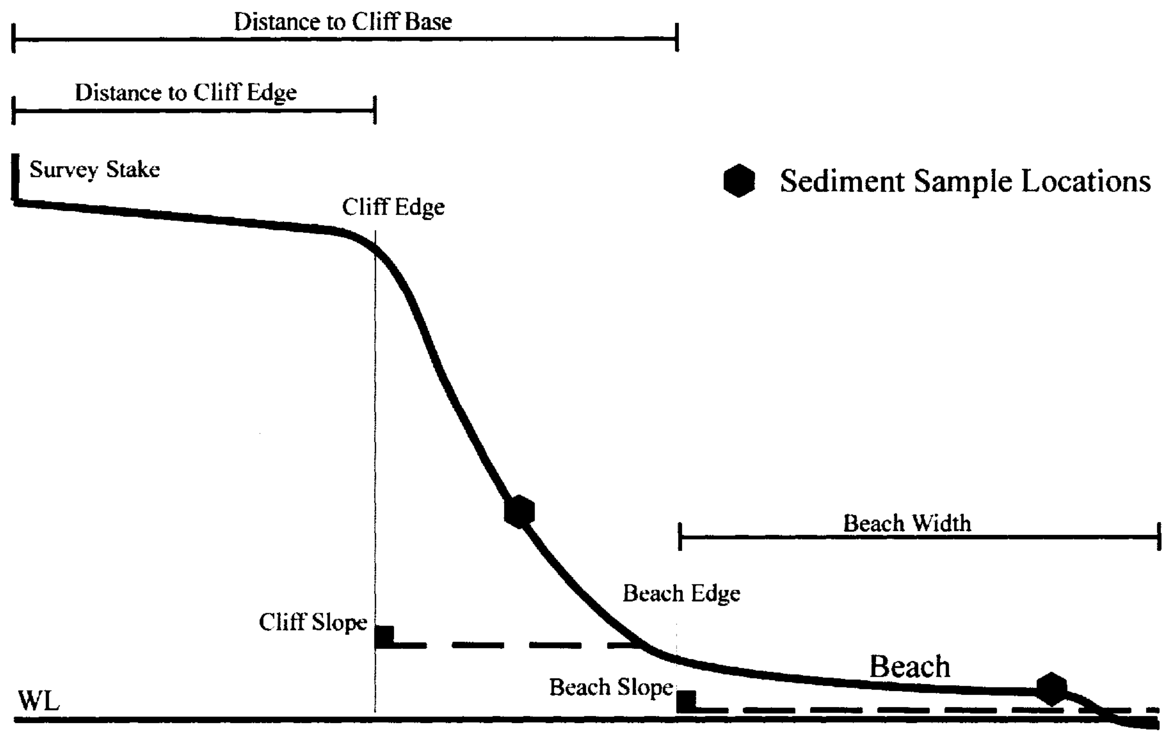


Figure 4.2: Graphic representation of calculations and areas of each coastal survey including the cliff and beach slopes, beach width, water line (WL) and distance to the cliff edge and cliff base.

4.1.1 – Southeast of Sachs Harbour

The Sachs Spit Line 1 (SS Ln1) was located at the edge of a navigation beacon in an area of exposed ground ice in the Sachs Lowlands (Figure 4.1) (Table 4.1). The survey was sparsely vegetated to the cliff edge, with exposed well sorted sand present throughout. The cliff edge was approximately 6 m asl and actively retreating with slumped material evident along the unvegetated slope (Appendix A). Massive ice was exposed on the well sorted medium sand slope, and was dominantly composed of quartz and feldspar with garnet and amphibole grains. The slope base was partially covered by an ice foot about 1 m wide. The beach was very narrow and composed of well sorted medium sand of similar composition to the slope, dominated by quartz and feldspar grains with garnet and amphibole grains present (Appendix D).

Sachs Spit Line 1 bathymetric survey showed three distinct nearshore bars. The first bar crest was at 0.5 m depth about 25 m off the beach, the second at about 1.5 m depth about 120 m offshore, and the third at about 2.5 m depth about 330 m offshore. The troughs have depths of 0.9 m, 2.2 m, and 3.9 m, respectively (Appendix C). This area is open to sea-ice movement and is subject to ice scour, which may explain the irregularity on the crest of the middle bar. Sediment samples were collected at 20, 100 and 780 m offshore. At both 20 m and 100 m, the substrate was composed of very well sorted fine sand dominated by quartz, feldspar, garnet and amphibole grains (Appendix D). Further offshore at 780 m the substrate was moderately well sorted fine sand of similar composition (Appendix D).

Sachs Spit Line 2 (SS Ln2) was located near the southern (proximal) end of the Sachs Spit (Figure 4.1) (Table 4.1). This survey extended the entire width of the spit and had little variation in elevation along the survey, with a flat crest at 0.4 m in height (about 0.7 m asl) which was the highest elevation (Appendix A). The entire survey is dominated by wave action and washover. Both ends of this survey (both sides of the spit) were composed of fine grained well sorted sand dominated by frosted quartz, feldspar and amphibole grains (Appendix D). Frosted quartz grains and other aeolian features such as sand ripples and adhesion wrinkles were present along the survey.

The Sachs Spit Line 2 bathymetric survey was completed on the western side of the spit. A series of crests and troughs were apparent along the first 100 m of the survey, and appeared to be the same nearshore bars evident in Sachs Spit Line1 before gradually deepening to 5 m at the end of the survey (Appendix C). A sediment sample collected at 100 m offshore indicated a substrate composed of moderately well sorted medium sand, dominated by quartz, feldspar, garnet, and amphibole grains (Appendix D).

Sachs Spit Line 3 (SS Ln3) was located midway along the Sachs Spit (Figure 4.1) (Table 4.1). This survey spans the entire width of the spit from the eastern to western waterline (Appendix A). Similar to Sachs Spit Line 2, this survey had little variation in elevation and was clearly a product of wave overwash, with a crest of approximately 0.2 m (0.6 m asl). Both sides of this survey are composed of medium well sorted sand dominated by frosted quartz, feldspar and amphibole grains (Appendix D). Frosted quartz grains and aeolian features such as sand ripples and wrinkles were present along this survey.

The Sachs Spit Line 3 bathymetric surveys were surveyed on both (inner and outer) sides of the spit. The western (outer) survey showed two clear nearshore bars with an indistinct inner terrace (Appendix C). The bar crests were at depths of about 0.9 and 1.8 m at distances of approximately 60 m and 180 m offshore, respectively. Both sediment samples taken at 20 m and 100 m offshore indicate a substrate of well sorted fine sand, dominated by quartz, feldspar, garnet and amphiboles (Appendix D).

The eastern (inner) bathymetric survey extended from the eastern side of the Sachs Spit into a deep basin. This line crossed bathymetry less than 4 m in depth before crossing a large basin and its associated shallow sill (approximately 2 m depth). The bathymetry deepened into the basin at approximately 600 m along the survey line to its maximum depth of about 36 m at the end of the survey (Appendix C). No sediment samples were taken along this survey.

4.1.2 – Southwest Coastline

Sachs Harbour Line 0 (Ln 0) was located at the western edge of a symmetrical spit east of the community (Figure 4.1) (Table 4.1). The cliff was approximately 5 m high (6 m asl) and showed evidence of active slumping, slope fractures and gullying. Ground ice was visible in the fine grained sand along the cliff slope (Appendix A). The cliff slope was unvegetated and composed of moderately well sorted fine sand dominated by quartz, feldspar and dolomite fragments. No vegetation was present along the base of the cliff or the beach edge. The beach was narrow and composed of poorly sorted gravel dominated by dolomite and gabbro fragments as well as quartz and feldspar grains (Appendix D). The spit to the east appeared to be overwashed by waves and showed signs of disturbance from ATV tracks, garbage disposal, docked boats and fishing equipment.

The Sachs Harbour Line 0 bathymetric survey was shallow with a small basin approximately 7 m in depth. This basin is likely a channel of the Sachs River developed as it empties into the harbour. The survey shallows to less than 1 m depth at the end near the Sachs Spit to the southwest (Appendix C). At 10 m offshore from Line 0, the substrate was composed of very well sorted fine sand dominated by quartz and feldspar grains with gabbro and dolomite fragments and a film of silt on the larger grains (Appendix D). At 100 m offshore the moderately sorted fine grained sand was dominated by quartz and feldspar with iron staining evident on the feldspar grains (Appendix D). Finer silt found on the larger grains was sediment from the Sachs River.

The Sachs Harbour Beacon Line (Bcn Ln) was completed adjacent to a government navigation beacon in an area of active gullying and cliff retreat west of the community (Figure 4.1; Figure 4.3) (Table 4.1). The cliff was approximately 9.5 m high (11 m asl) and the slope was sparsely vegetated with fractures near the cliff edge and vegetated blocks slumping onto the unvegetated slope. The slope was composed of fine sands and silts dominated by dolomite fragments and feldspar and quartz grains. The cliff base was unvegetated and showed evidence of mechanical erosion from wave action (Figure 4.3). The narrow beach was composed of poorly sorted coarse grained sand dominated by feldspar and quartz with oolitic limestone, dolomite and gabbro fragments (Figure 4.4) (Appendix D). Large gabbro boulders originating from within the cliff were present across the beach width (Figure 4.3).

The Sachs Harbour Beacon Line bathymetric survey gradually deepened to approximately 10 m offshore then dropped to approximately 21 m (Figure 4.5) as it entered a deep basin visible on satellite images. Sediment samples were taken at 20 m and 100 m offshore. At 20 m, the substrate was composed of moderately sorted fine sand dominated by quartz, feldspar, garnet grains and gabbro fragments (Figure 4.6) (Appendix D). At 100 metres the substrate was moderately sorted very fine sand with similar composition of feldspar grains, dolomite and gabbro lithic fragments (Figure 4.7) (Appendix D).

Sachs Harbour Wide Beach Line 1 (WB Ln1) was an area with a low slope and a wide beach, approximately 2.7 m in height, 4.7 m asl (Figure 4.1) (Table 4.1). The cliff edge and cliff slope appeared stable and vegetated along the cliff edge and cliff slope (Appendix A). The wide beach was composed of moderately well sorted medium sand dominated by feldspar, dolomite, frosted quartz, garnet grains and gabbro fragments (Appendix D). The beach slope had several wide berms, up to 2 m asl (Appendix A).

Sachs Harbour Wide Beach Line 1 bathymetric survey gradually deepened throughout with a small channel approximately 7.7 m in depth (Appendix C). Less than 2 m of variation in depth occurred between 100 m and the offshore end of the survey (Appendix C). A sediment sample collected 100 m offshore indicated a substrate of moderately well sorted fine sand dominated by feldspar and quartz grains with gabbro and dolomite fragments (Appendix D).

The Sachs Harbour Wide Beach Line 2 (WB Ln2) was located near Martha Point (Figure 4.1) (Table 4.1). The cliff edge (< 5m asl) and cliff slope did not show signs of active retreat although the cliff slope was unvegetated (Appendix A). No wave interaction with the cliff base was observed. The beach was wide with multiple berms and composed of well sorted fine sand dominated by feldspar, frosted quartz and garnet grains, with gabbro fragments (Appendix D).

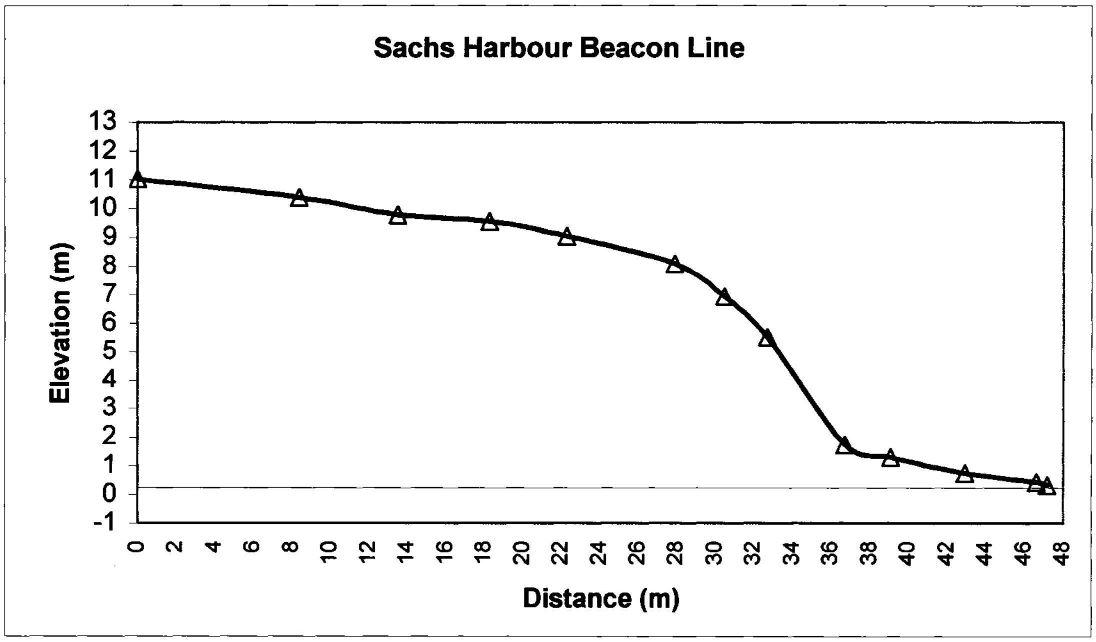


Figure 4.3: The Beacon Line located 1.7 km west of the community. The cliff slope was unvegetated and the base of the slope had been truncated by wave action. UTM coordinates: 421068 E, 7988790 N, (2x Vertical exaggeration) Photo taken July 26, 2005.

Figure 4.4: Sediment sample taken near the water line of the Sachs Harbour Beacon Line. UTM Coordinates: 421070 E, 7988784 N

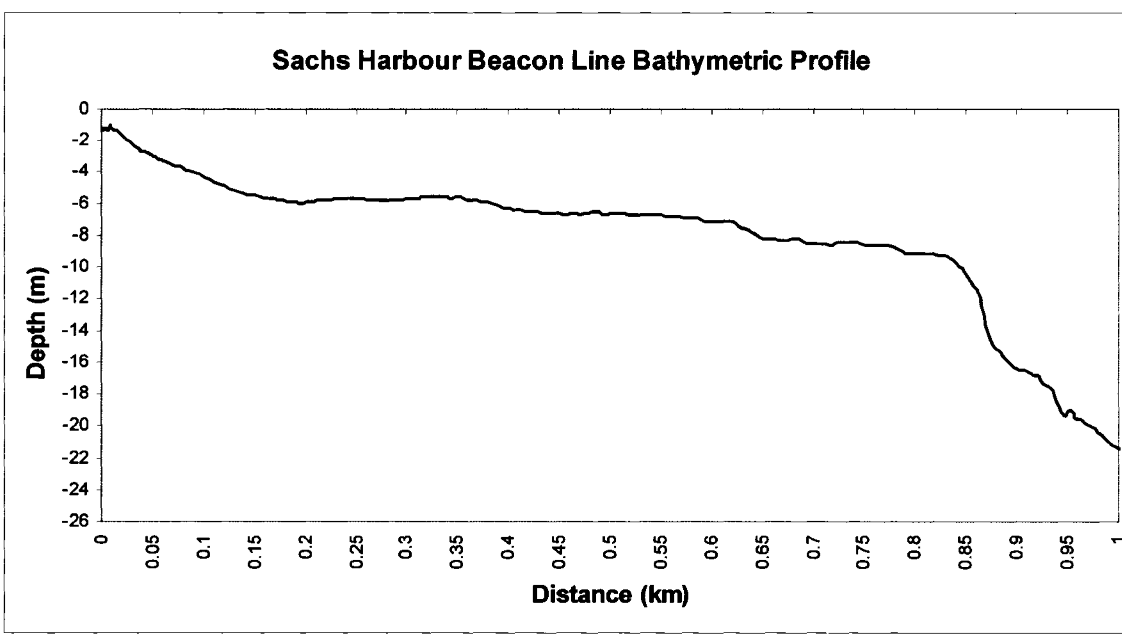


Figure 4.5: Sachs Harbour Beacon Line bathymetric survey 1 km in length with a maximum depth of 24.7 m (25x vertical exaggeration).

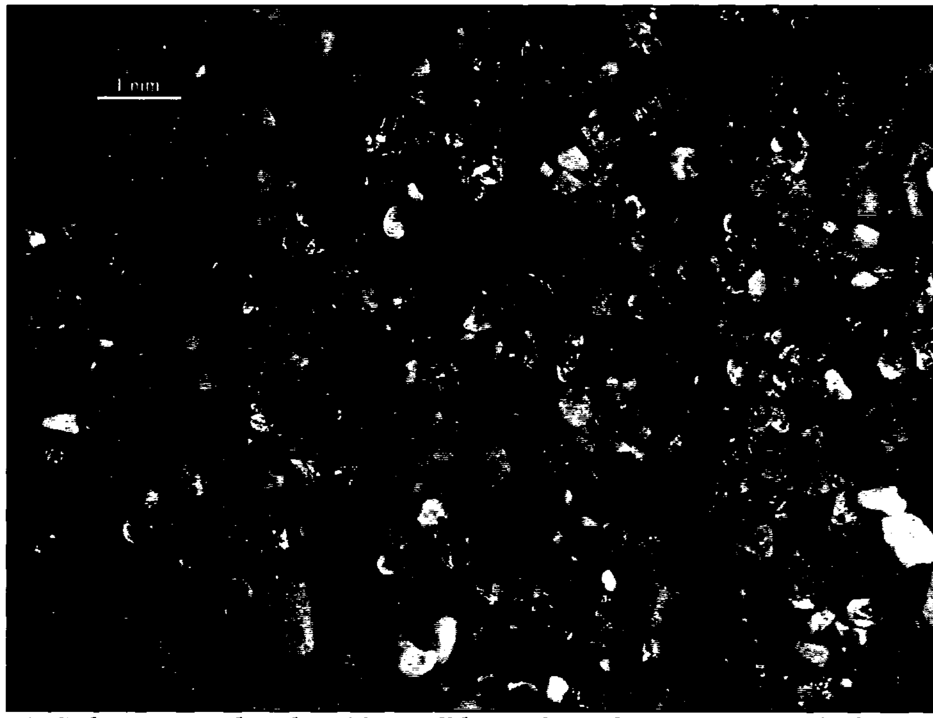


Figure 4.6: Sediment sample taken 20 m offshore along the Beacon Line bathymetric survey. UTM Coordinates: 421070 E, 7988761 N.

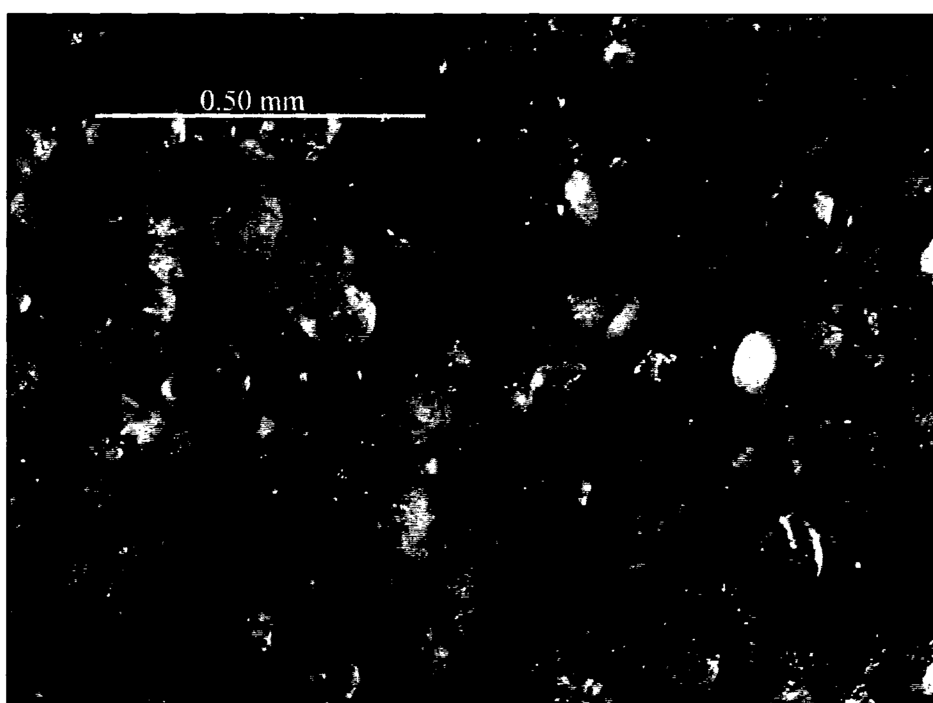


Figure 4.7: Sediment sample taken at 100 m offshore along Beacon Line bathymetric survey. UTM Coordinates: 421068 E, 7988682 N.

The Sachs Harbour Wide Beach Line 2 bathymetric survey had a very shallow nearshore terrace about 30 m wide, then sloped more steeply 60 m off the beach (to a depth of 2 m). From that point the bottom was undulating in depths between 1.8 and 2.8 m, with a deeper channel to 3.7 m depth near the end of the survey (Figure 4.1) (Appendix C). Sediment samples indicate that at 20 m offshore the substrate was moderately well sorted medium sand while at 100 m the substrate was moderately sorted very fine sand (Appendix D). Both samples indicated that petrology was dominated by quartz, feldspar, and dolomite fragments.

The Sachs Harbour Ground Ice Line (GI Line) was surveyed in an area of exposed ground ice (Figure 4.1; Figure 4.8) (Table 4.1). The cliff edge, about 5 m asl, contained large vegetated blocks slumping onto the slope. The slope was unvegetated and included a >2 m vertical exposure of massive ice (Figure 4.8). The base of the cliff slope contained slumped vegetated blocks of fine grained sand and silt eroded from the cliff edge, accounting for the increase in elevation at the cliff base (Figure 4.8). Vegetated blocks were also present on the beach where exposure to waves dispersed fine-grained material and vegetation into the nearshore. The narrow, medium sand beach was composed of feldspar, garnet, quartz, gabbro fragments and vegetative material such as plant roots.

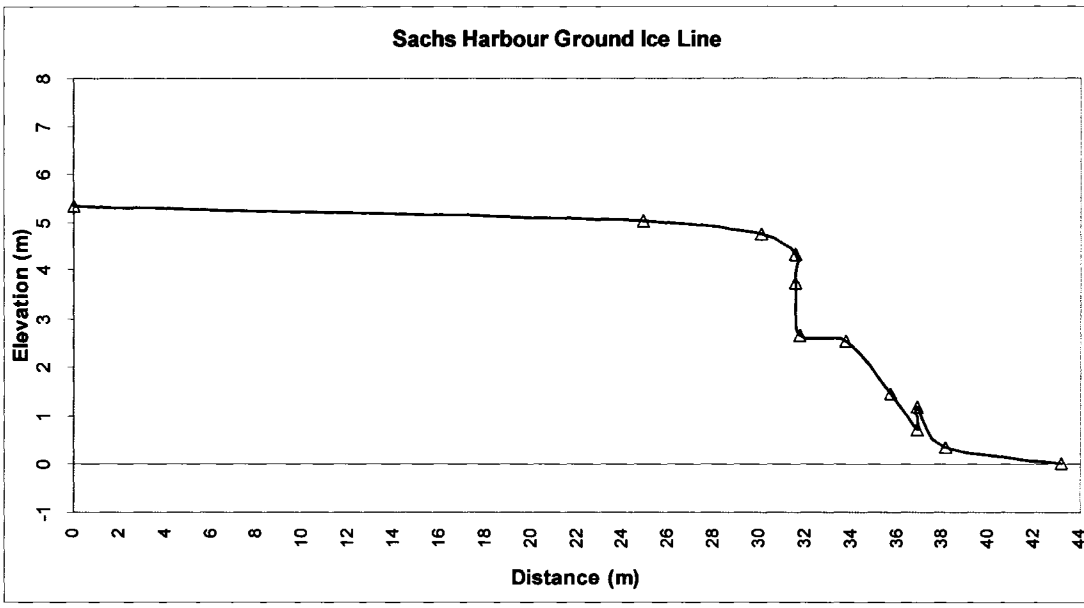


Figure 4.8: Ground Ice Line located 5.5 km west of the community. Vegetated blocks have slumped from the cliff edge onto the slope. Ground ice was exposed in the near-vertical cliff face. The cliff base had been truncated by waves during a wind/rain event and the high water mark was approximately 1 m from the cliff base. UTM Coordinates: 417012 E, 7988505 N (2x vertical exaggeration). Photo taken August 10, 2005.

The GI bathymetric survey indicated a gradual deepening with two offshore bars, evident in other bathymetric surveys, which are also visible on satellite imagery of the area (Figure 4.9). These offshore bars occur at approximately 80 m offshore at 1.5 m in depth, and at 270 m offshore at 3.5 m in depth. Both of the sediment samples taken at 20 m and 100 m offshore indicated a moderately well sorted fine grained sand substrate dominated by quartz, feldspar and dolomite and gabbro fragments (Figure 4.10; Figure 4.11) (Appendix D).

The Duck Hawk Bluffs Line 1 (DHB Ln1) was located near the Mary Sachs River at the eastern end of the Duck Hawk Bluffs (Figure 4.1) (Table 4.1). The survey line was sparsely vegetated along the top of the survey to the cliff edge about 8 m in height, 10 m asl, which was actively retreating (Appendix A). The cliff slope was unvegetated with a hard-packed surface composed of poorly sorted gravel containing dolomite fragments, quartz, and feldspar. The beach was about 30 m wide and composed of moderately sorted very coarse sand dominated by dolomite and gabbro fragments, and feldspar, similar in composition to the cliff slope (Appendix D).

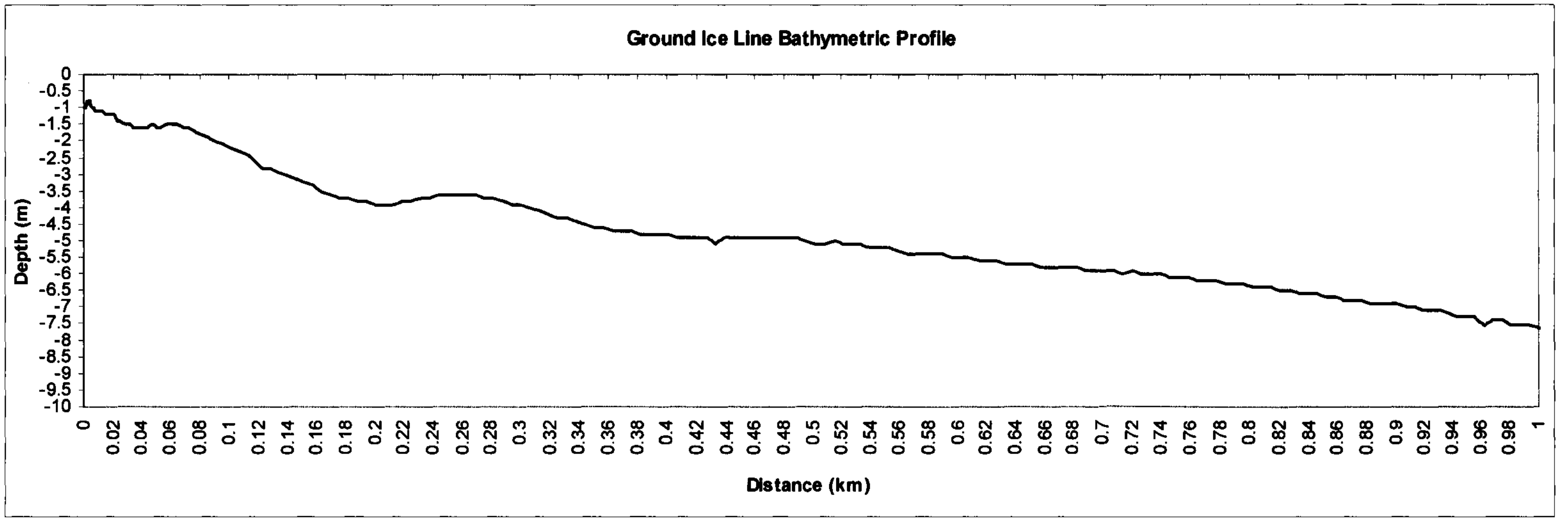


Figure 4.9: Ground Ice Line bathymetric survey. This survey was 1.07 km long with a maximum depth of 8.1 m (25x vertical exaggeration).

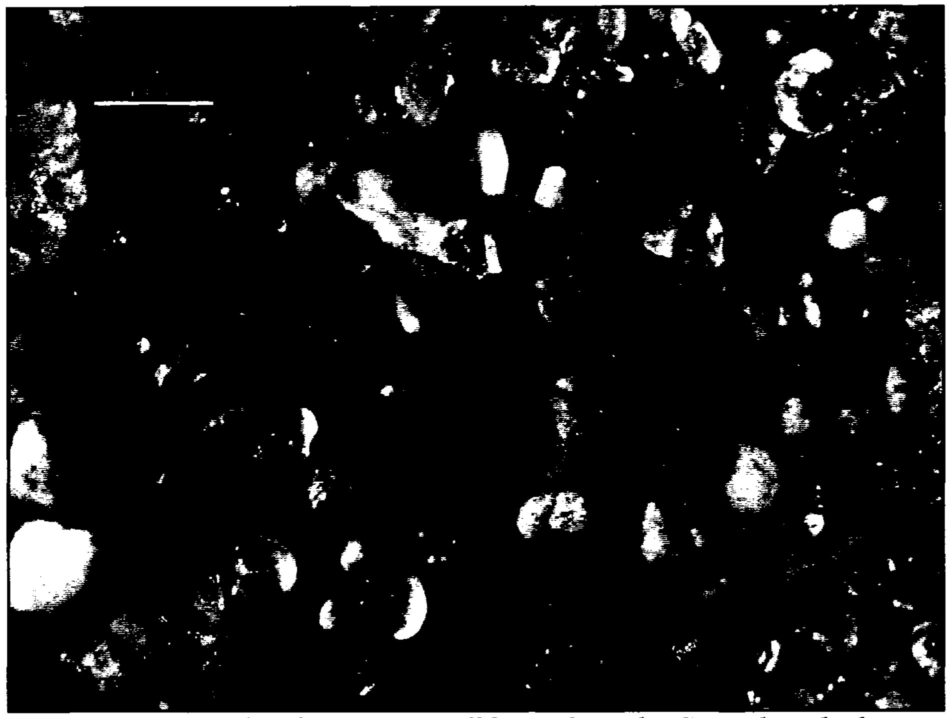


Figure 4.10: Sediment sample taken at 20 m offshore along the Ground Ice bathymetric survey. UTM Coordinates: 417012 E, 7988484 N

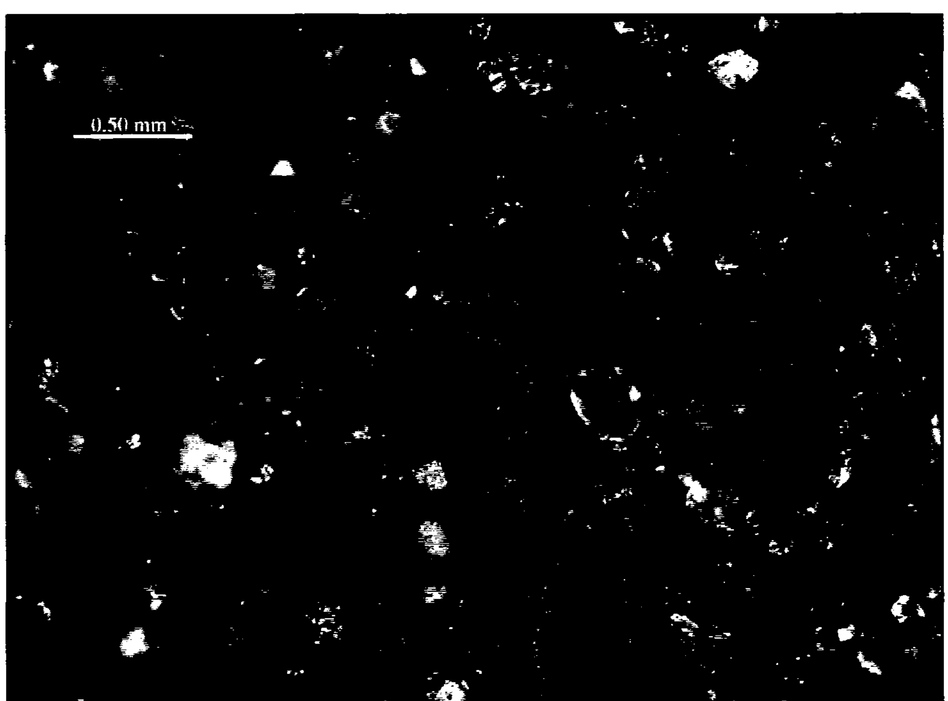


Figure 4.11: Sediment sample taken at 100 m offshore along the Ground Ice bathymetric survey. UTM Coordinates: 417011 E, 7988400 N.

The Duck Hawk Bluffs Line 1 bathymetric survey showed a bar crest or ice-pushed ridge 1 m deep about 10 m off the beach and another bar crest 3.5 m deep about 140 m offshore; the trough inside the second bar was about 4 m deep (Figure 4.1) (Appendix C). The survey showed a broad terrace 9 m depth about 800 m offshore and then deepened smoothly to >14 m depth 1 km off the beach. Sediment samples were taken at 20 m and 100 m offshore. The sediment sample taken at 20 m indicated a moderately sorted gravely substrate dominated by lithic fragments (including gabbro fragments) (Appendix D). The sediment sample at 100 m in the bar trough contained moderately well sorted gravel substrate similar in composition with a large variation in clast sizes, dominated by quartz, feldspar, garnet and dolomite and gabbro fragments (Appendix D).

Duck Hawk Bluffs Line 2 (DHB Ln2) was located at the western end of the Duck Hawk Bluffs (Figure 4.1) (Table 4.1). This survey was the highest cliff surveyed 14 m in height (16 m asl) and was an unvegetated and actively retreating slope, with slumped material and vegetated blocks found along the cliff slope (Figure 4.12). The slope was composed of loose gravel, pebbles and cohesive silts and clay. Vegetative debris such as plant roots were found throughout the slope. Vegetated blocks were found at the cliff base and the beach edge, both of which showed signs of mechanical erosion from wave interaction (Figure 4.12). The poorly sorted gravel beach was composed dominantly of sedimentary lithic and gabbro fragments (Figure 4.13) (Appendix D).

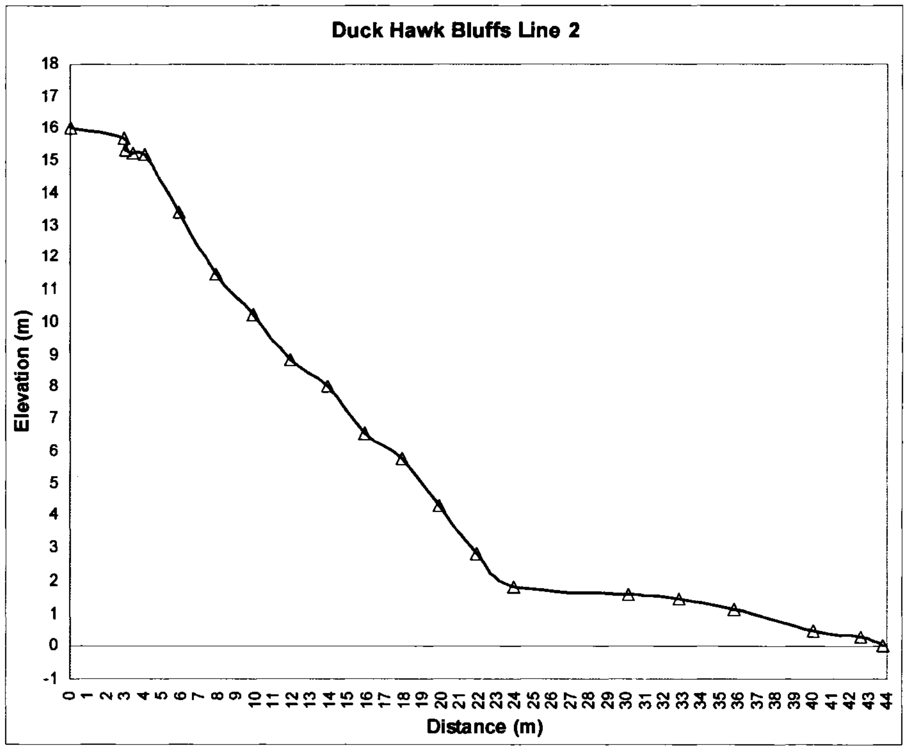


Figure 4.12: Duck Hawk Bluffs Line 2 located 12 km west of the community. Note slumping along the cliff edge and cliff slope. Vegetated debris was found throughout the slope. UTM Coordinates: 411492 E, 7987550 N (2x vertical exaggeration). Photo taken August 1, 2005.

Figure 4.13: Sediment sample taken near the waterline along Duck Hawk Bluffs Line 2. UTM Coordinates: 411494 E, 7987556 N.

The Duck Hawk Bluffs Line 2 bathymetric survey was highly irregular, reflecting a combination of differential wave erosion and heavy ice scour (Figure 4.14). A sediment sample taken at 100 m offshore indicated a poorly sorted gravel substrate dominated by lithic fragments including dolomite and gabbro as well as feldspar and quartz (Figure 4.15) (Appendix D).

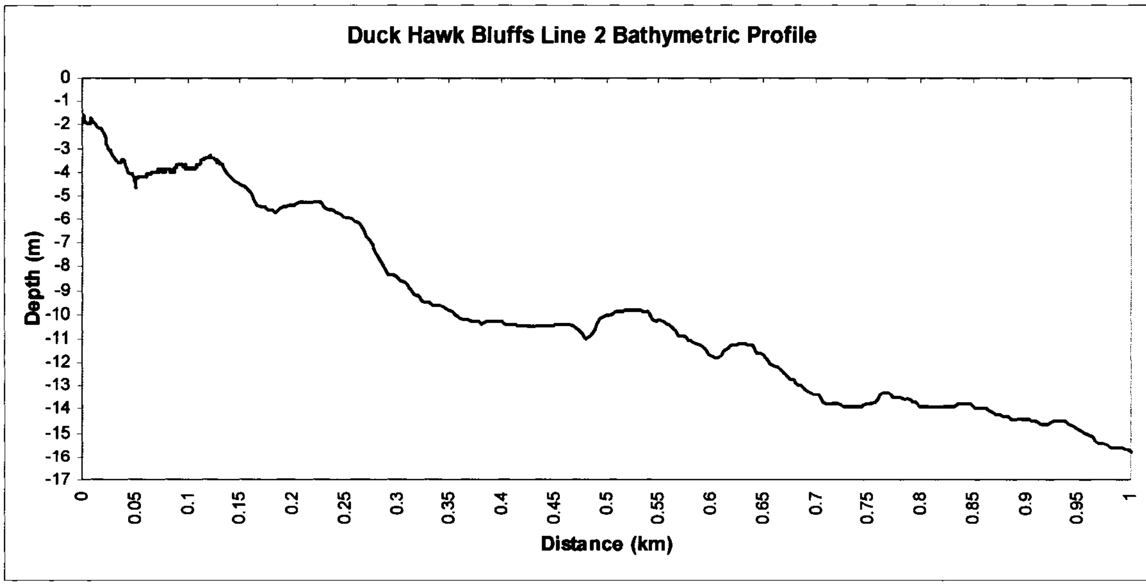


Figure 4.14: Duck Hawk Bluffs Line 2 bathymetric survey, showing a highly irregular seabed morphology extending to 1.15 km offshore with a maximum depth of 16.4 m (25x vertical exaggeration).

Figure 4.15: Sediment sample taken from 100 m offshore along the Duck Hawk Bluffs Line 2. UTM Coordinates: 411491 E, 7987449 N

4.1.3 – Cape Kellett Spit

Cape Kellett Line 4 (CK Ln4) was located in an area exposed to sea ice on the Cape Kellett spit (Figure 4.1) (Table 4.1). Evidence of ice shove (indicated by dips along the survey) were present along both the eastern and western edge of this survey line including kettle marks and ice push ridges (Figure 4.16) (Appendix A). The centre of this survey line was relatively stable with several species of lichens and arctic poppies (*Papaver radicatum*) found growing on the gravel-cobble substrate. Driftwood was found throughout the survey indicating wave formation of the deposit or ice push after initial drift transport. The beach at the western end of the survey was composed of poorly sorted gravel, while the eastern (inner) shoreline of the survey, in an area with less exposure to sea ice, was composed of moderately sorted gravel (Appendix D). The western shoreline was composed of well sorted gravel while the eastern shoreline was composed of moderately well sorted very coarse sand (Appendix D). Both samples were dominated by lithic fragments, gabbro fragments, garnet and feldspar. No bathymetric surveys or grab sediment samples were obtained from this survey.

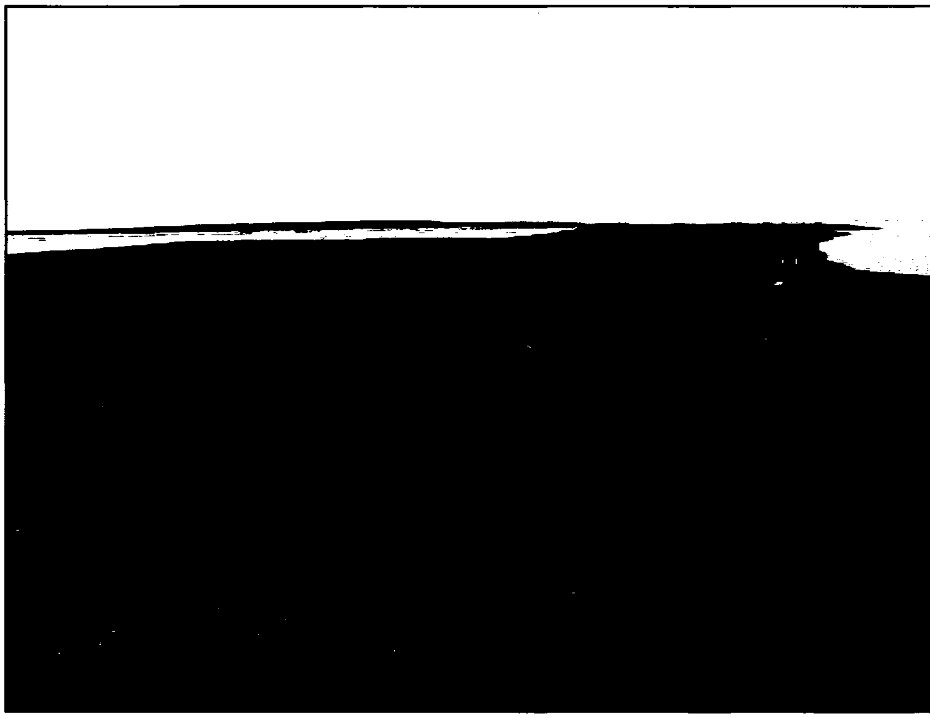


Figure 4.16: Ice push features and pocket marks found along all transects completed on Cape Kellett. UTM Coordinates: 399282 E, 7987399 N. Photo faces eastward and was taken August 1, 2005.

Cape Kellett Line 5 (CK Ln5) was located at the northern tip the Cape Kellett spit (Figure 4.1) (Table 4.1). The survey was dominated by sea ice melt pits, ice push ridges and a series of small crests and troughs evidence of spit migration through time (Figure 4.17; Figure 4.18). Active ice push was observed along both the eastern and western edges of the survey line with sea ice slabs greater than 2 m thick pushing onshore. The poorly sorted gravel spit was dominated by sedimentary clasts, gabbro fragments, garnet and feldspar (Figure 4.19) (Appendix D).

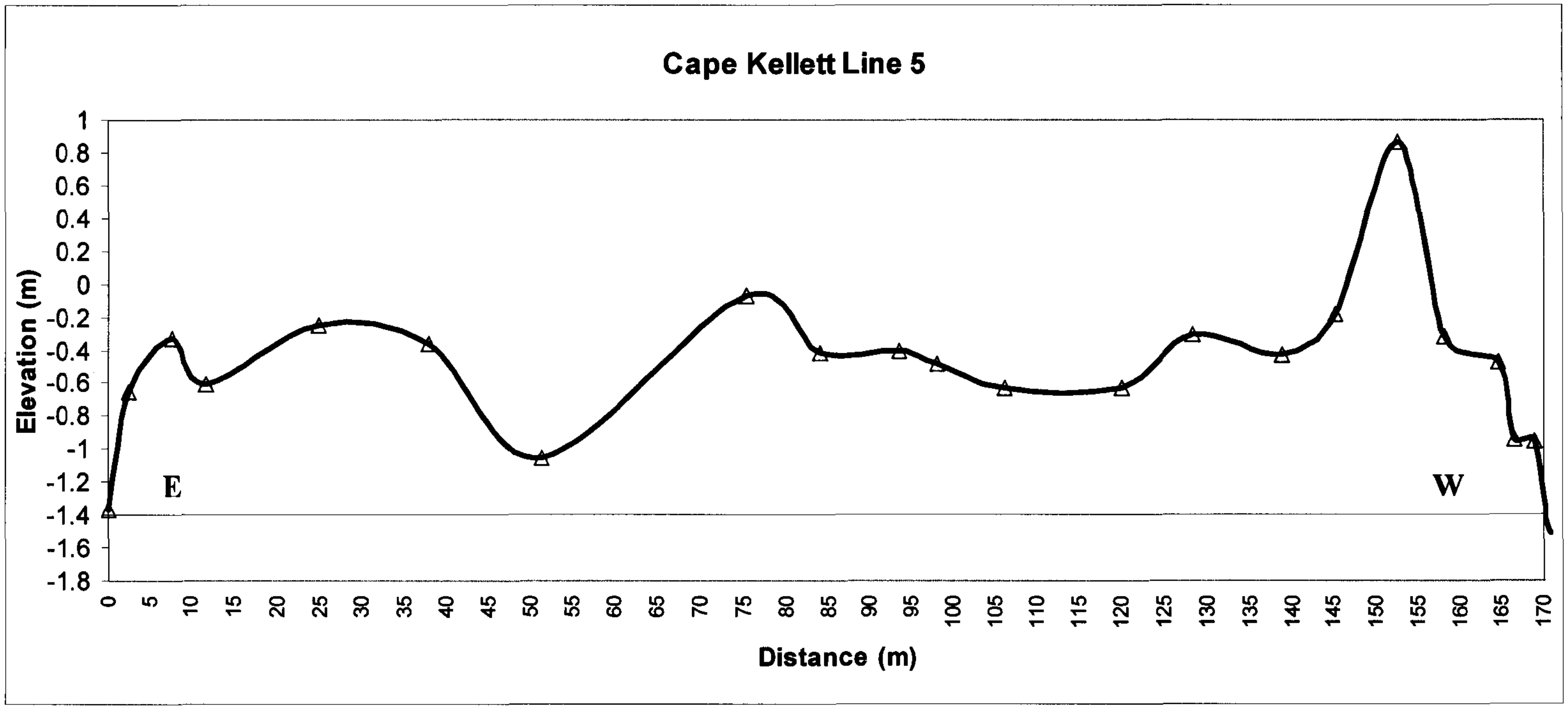


Figure 4.17: Cape Kellett Line 5. A 25x vertical exaggeration has been used to emphasize the ice push ridges.

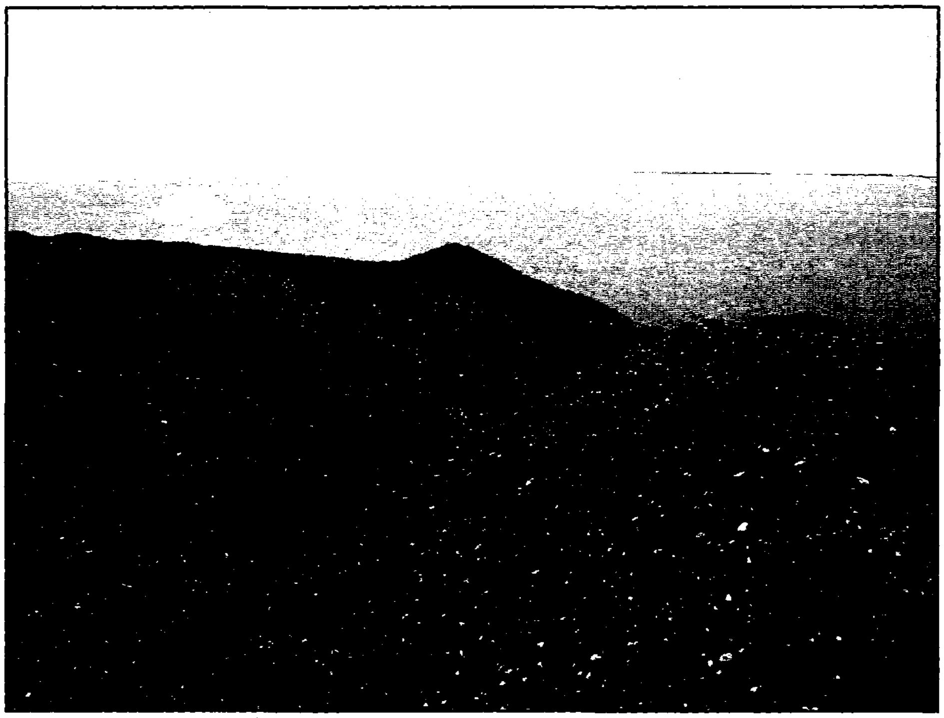


Figure 4.18: Active ice push of elevations >2 m were observed. UTM Coordinates: 397970 E, 7990333 N. Photo faces south-westward and was taken August 1, 2005.

Figure 4.19: Sediment sample taken near the northwestern water line of Cape Kellett survey line 5. UTM Coordinates: 397973 E, 7990337 N

The Cape Kellett Line 5 bathymetric survey was completed on the eastern side of the spit and ran parallel to and north of the main east-west segment towards the western coastline of Banks Island. The survey dropped off abruptly to a narrow terrace at 3 m and then deepened steeply to a flat seabed between 9.5 and 10 m depth, which extended across the bay toward the east (Figure 4.20). A series of crests and troughs with relief of about 0.6 m occurred throughout and may be evidence of ice scour due to active sea-ice movement from the north. A sediment sample taken 100 m offshore showed a silty substrate with no distinguishable mineralogy (Appendix D).

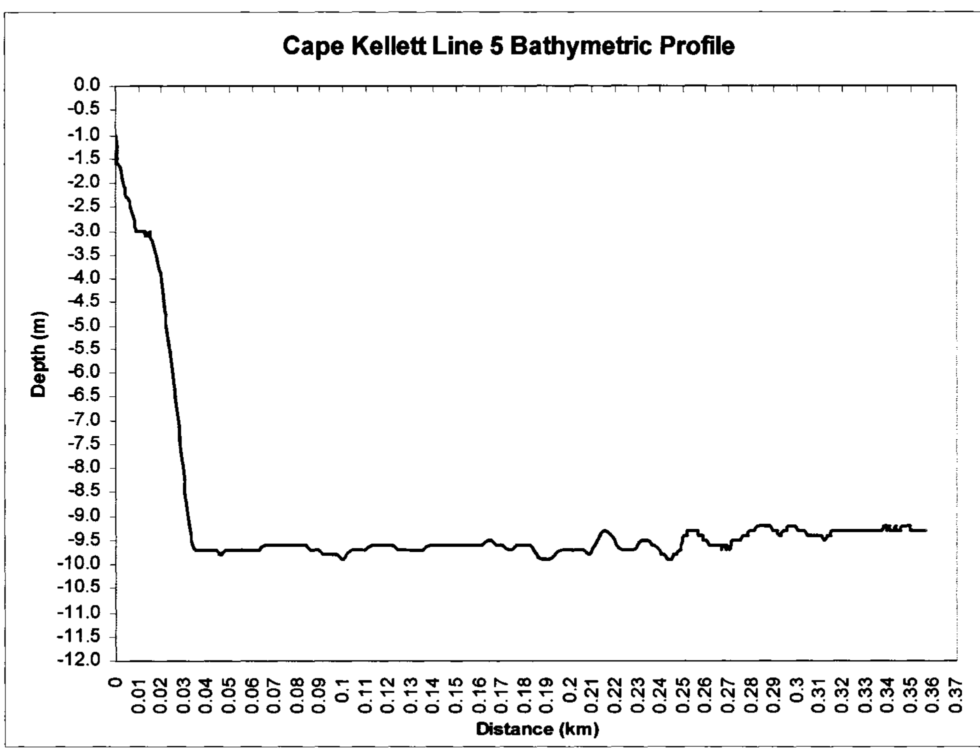


Figure 4.20: Cape Kellett line 5 bathymetric survey 0.36 km in length with a maximum depth of 9.9 m (25x vertical exaggeration).

4.2 – Resurveyed Locations

4.2.1 – Southwest Coastline

Sachs Harbour Survey Line 1 (Ln1) was located at the eastern edge of the community (Figure 4.21; Figure 4.22). The cliff edge varied between approximately 4.2-4.4 m asl, and the slope showed active retreat, particularly along the unvegetated slope. The cliff slope showed an overall steepening over the years of survey, although there was no measured cliff top retreat (Table 4.2) (Appendix B). The beach was eroding with a narrower beach and decreasing slope evident in successive surveys (Table 4.2). Removal of sediment is likely due to incremental, persistent sediment transport, as this area is sheltered from storm waves by the Sachs Spit to the south.

The Sachs Harbour Line 1 bathymetric survey extended into a basin 6.5 m deep at approximately 130 m offshore then gradually shallowed and deepened to a depth of 5 m at the end of the survey (Appendix C). No offshore sediment samples were taken along this transect.

Figure 4.21: Location of resurveyed surveys completed in the study area from 2002 - 2005. These lines were concentrated in Sachs Harbour and to the west of the community. Bathymetric surveys were completed shore normal from each survey (modified from imagery © Digital Globe).

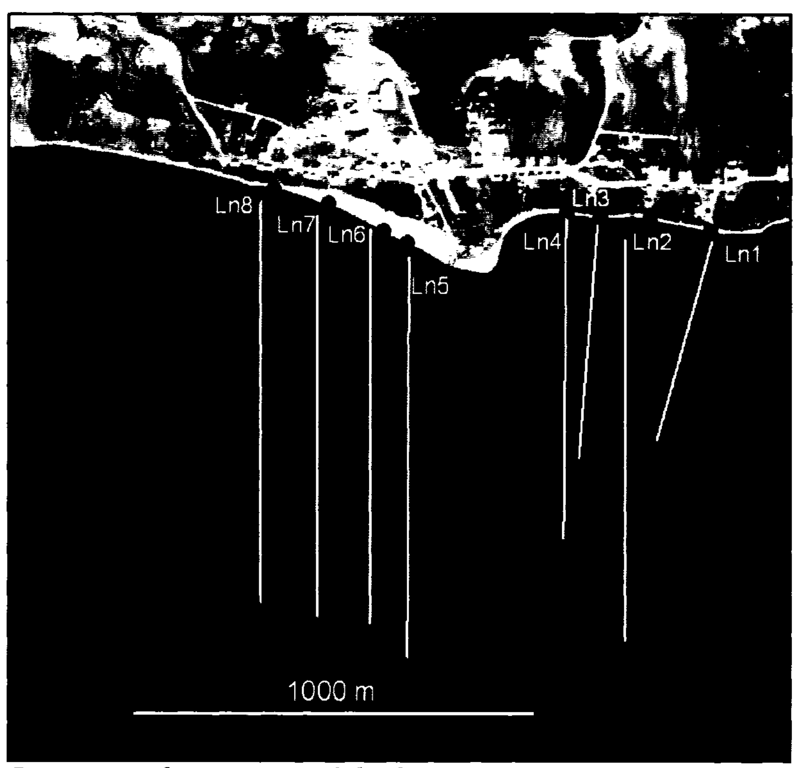


Figure 4.22: Location of surveys and bathymetric surveys around the community of Sachs Harbour. Bathymetric surveys offshore of the survey lines were at maximum 1 km in length (modified from imagery © Digital Globe).

Table 4.2: Summary of resurveyed Locations including UTM coordinates, distance to cliff top, distance to cliff base, beach width, beach slope and Cliff slope. All elevations were taken above the WL during surveying and beach width calculations were taken from the cliff base to the waterline (Figure 4.2).

Line	End Point Coordinates WGS 84	Distance to cliff top (m)	Distance to Cliff base (m)	Beach width (m)	Beach Slope (degrees)	Cliff Slope (Degrees)
2002 2003 2004 2005	**End point location for all survey years**	**Distance to cliff edge from endpoint**	**Distance to cliff base from endpoint**	**Width from waterline to cliff base**	**Slope across entire beach width**	**Slope of the cliff from edge to cliff base**
Line 1	423184 E 7988568 N	0.0 0.0 0.0	3.2 4.1 3.7	3.6 4.9 5.0	9.3 7.0 5.9	/ 66.8 69.4
Line2	423032 E 7988599 N	6.3 5.9 5.5	13.2 14.1 14.2	3.9 5.1 5.2	8.6 5.4 8.8	71.1 66.8 59.6
Line 3	422909 E 7988602 N	49.1 49.0 49.2	52.8 52.2 52.6	3.7 4.1 4.6	6.2 6.0 7.2	52.9 70.4 58.9
Line 4	422822 E 7988613N	103.8 103.5 103.2	112.9 112.6 112.5	5.1 3.6 5.7	7.8 5.9 8.0	37.9 40.3 37.0
Line 5	422423 E 7988541 N	0.0 0.0 0.0 0.0	19.1 19.1 18.1 18.9	62.4 60.5 67.5 43.3	1.2 1.0 1.4 1.0	11.8 13.1 11.5 13.0
Line 6	422362 E 7988571 N	9.5 9.7 9.3 9.1	89.4 88.0 87.9 88.0	54.2 52.4 55.1 54.6	1.4 1.1 1.5 1.2	7.7 7.8 7.8 7.9
Line 7	422225 E 7988637 N	51.4 55.0 55.0 53.9	58.7 58.6 58.5 58.5	30.2 28.7 29.0 33.2	3.3 3.3 3.8 4.0	11.8 12.4 12.5 12.5
Line 8	422087 E 7988673 N	52.5 51.9 55.4 55.1	58.3 57.4 58.6 58.4	9.7 8.9 10.8 12.0	5.9 7.6 5.1 5.4	47.9 49.4 40.6 40.3
Line 9	417651 E 7988546 N	27.6 27.5 26.7	30.2 30.7 32.5	64.4 70.4 72.3	0.5 0.5 0.5	26.1 23.6 18.5

Line 10	416709 E 7988480 N	47.4 43.5 41.5	52.1 49.4 49.2	6.0 4.9 4.6	5.4 5.5 6.2	63.3 43.9 34.8
Line 11	414986 E 7988290 N	46.9 46.8 44.5	80.7 78.0 74.0	6.2 8.1 8.9	4.4 4.9 7.1	19.6 21.0 18.2
Line 12	414436 E 7988202 N	32.7 32.9 31.7	44.4 43.6 44.2	11.3 9.7 8.9	2.2 4.9 7.0	69.4 72.8 54.1
CK Ln1	401611 E 7986845 N	No cliff edge	No cliff base	172.6 167.8	Variable	No cliff slope
CK Ln2	399286 E 7987396 N	No cliff edge	No cliff base	68.0 73.6	Variable	No cliff slope
CK Ln3	396141 E 7988428 N	No cliff edge	No cliff base	486.6 497.6	Variable	No cliff slope

Sachs Harbour Survey Line 2 was located at the front of the Parks Canada house aligned with the flag tower (Figure 4.21; Figure 4.22). The cliff top at about an elevation of 8 m asl, showed signs of active failure, with slumping vegetated blocks along the top edge and fallen cliff material on the beach (Figure 4.23). The cliff face was unvegetated and composed of fine silt to medium sand (Figure 4.23). During the field visit it was noted that community members walked along this slope, potentially influencing cliff retreat. The cliff top edge retreated 0.8 m from 2003 to 2005 equivalent to 0.4 m/a (Table 4.2). Except at the base, the entire cliff face receded over the two years. The beach slope varied less than one degree, reflecting infilling of a wave-cut notch between 2003 and 2004 (Table 4.2). Beach slope and width in 2003 and 2005 were similar, indicating that fallen cliff material does not remain on the beach indefinitely.

The Line 2 bathymetric survey traversed a small channel at 100-150 m and another at 700-800 m, a channel visible in satellite images (Figure 4.24) (Table 4.3). This basin is visible on satellite images and was the remains of a submerged thermokarst lake. A sediment sample taken at 100 m offshore indicated a moderately well sorted, very coarse sand substrate dominated by feldspar and quartz grains with gabbro fragments (Figure 4.24) (Appendix D). A yellow discolouration due to iron staining was present on the clasts (Figure 4.25).

Sachs Harbour Line 3 was located in an area without infrastructure near the centre of the community (Figure 4.21; Figure 4.22). The cliff edge was vegetated and showed signs of active slumping (Appendix B). The cliff was about 4 m high (5 m asl) and is composed of fine sediment. The cliff face was unvegetated with downslope transport of slumped blocks and loose sediment. There was no clear evidence of cliff retreat over the survey years 2002-2005, although downcutting at the base and the top edge occurred from 2002 to 2003 (Table 4.2). The slope angle varied between surveys with a steeper slope in 2003 due to slumping near the cliff top (Table 4.2). The beach was wider in 2005 by approximately 0.8 m and had a steeper slope than previous surveys, indicating that material was being added to the beach increasing its width and slope (Appendix C) (Table 4.2). This survey line was east of the Sachs Harbour Landing Beach, which appeared to be prograding and migrating east. Sediment mobilized from the Sachs Harbour Landing Beach was being transported to this survey.

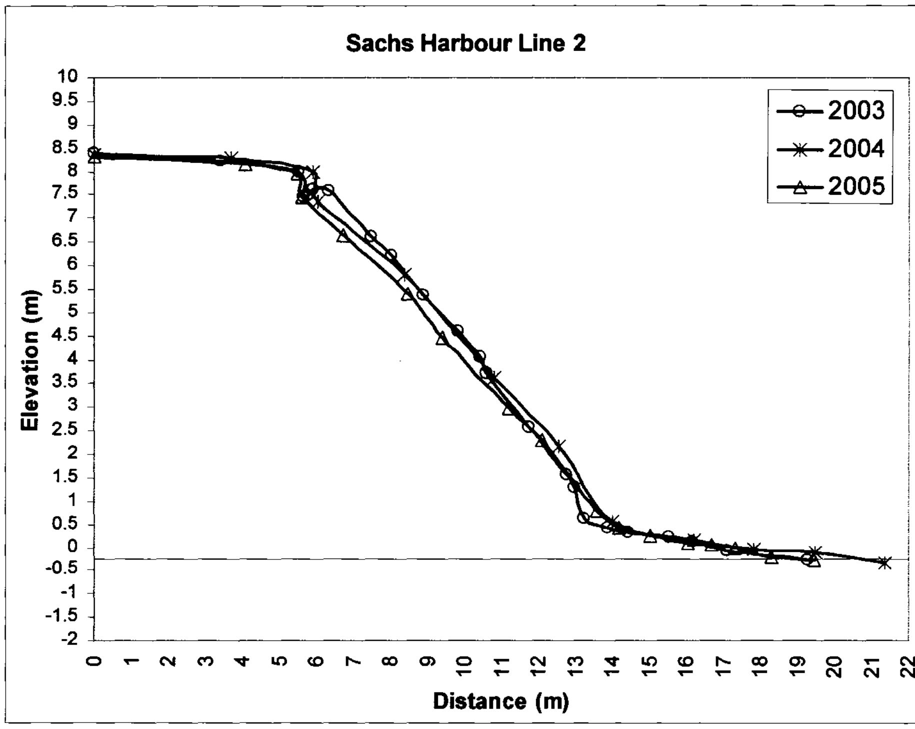


Figure 4.23: Sachs Harbour Line 2 indicating retreat during the survey years (above). The slope was unvegetated with slumped material at the cliff base and on the beach. Note the proximity of the waterline to the cliff base. UTM Coordinates: 423010 E, 7988618 N (2x vertical exaggeration). Photo taken July 20, 2005.

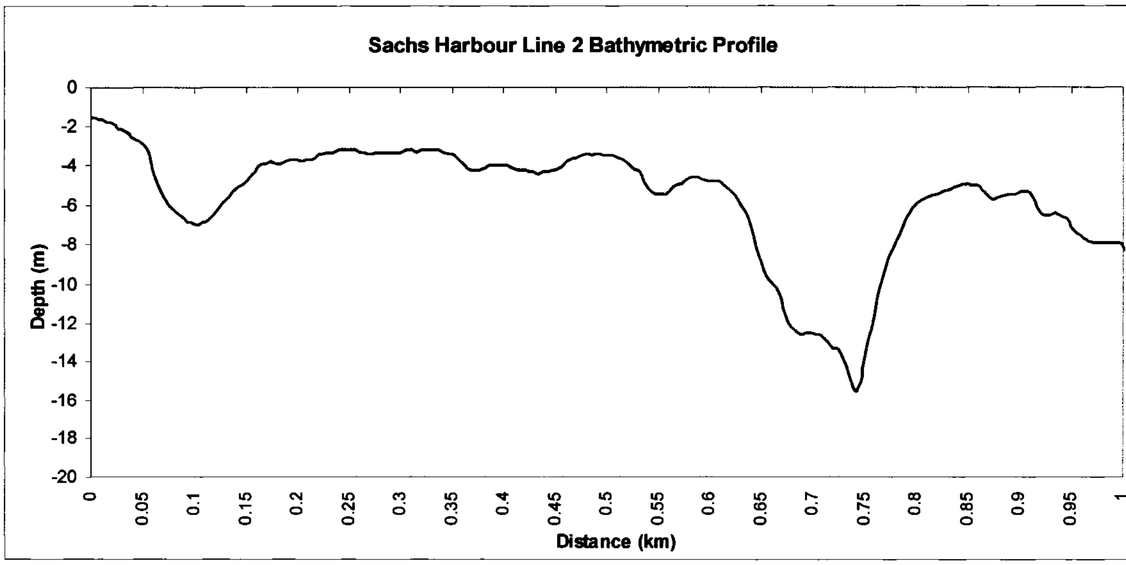


Figure 4.24: Bathymetric survey of Sachs Harbour Line 2 approximately 1 km in length and a maximum depth of 15.5 m (25x vertical exaggeration).

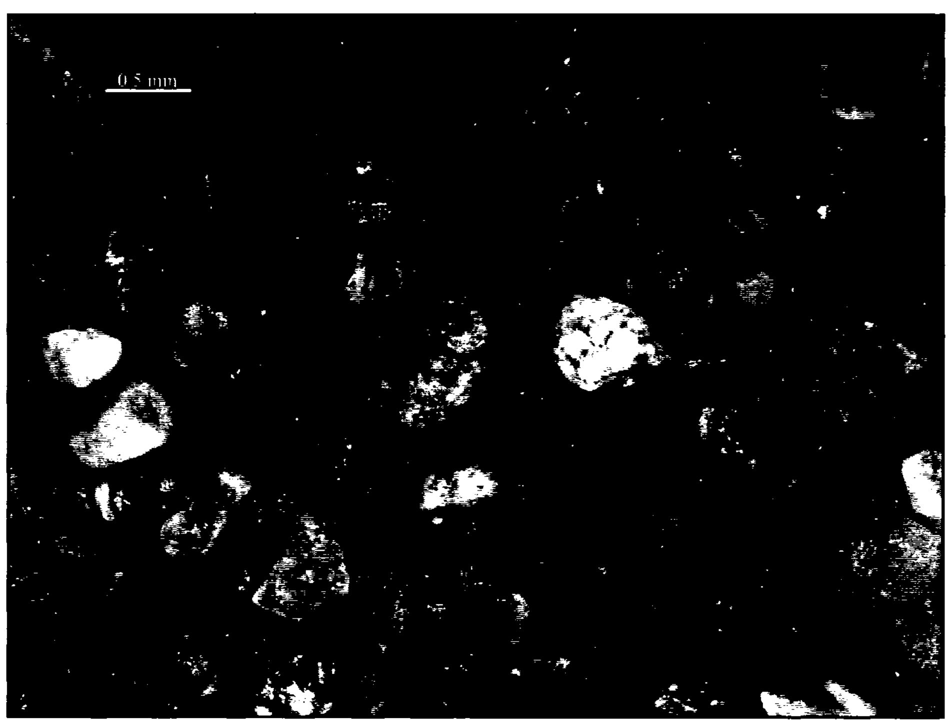


Figure 4.25: Sediment sample completed at 100 m offshore of Sachs Harbour Line 2. Note yellow staining on quartz and feldspar clasts. UTM Coordinates: 423032 E, 7988599 N.

The Sachs Harbour Line 3 bathymetric survey crosses a basin or channel 6.0 m deep 100 m off the beach. Depths were relatively shallow (< 4 m depth) beyond this channel (Appendix C). This survey is on a shallow sill between two deeper basins. No offshore sediment samples were taken along this transect, however visual inspection indicated a fine substrate of sand and silt.

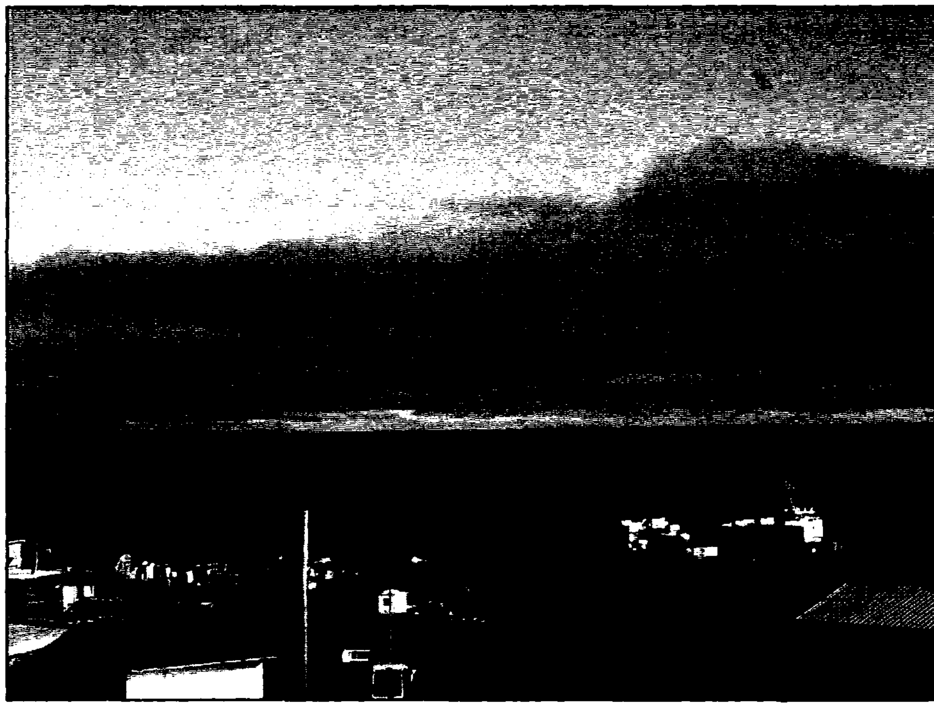
Sachs Harbour Line 4 was located in the middle of the community on the eastern edge of the Sachs Harbour Landing Beach (Figure 4.21; Figure 4.22). The cliff is about 6 m high (5 m asl) and the cliff face retreated approximately 0.7 m between 2003 and 2005 (Table 4.2). The cliff slope was vegetated and showed evidence of anthropogenic disturbance (footprints and garbage along the slope) (Table 4.2) (Appendix B). Cliff top retreat was likely due to blocks failing along the upper edge. Midway along the slope, the 2003 and 2004 surveys show a small increase in slope due to the presence of a slumped block. The latter was not visible in 2005, indicating erosion of the cliff face between 2004 and 2005 (Appendix B). Beach width decreased from 2003 to 2005 by 0.7 m, due to movement of sediment along the Sachs Landing Beach from boat activity and creation of a temporary dock for the yearly barge (Figure 4.26) (Table 4.2).

Sachs Harbour Line 4 bathymetric survey deepened into an approximately 6.0 metres deep channel at 100 m similar to the other inner basin surveys. Near the end of the survey there was an increase in depth to approximately 12 m as the survey approached the basin of a submerged thermokarst lake (Appendix C). No offshore sediment samples were taken along this survey.

Sachs Harbour Line 5 was located within the western portion of the community (Figure 4.21; Figure 4.22). This survey area was heavily used by the community for recreation with a playground along the survey line and all terrain vehicle (ATV) tracks visible throughout the survey (Figure 4.27; Figure 4.28). The top of the slope is 5 m (4.5 m asl) and is vegetated. The beach face region appeared to be aggrading in 2004, which was not evident in other years and was attributed to anthropogenic activity. The community moves large amounts of sediment to make a dock for the yearly barge. The dock had been created prior to 2004 surveying (Figure 4.27; Figure 4.28). There was little evidence of change in the survey years and no evidence of retreat seen along the vegetated cliff edge and the cliff slope (Table 4.2).

Sachs Harbour Line 5 bathymetric survey had an approximately 6 m deep channel near the shoreline (at 100 m) (Figure 4.29). Beyond this channel the survey was shallow throughout before deepening at the end of the survey to 9.5 m where it appeared to approaches a submerged thermokarst lake basin (Figure 4.29). No offshore sediment samples were taken along this survey.

Sachs Harbour Line 6 was located in the western side of the community at approximately 11 m asl (Figure 4.21; Figure 4.22). This survey line was vegetated throughout, did not show evidence of retreat, and little variation is indicated between survey years in either the slope or beach (Appendix B) (Table 4.2).



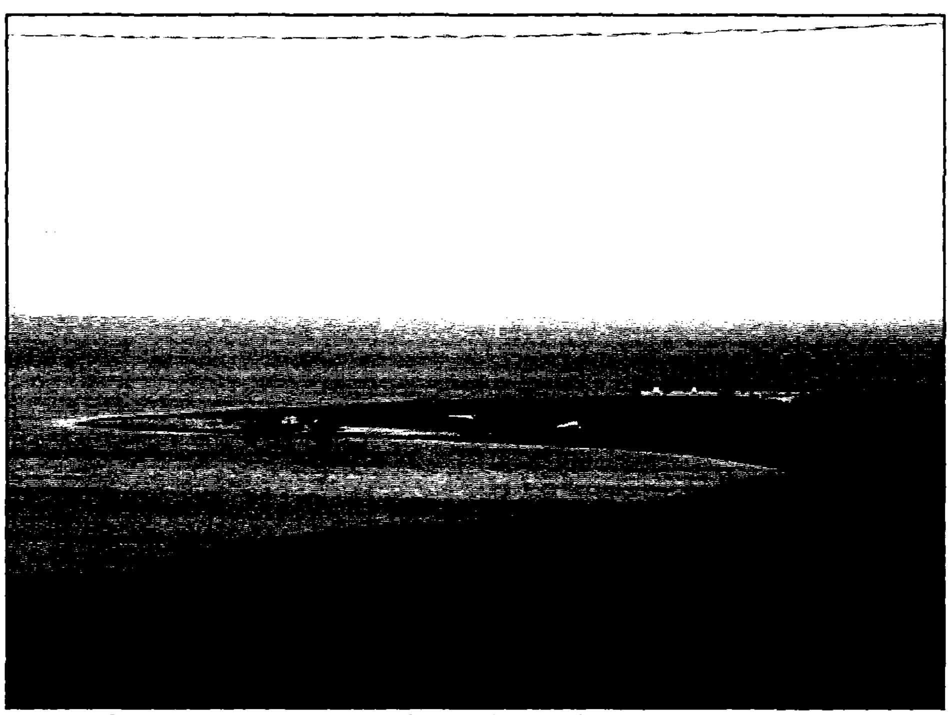


Figure 4.26:Anthropogenic activity on the Sachs Harbour Landing Beach by the community including creation of a dock for the annual barge for unloading shipments (above) and as a landing for local fishing boats (below).UTM Coordinates (above): 422179 E, 7988783 N, (below): 422757 E, 7988661 N. Photos taken August 13, 2005 (above) and July 16, 2005 (below).

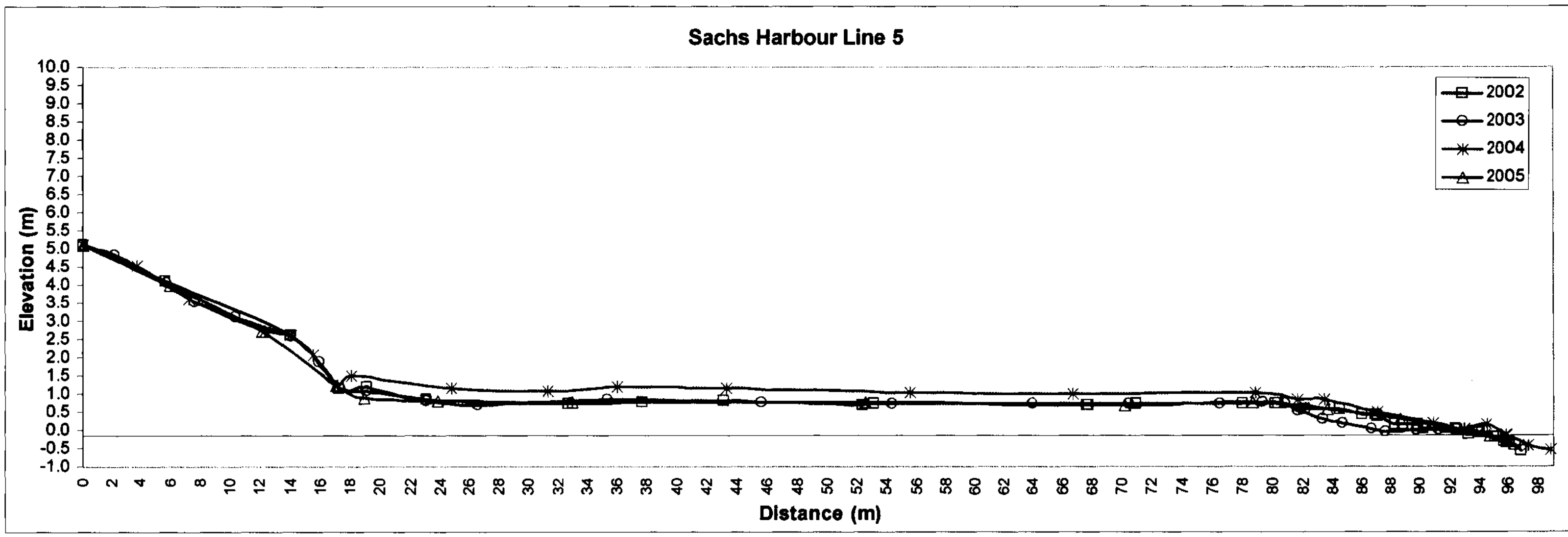


Figure 4.27: Sachs Harbour Line 5 located within the community of Sachs Harbour (2x vertical exaggeration). The beach width varies between survey years and is an area of construction for the annual barge.

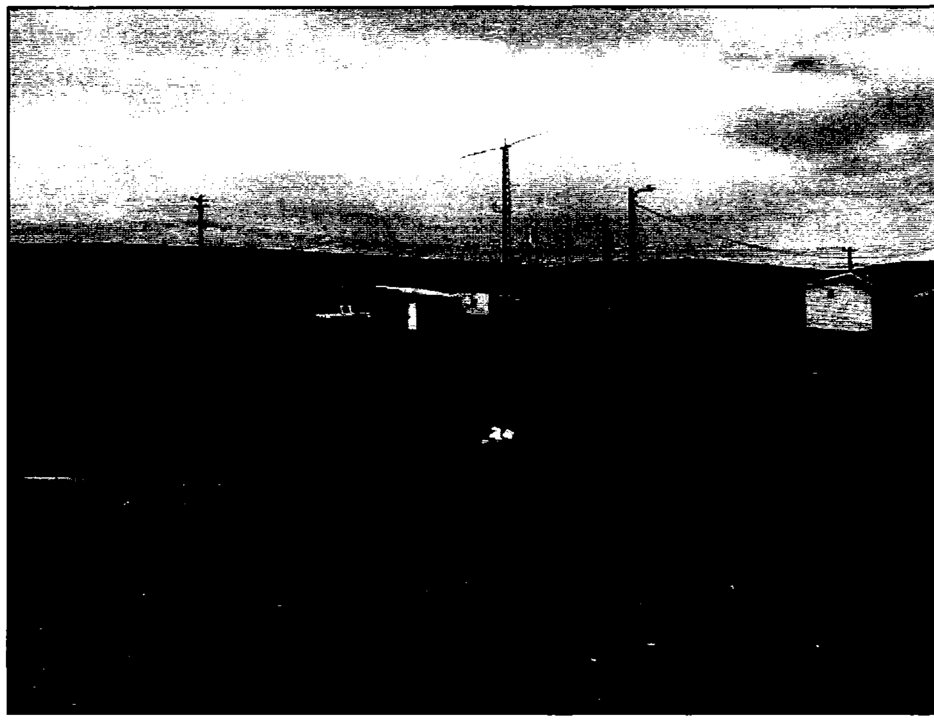


Figure 4.28: Playground in the centre of Sachs Harbour Line 5 which began near the northern corner of the brown RCMP building UTM Coordinates: 422428 E, 7988551 N. Photo taken July 30, 2005 and faces north.

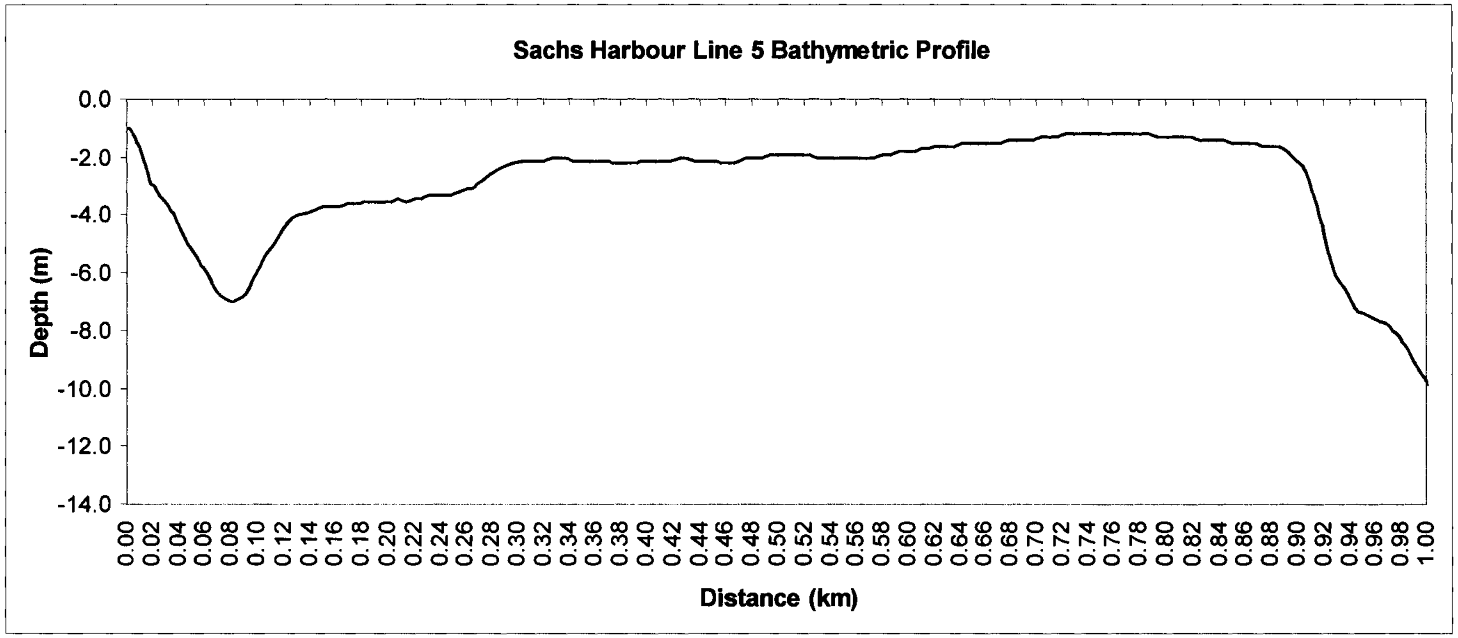


Figure 4.29: Sachs Harbour Line 5 bathymetric survey approximately 1 km in length with a maximum depth of 9 m (25x vertical exaggeration).

Sachs Harbour Line 6 bathymetric survey extended southwards into the centre of a submerged thermokarst lake basin to the south of the community (Appendix C). At 100 m offshore the survey deepened into a channel approximately 6.0 m deep (Appendix C). No offshore sediment samples were taken along this survey.

Sachs Harbour Line 7 was located in the western side of the community at the western edge of the Sachs Landing Beach (Figure 4.21; Figure 4.22). The slope of this survey line, at approximately 5 m asl, was vegetated for most of the survey with some exposed substrate present along a driveway and roadway. This survey line showed little change over the survey years with no measured cliff edge retreat throughout the survey period (Appendix B) (Table 4.2). The beach width varied between 2002 and 2005. The suggested cause is due to anthropogenic disturbance along this beach as it is heavily trafficked by ATV's (Table 4.2).

Sachs Harbour Line 7 bathymetric survey deepened into a channel approximately 6 m deep at 100 m then shallowed to the end of the survey as it neared the Sachs Spit to the south (Appendix C). This survey flanked thermokarst basins. No offshore sediment samples were taken along this survey; however, visual inspection indicated a substrate of sand and silt.

Sachs Harbour Line 8 was at the western edge of the community (Figure 4.21; Figure 4.22). The slope of this survey line was fine grained, had little vegetation and showed signs of erosion with a cliff top retreat (4.5 m asl in elevation) of approximately 3 m between 2002 and 2005 (Table 4.2) (Appendix B). The slope in 2002/2003 was steeper than the later surveys 2004/2005 indicating that slumping along the cliff slope reduced the slope angle (Table 4.2). Variation along the beach width occurred between the survey years likely due to anthropogenic disturbance by the community (Figure 4.30) (Table 4.2).

Sachs Harbour Line 8 bathymetric survey deepened into an approximately 6.5 m deep channel in the nearshore zone (approximately 150 m offshore) then entered a deep submerged thermokarst lake basin approximately 700 m in width and 22.9 m in depth before shallowing to 8 m at the end of the survey (Appendix C). No sediment samples were taken along this survey.

Figure 4.30: Anthropogenic activity on the western side of the Sachs Landing Beach such as ATV tracks and houses scheduled for demolition due to their proximity to the beach. UTM Coordinates: 422225 E, 7988679 N. Photo taken August 1, 2005.

All bathymetric surveys completed near the community showed an approximately 6 metre deep channel, at approximately 100 m offshore, evident from Line 0 to Line 8. This deeper channel was carved by the Sachs River which empties into the harbour south of the community.

Sachs Harbour Line 9 was located at the western edge of Martha Point Spit (Figure 4.21; Figure 4.22) (Figure 4.31; Figure 4.32). The cliff edge, at 1.5 m asl and slope of this survey did not vary between survey years, and both the cliff edge and slope were vegetated with no signs of active retreat (Table 4.2). The beach has prograded about 1 m between 2003 and 2004 and 2 m between 2004 and 2005 (Table 4.2). Study of aerial photographs indicates that the Martha Point Spit has been prograding since the 1950s. Channels overwashed during storm events vary in location between survey years, although the overall beach angle is similar throughout the surveys (Figure 4.31; Figure 4.32). A sediment sample taken near the waterline indicated that the beach is composed of poorly sorted gravel dominated by dolomite, quartz and feldspar (Figure 4.33) (Appendix D).

Sachs Harbour Line 9 bathymetric survey was relatively shallow along its entire 200 m, approximately 2.5 m in depth. It crosses a longshore bar (Figure 4.34). A sediment sample taken at 20 m offshore indicated that the substrate was composed of well sorted fine grained sand, dominated by quartz and feldspars (Figure 4.35) (Appendix D).

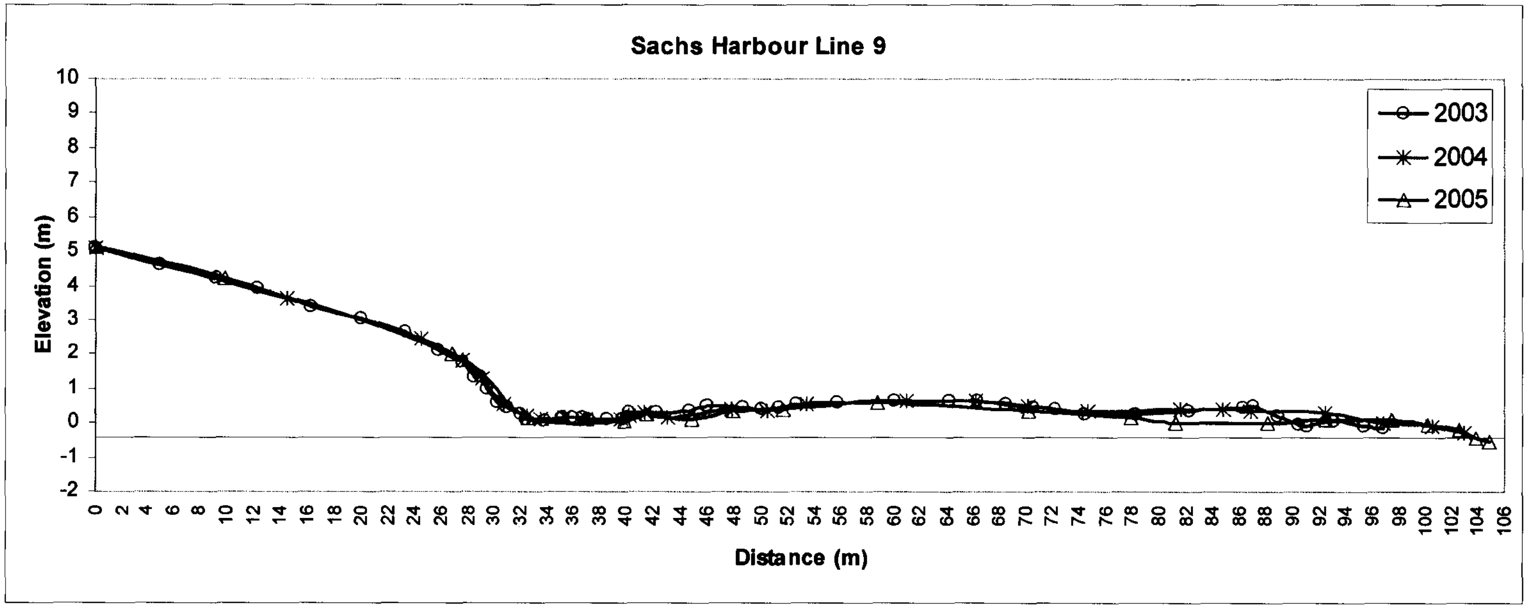


Figure 4.31: Location of Sachs Harbour Line 9 at the western edge of Martha's Point (2x vertical exaggeration). Overwash channels are evident along the beach width and vary from year to year. This line has prograded in each survey year.

Figure 4.32: Location of Sachs Harbour Line 9 at the small basin in the photo. Slopes are low and vegetated, and a wide beach front is present. UTM Coordinates: 417648 E, 7988650 N. Photo taken July 22, 2005.

Figure 4.33: Sediment sample taken from Sachs Harbour Line 9 at the beach edge. UTM Coordinates: 417650 E, 7988544 N.

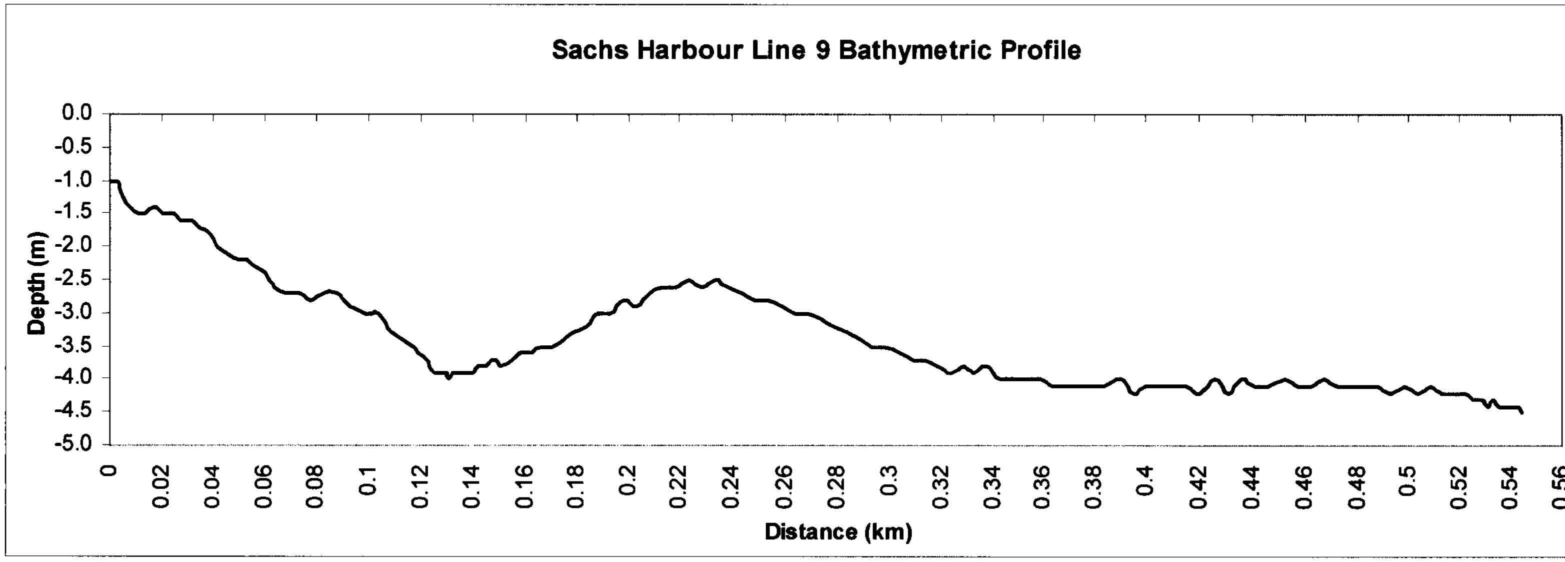


Figure 4.34: Sachs Harbour Line 9 bathymetric survey approximately 0.54 km in length with a maximum depth of 4.5 m (25x vertical exaggeration).

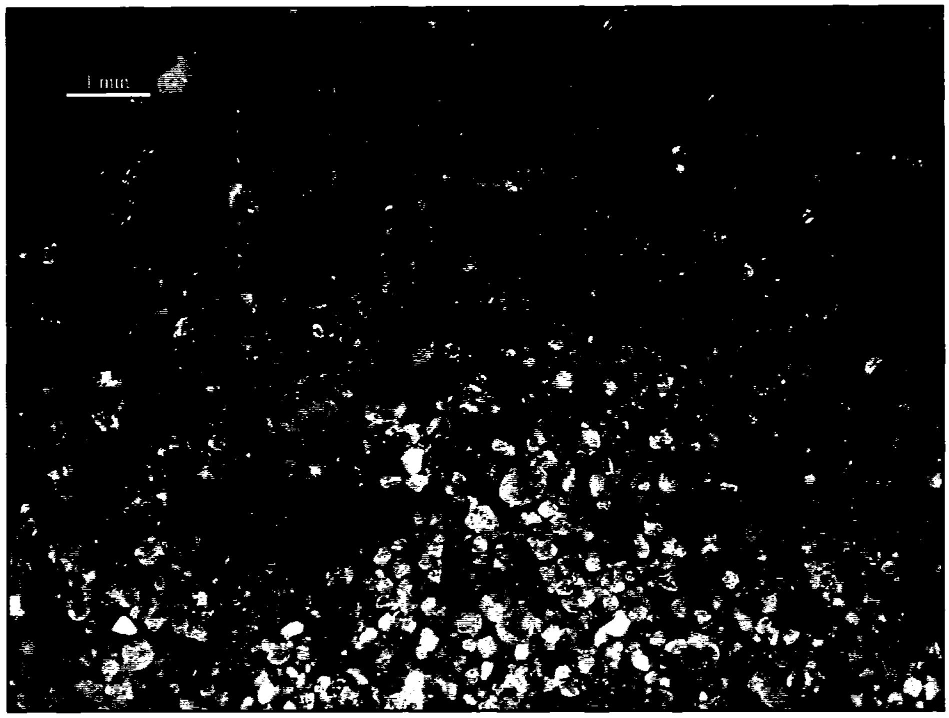
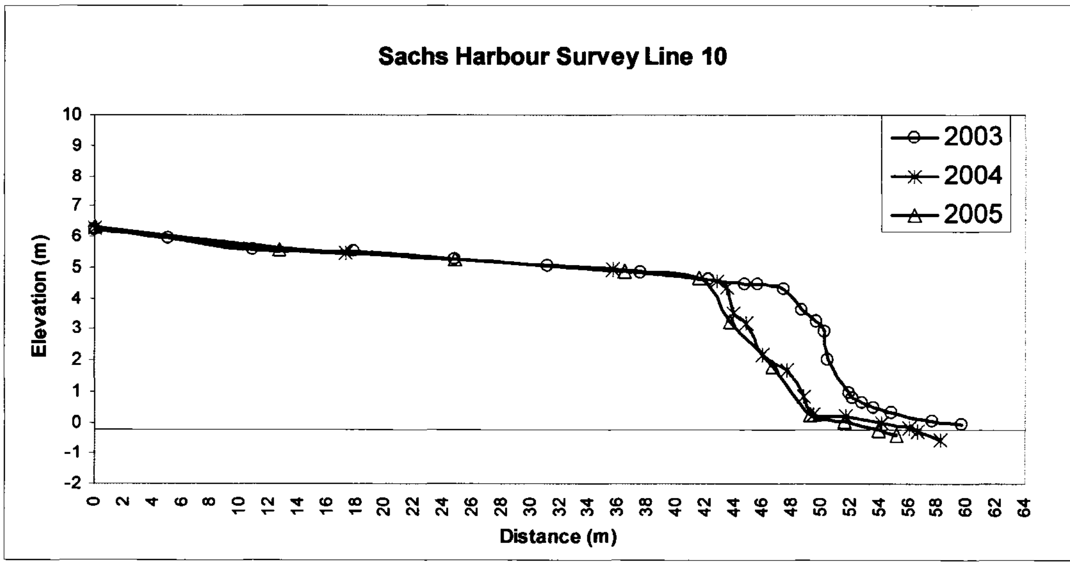


Figure 4.35: Sediment sample taken 20 m offshore along Sachs Harbour Line 9. UTM Coordinates: 417651.6478 E, 7988546.767 N

Sachs Harbour Line 10 was located in an area of exposed ground ice (Figure 4.21; Figure 4.22). The cliff edge of this survey, at 5 m asl, showed active retreat and slumping of vegetated blocks from above onto the unvegetated slope composed of moderately well sorted silt (Figure 4.36). Cliff edge retreat observed in successive survey years were 3.9 metres between 2003 and 2004 and 2 m between 2004 and 2005 (Figure 4.36) (Table 4.2). Since 2003 this cliff edge has retreated 5.9 m (Table 4.2). The cliff slope has become gentler in successive survey years. Melting of ground ice near the surface and stabilization of thaw flows likely contributed to the declining slope. The beach also indicated retreat between successive surveys of approximately 1 m between 2003 and

2005 (Table 4.2). Retreat of the cliff edge, slope and a decreasing beach width indicates that material slumping from the cliff edge onto the beach is removed, likely by storm waves (Table 4.2). A sediment sample taken from near the waterline indicated a beach substrate of poorly sorted very coarse grained sand dominated by dolomites, feldspars and quartz (Figure 4.37) (Appendix D).

Sachs Harbour Line 10 bathymetric survey gradually deepened along the survey length to its maximum depth at the end of the survey (Figure 4.38). In both sediment samples taken at 20 and 90 m, the substrate was composed of well sorted fine grained sand dominated by quartz, feldspar and garnet (Figure 4.39; Figure 4.40) (Appendix D).



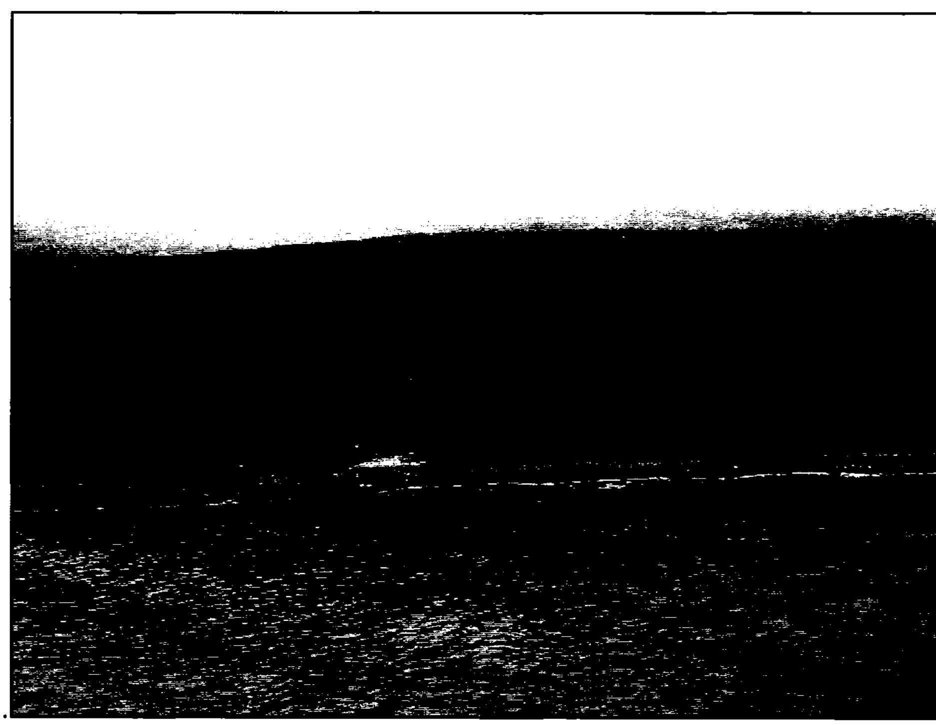


Figure 4.36: Sachs Harbour survey Line 10 located 6 km west of the community. This line had an unvegetated slope and slumped material at the cliff base and the proximity of the waterline to the cliff base. UTM Coordinates: 416707 E, 7988465 N (2x vertical exaggeration). Photo taken August 8, 2005.

Figure 4.37: Sediment sample taken from Sachs Harbour Line 10 at the beach edge. UTM Coordinates: 416708 E, 7988479 N.

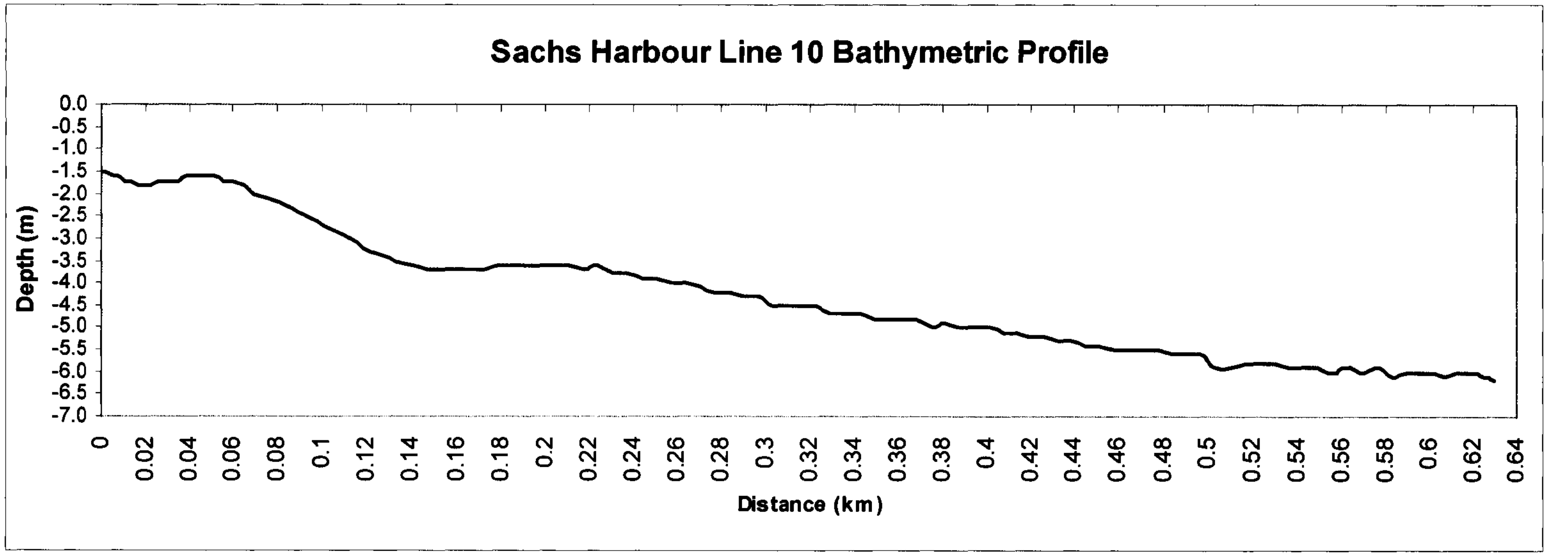


Figure 4.38: Bathymetric survey completed offshore of Sachs Harbour Line 10. This survey was approximately 0.63 km in length with a maximum depth of 6.2 m (25x vertical exaggeration).

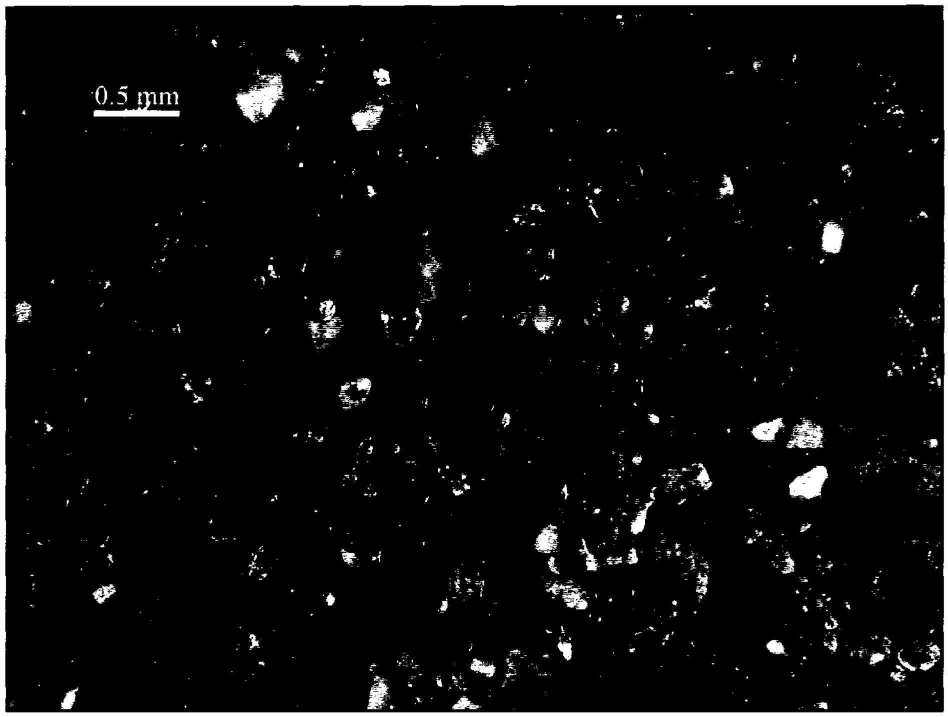


Figure 4.39: Sediment sample taken 20 m offshore along Sachs Harbour Line 10. UTM Coordinates: 416708 E, 7988467 N

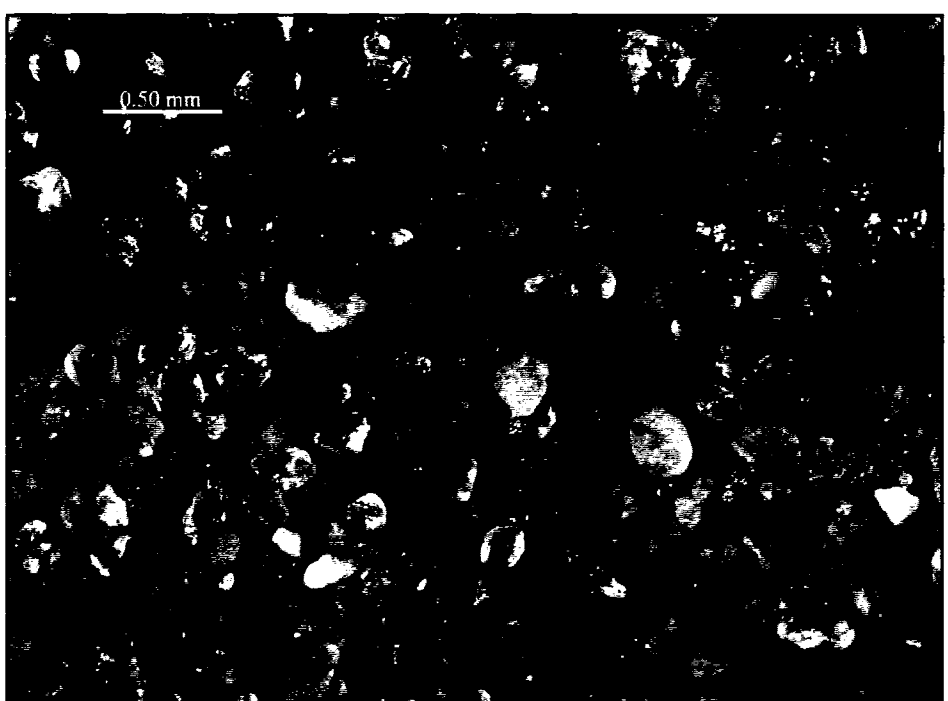


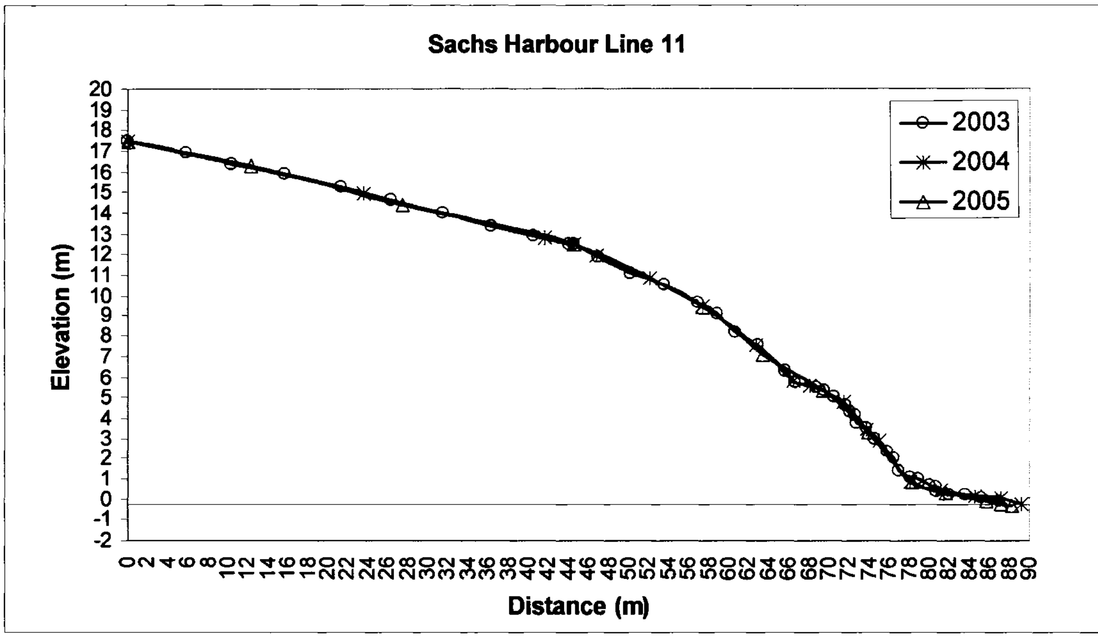
Figure 4.40: Sediment sample taken 90 m offshore along Sachs Harbour Line 10. UTM Coordinates: 416707 E, 7988369 N.

Sachs Harbour Line 11 was located in an area of cliffs with higher sand content and no visible ground ice (Figure 4.21; Figure 4.22). Along the length of the survey there was little variation between survey years with no change of the cliff edge between transects (Figure 4.41) (Table 4.2). The cliff edge, at approximately 17 m asl, was vegetated with little evidence of slumping (Figure 4.41). The cliff slope was unvegetated and composed of gravel with finer grained silt. A sediment sample taken from near the water line indicated that the beach substrate was composed of poorly sorted very coarse sand dominated by dolomites, feldspars and gabbro fragments (Figure 4.42) (Appendix D).

Sachs Harbour Line 11 bathymetric survey was shallow along its entire length with a maximum depth of 3.7 m (Figure 4.43). A sediment sample was taken at 100 m offshore, showing a well sorted fine grained sand substrate dominated by quartz and feldspars (Figure 4.44) (Appendix D).

Sachs Harbour Line 12 was vegetated along the upper portion of the survey from the start point to the cliff edge while the cliff edge appeared to be actively slumping (Figure 4.21; Figure 4.22). The cliff slope, at 11.5 m asl, was unvegetated and composed of poorly sorted coarse grained sand, did not show active retreat, however evidence of former slumps was visible along the slope and the slope base (Appendix D). There were variations throughout this survey line between survey years, on the cliff slope and on the beach (Appendix B). Slope steepness decreased between 2003 and 2005 with a shallower slope in 2005 than in other survey years (Table 4.2). The beach width decreased while the beach slope increased indicating loss of sediment from the beach slope being reworked in the beach zone by wave action and sediment transport (Table 4.2). A sediment sample taken near the waterline indicated a beach substrate composed of poorly sorted very coarse sand, similar to the cliff material (Appendix D).

Sachs Harbour Line 12 bathymetric survey had one small channel approximately 3.5 m in depth (100 m offshore), seen in survey 9 and the Ground Ice Line and also visible on satellite images (Appendix C). This survey then gradually deepened to about 8 m. A sediment sample taken at this channel indicated a substrate composed of well sorted gravel dominated by lithic fragments (including dolomite and gabbro) and quartz grains (Appendix D).



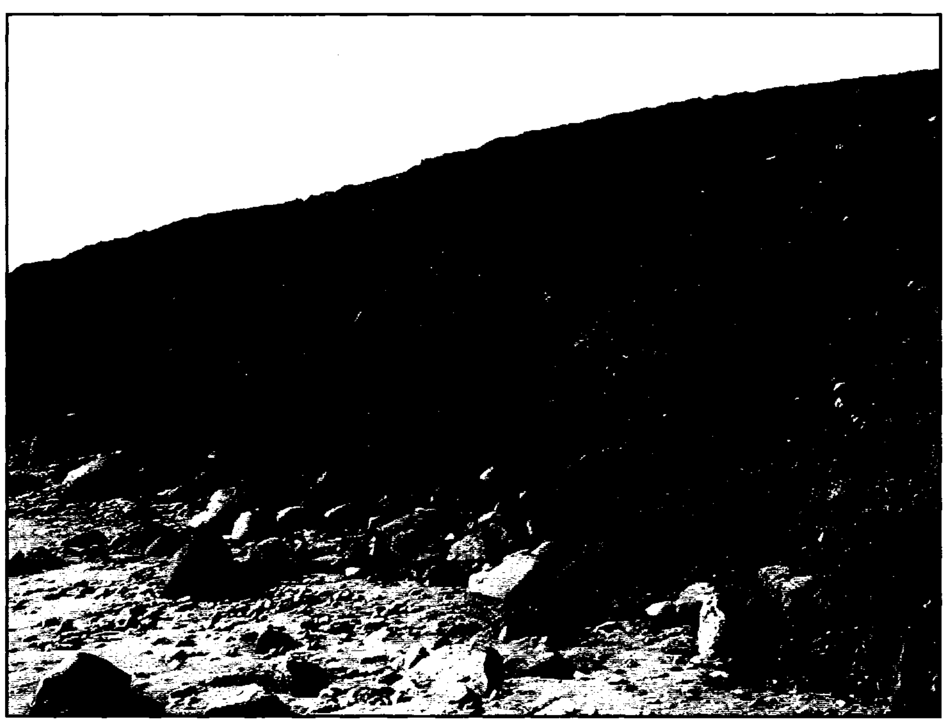


Figure 4.41: Sachs Harbour Line 11. Note the partially vegetated slope and presence of boulders at the cliff base. UTM coordinates: 414975 E, 7988295 N (2x vertical exaggeration). Photo taken August 2, 2005 and facing northeast.

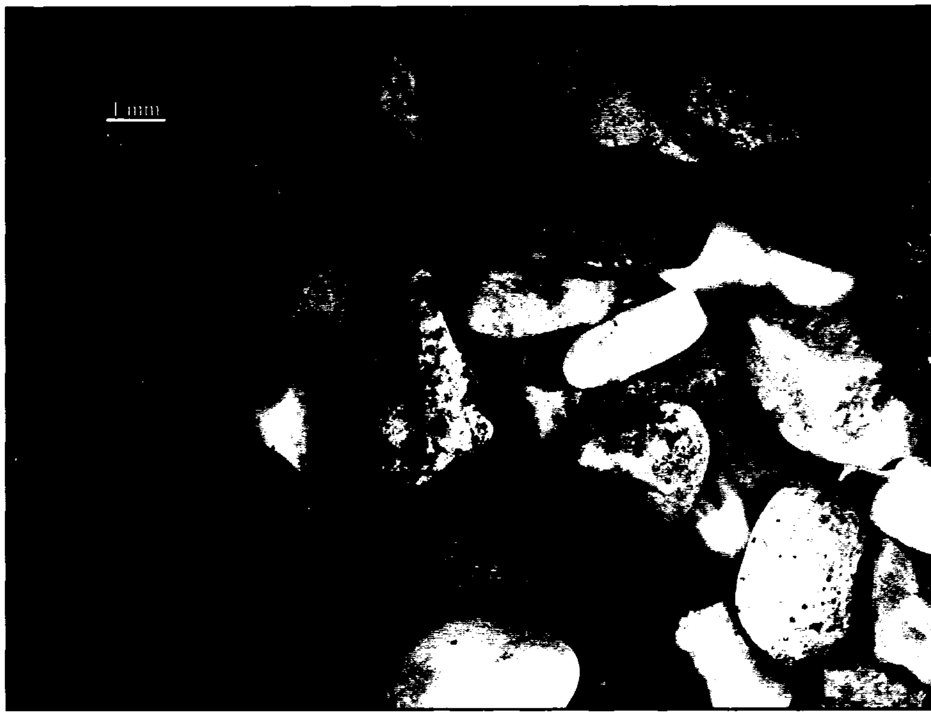


Figure 4.42: Sediment sample taken near the waterline along Sachs Harbour Line 11.

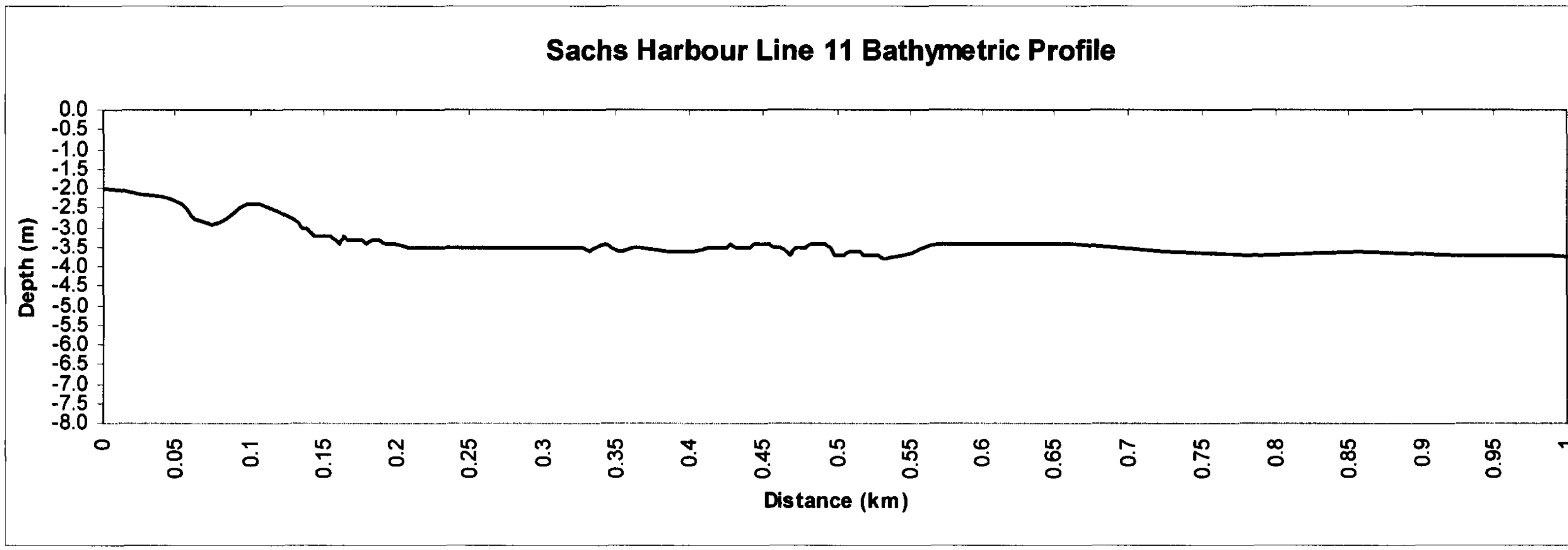


Figure 4.43: Sachs Harbour line 11 bathymetric survey. Note the deeper basin midway along the transect length. This survey was approximately 1 km in length with a maximum depth of 3.7 m (25x vertical exaggeration).

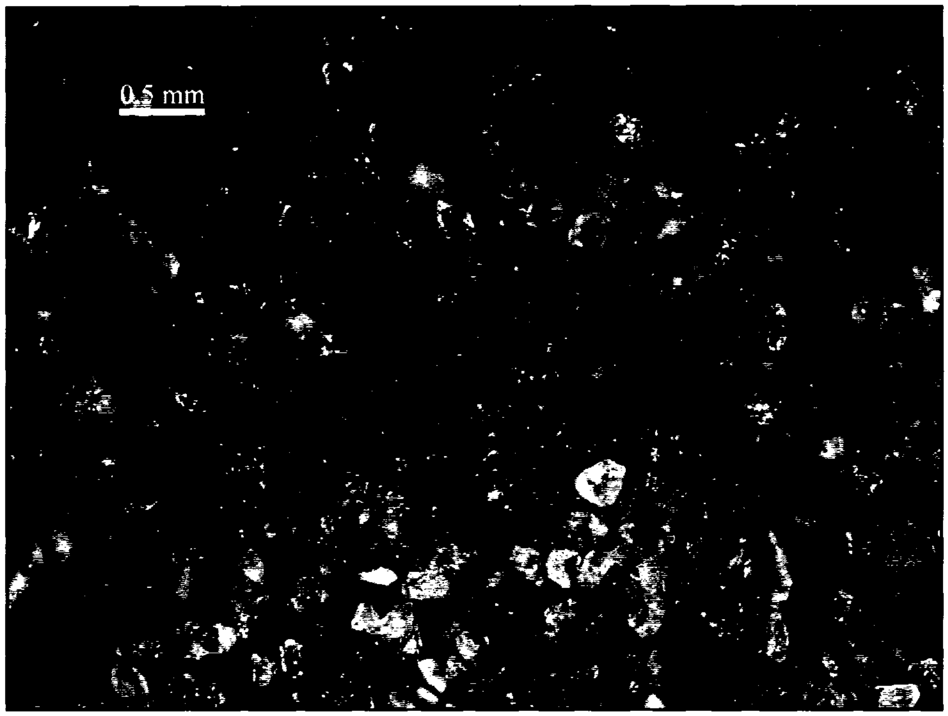


Figure 4.44: Sediment sample taken 100 m offshore along Sachs Harbour Line 11. UTM Coordinates: 414983 E, 7988185 N.

4.2.2 – Cape Kellett

Cape Kellett Line 1 was located at the eastern (proximal) end of the Cape Kellett Spit (Figure 4.21; Figure 4.22). This line had a maximum elevation of 1 m asl. There were differences between years on both the northern (inner) and southern (outer) sides of the spit due to sea ice pushing onshore (Table 4.2) (Appendix B). Kettle shaped melt marks and ice-push ridges were visible on this survey and varied between 2003 and 2005. Alteration by sea ice accounts for most of the variation on this line. A sediment sample taken at the southern end of the survey (outer beach) indicated moderately sorted gravel, dominated by lithic fragments (Appendix D).

The Cape Kellett Line 1 bathymetric survey was very steep in the nearshore, dropping to 5 m in the first 100 m off the beach and to 8 m at 300 m (Appendix B). Several troughs and sharp-crested ridges with relief of about 2 m are found across the survey (Appendix C), suggesting extensive ice scour. A sediment sample taken 100 m offshore was composed of very poorly sorted very coarse sand dominated by lithic fragments (Appendix D).

Cape Kellett Line 2 was located 2.3 km west from the landward end of the spit (Figure 4.21; Figure 4.22). This line, extending across the narrowest part of the spit, had a maximum elevation of 1.2 m asl. The variation between 2003 and 2005 was similar to Line 1, resulting from sea ice pushing onshore on both the northern and southern sides of the spit (Table 4.2) (Appendix B). Kettle melt marks and ice-push ridges were present at the time of the 2005 survey. A sediment sample taken on the southern shore of the spit indicated that the beach along this survey was composed of well sorted gravel (Appendix D).

The Cape Kellett Line 2 bathymetric survey completed at the southern edge of the land survey, remained a constant depth of less than 8 m for the first 150 m of the survey before deepening to 12 m however the survey is irregular in nature, similar to Cape Kellett Line 1, suggesting extensive ice scour in the nearshore (Appendix C). Several troughs and ridges occurred which varied between 1 and 2 m in height along the length of the survey (Appendix C). A sediment sample taken at 100 m offshore indicated a substrate composed of poorly sorted very coarse sand, dominated by lithic fragments and quartz grains (Appendix D).

Cape Kellett Line 3 was completed along the widest section of the Cape Kellett Spit where it curved towards the north (Figure 4.21; Figure 4.22). Variations between years on both the eastern and western edges of the survey were due to sea ice interaction (Appendix B). Kettle melt marks and sea ice sediment push ridges were present along the length of the survey and varied between survey dates. The maximum elevation of the survey was on an ice push ridge 1.8 m asl. Sediment samples were taken from both the eastern and western edges of the survey. The sample taken at the eastern edge was composed of well sorted gravel, dominated by lithic fragments (Appendix D). The sample taken at western edge beach was composed of poorly sorted gravel, also dominated by lithic fragments (Appendix D).

In the nearshore of the Cape Kellett bathymetric surveys 1 and 2, small ridges and troughs are evident between 0.5-2 metres in depth and are likely attributed to sea ice scour. This area is open to the Beaufort Sea and showed signs along the spit of ice pushing onshore. Active ice movement in the region may lead to scour in the nearshore environment.

Chapter 5 – Results: Storm Events, Ice Records and Suspended Particulate Matter

5.1 – Meteorological Records

The weather station in Sachs Harbour has continuously recorded temperature, wind direction and wind speed since 1956 for at least six hours daily (Environment Canada 2006a). Previous studies (Harry *et al.* 1983) have analyzed weather records to determine storm events. Sea-ice charts for the western Arctic and Beaufort Sea region have been recorded on a weekly basis from the 1969 to present and give an indication of the amount of ice present within the region during breakup and freeze-up as well as during the open-water season (July – October). From sea-ice records, open-water fetch directions and fetch lengths can be determined.

5.1.1 – Meteorological Records 1978 – 2005

Hourly observations from the Sachs Harbour weather station between the months of July to September (for comparison with the previous Harry *et al.* 1983 study), and from July to October were examined to determine the dominant wind directions influencing the community during the open-water season. These data were examined from 1978 to 2005 to determine potential wind directions from which storm events may originate. Previous studies of wind directions during July to September (1971 – 1977) were used as a comparison (Harry *et al.* 1983).

Mean wind direction frequencies from July to September 1978 – 2005 indicated two dominant wind directions in the community of Sachs Harbour (Figure 5.1). Winds from the SSE had a frequency of 11.7%, while winds from the NNW had a frequency of

11.9% (Figure 5.1) (Appendix F). The NNW winds have less impact on southwest coast as they blow offshore, while SSE winds originate offshore to the south with a potentially long fetch distance over the Amundsen Gulf. Wind data from a previous study from July – September 1971 – 1977 also indicated winds from the SE had the highest frequency, with a frequency of 9.9% and also a high frequency of winds from the NNW with 9.1%.

When the October data were included for the same time interval, the dominant wind direction was from the ESE with a frequency of 11.6%, with winds from the NNW having slightly lower frequency of 10.7% (Figure 5.2) (Appendix F). More frequent winds from the ESE during October may result in coastal modification. Winds from the east-southeast originate over the Amundsen Gulf, with long open-water fetch dependent on sea ice conditions.

5.1.2 – Storm Records 1969 - 2005

Storm events, as defined by Atkinson (2005) (pg 38, 39), were recorded from 1969 (1968 was the first year of available sea-ice records for the region) to 2005, between July and October. Storm frequencies were divided into either total frequency of events during the open-water season or the frequency of storm events with open-water fetch (Figure 5.3; Figure 5.5). Data were omitted for 1973, 1986 and 1987 due to lack of wind data for these years.

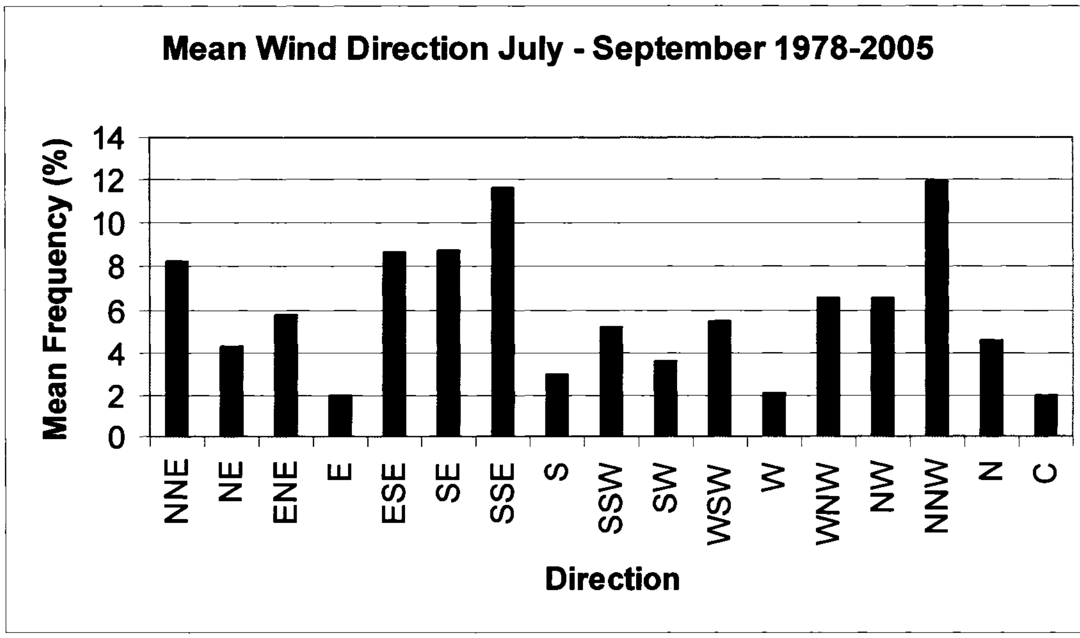


Figure 5.1: Summary of mean frequency of wind directions between July-September 1978-2005 for the community of Sachs Harbour. Wind directions with the highest frequencies during this period, NNW and SSE.

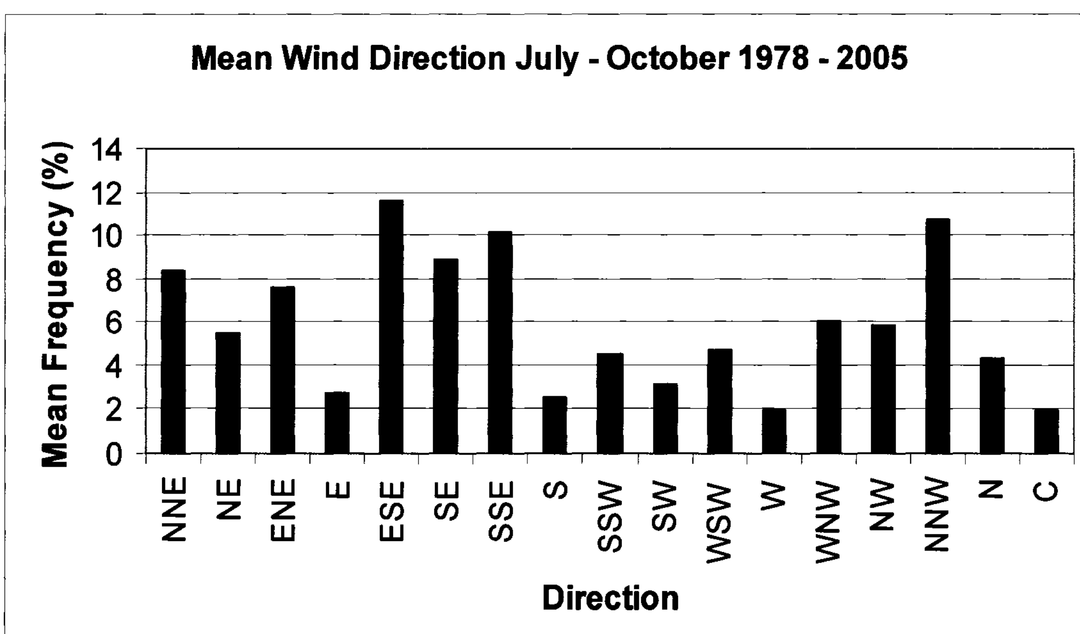


Figure 5.2: Summary of the mean frequency of wind directions from July to October 1978-2005 for the community of Sachs Harbour. Wind directions with the highest frequency, ESE and NNW.

During storm events, precipitation and surface runoff from slopes leads to increased slumping in areas of high ground ice concentration, with subsequent increased sediment removal from the cliff base and undercutting of coastal cliffs from high waves and storm surges (Kobayashi *et al.* 1999). Sediment removal from runoff and wave action during events can lead to an overall coarsening of beach sediments as finer grained materials are transported offshore (Harper 1990; Kobayashi *et al.* 1999). This coarsening is highly dependent on sediment composition of the cliffs and beaches. Removal of material from the coastal zone may lead to increased interaction of waves with the cliff base as the coastal zone becomes narrower (Kobayashi 1999). This sediment removal from the cliff base may also lead to undercutting of frozen cliffs causing bank instability, leading to block failure (Hill and Solomon 1999).

Along the southwest coast of Banks Island, surficial runoff has been noted during precipitation events leading to sediment plumes in the nearshore. No storm events have been recorded in the community since 2003, although past studies have shown evidence of undercutting of cliffs as well as removal of material from the coastal zone during storm events (Harry *et al.* 1983). Little evidence indicates a coarsening of beach sediments or a narrowing of the coastal zone. Melt-out of massive ice, icy lenses and block failure of coastal bluffs during the summer season is a dominant mechanism of coastal cliff failure on the southwest coast, bringing material from the cliff to the shore zone, causing retreat. Once in the coastal zone, material is removed during open-water events or from transport of sediment.

The complete storm frequency record shows that the highest frequency of events in the 1970s with the greatest number of storms in 1978 (25 events), and again in the late 1990s, with declining storm events in the 1980s and since 2000, with the lowest frequency in 2004, with only one event (Figure 5.3). With large variation in the frequency record, there is no linear trend in storm frequency. Between 1969 and present, 335 storm events have been recorded in Sachs Harbour with 13 events between 2002 and 2005. The seasonal distribution of storm events for Sachs Harbour indicates that storms are most frequent during the month of October with 33.3% of events occurring and least frequent during July with 14.4% of all events occurring (Figure 5.4). The months of August and September had comparable frequencies with 26.9% and 26.0%, respectively (Figure 5.4).

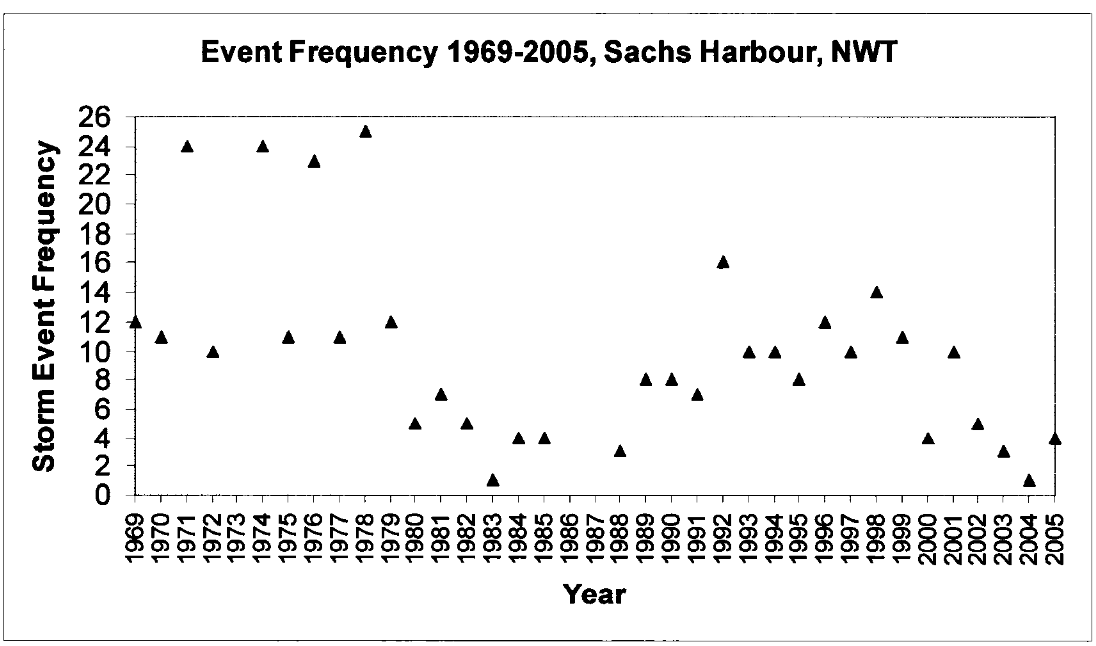


Figure 5.3: Storm event frequency during the open-water season from 1969-2005 in Sachs Harbour. All storm events were included, even if fetch was limited.

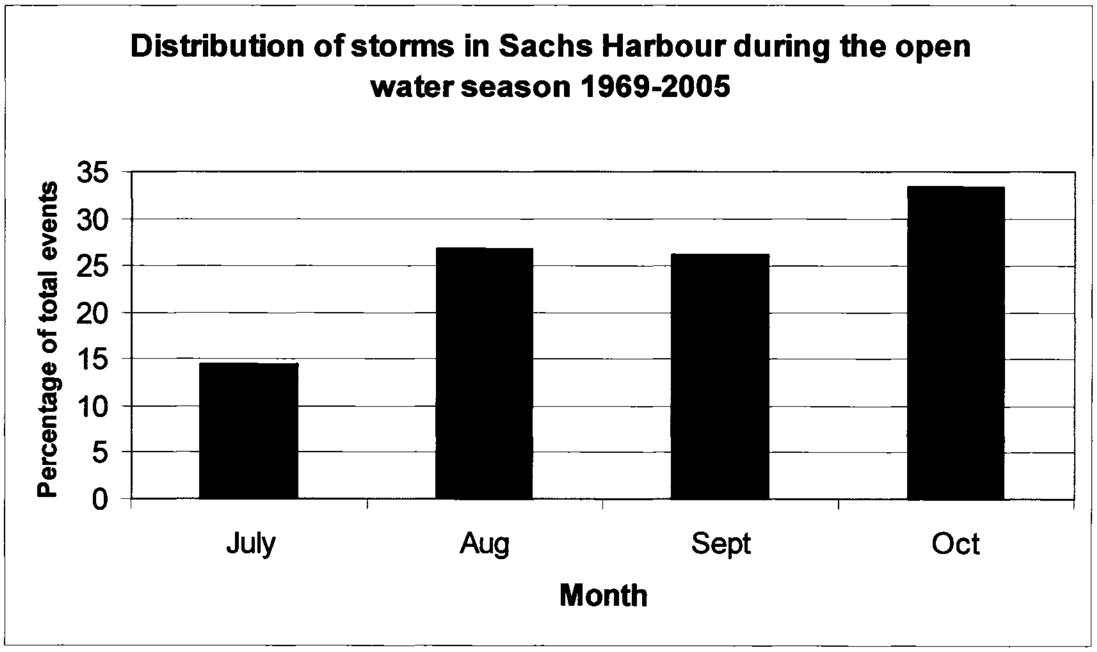


Figure 5.4: Distribution of storm events over the open-water season in Sachs Harbour from 1969-2005. October showed the greatest percentage of storm events.

5.1.3 – Storm records with Open-Water Fetch

Sea ice records examined for each event determined the presence of sea ice in the region and coastal environments. With large waves and possible storm surges, events with sufficient open-water fetch have the potential to influence the coastline near Sachs Harbour. Open-water events are defined as storm events with wind directions across areas of ice-free water, when no sea ice is present in the coastal zone. For Sachs Harbour, these wind directions are typically from the south (S), southeast (SE), south-southeast (SSE), east-southeast (ESE), southwest (SW), south-southwest, (SSW) and west-southwest (WSW) originating over the Amundsen Gulf or Beaufort Sea. Winds from the north through west also originate over the Beaufort Sea, but this area often has more extensive sea-ice cover. Winds from the north-northwest also move across land before reaching the southwest coastline and blow towards the offshore. Wind events with an open-water fetch were separately categorized to determine the event frequencies which impacted the coastline, causing an increase in coastal erosion and sediment removal from the coastal zone.

The frequency of open-water events had a similar pattern the overall events with a high frequency in the 1970s and 1990s and low frequency in the 1980s and 2000s (Figure 5.5). Although there is high variability, there is a similar pattern with total frequency of storm events over the same period. These events are related to sea-ice conditions both in coastal areas and in the Amundsen Gulf, which vary from year to year. There have been decreasing event frequencies in recent years; however, there is no evidence of a decreasing linear trend of storm event frequency over time.

The seasonal distribution of open-water fetch storm events indicate that storms are most frequent during September and October with 35.7% and 33.3% respectively (Figure 5.6). Storms are less frequent in July with 4.0% frequency. These late season events occur at the end of the summer season when warm temperatures have increased melting and thermal processes causing coastal cliff retreat and slumping of material onto the coastal zone. Although storms occur most frequently in September and October, freeze-up occurs in mid to late October. Storm events later in the season are less likely to have open-water fetch, therefore less likely to remove material slumped onto the coastal zone. Frequency of wind direction indicates that although there is an increase in winds from the ESE in the late fall; freeze-up decreases the open-water fetch and limits the ability of a storm event to impact the coastline.

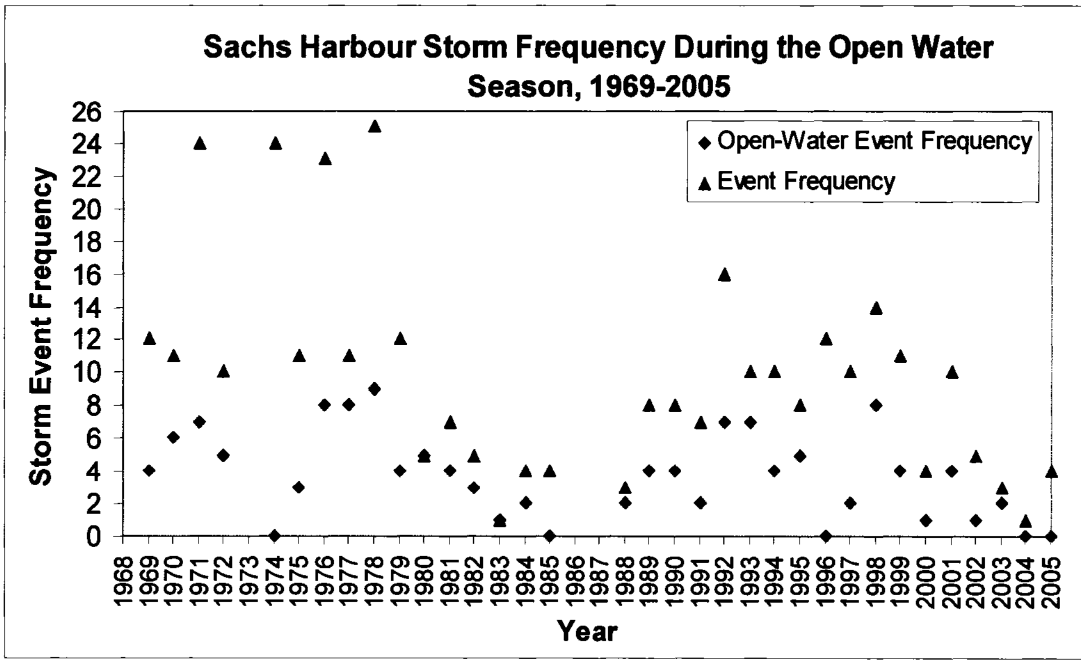


Figure 5.5: Frequency of storm events and open-water events during the open-water season from July-October, 1969-2005 in Sachs Harbour.

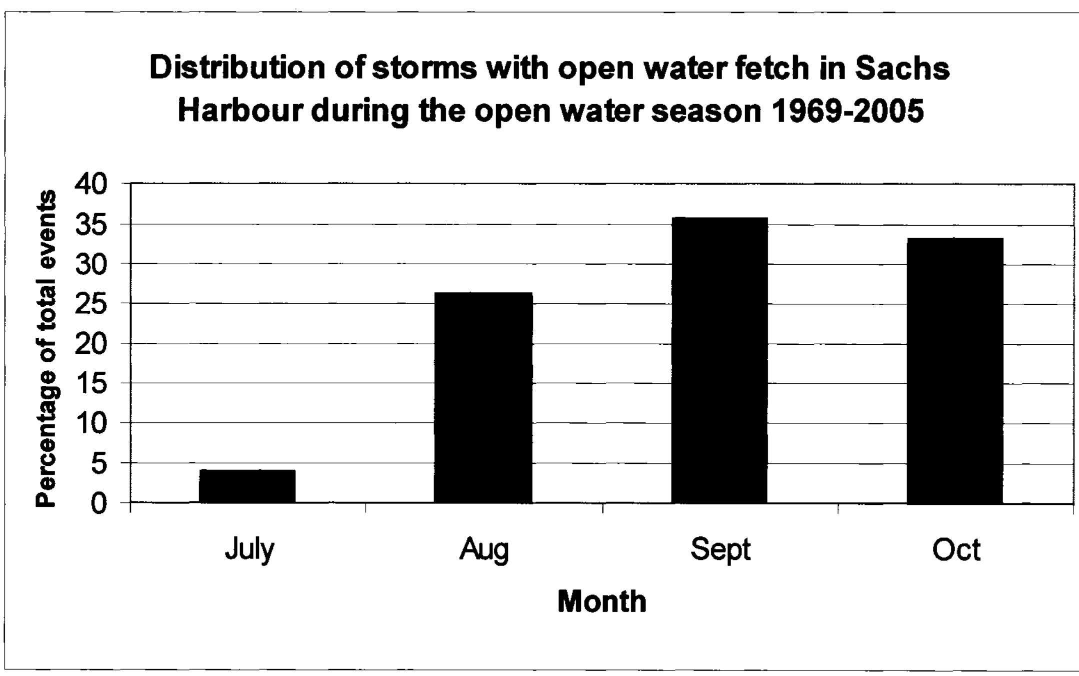


Figure 5.6: Distribution of storms with an open-water fetch in Sachs Harbour from 1969-2005. September has the highest percent frequency.

5.1.4 – Storm Events 2002 – 2005

During the survey period 2002–2005, sea-ice conditions, wind speeds and directions were examined for individual events which could affect the southwest coast of Banks Island and were considered individually. Although there were several events each year, only events combined with open-water conditions would have impacted the study area, aside from ice push. Of the total of 13 events which occurred from 2002 – 2005, only two events had open-water fetch and ice-free coastal conditions, both occurring in 2003. Sea-ice conditions prevented the other 11 events from impacting the coastline.

Between October 7th and 9th 2003 two storm events occurred with similar wind directions and sea-ice conditions. On October 7-8, a storm originating from the east-southeast over the Amundsen Gulf occurred for 6 hours with open-water fetch and a likely fetch distance of between 250-300 km with potential wave heights of approximately 4.5 m (Figure 5.7; Figure 5.9). Less than 24 hours later, on October 8th, a second event with similar ice conditions occurred with a 16 hour duration and winds from the east-southeast, southeast and east with similar fetch distances and potential wave heights of approximately 6 m (Figure 5.8). These combined events occurred over a 22 hour period and appear to have had a strong erosive impact on the coastline due to wave action. In the investigated areas susceptible to erosion, cliff retreat rates were greater between surveys in 2003 and 2004 than between 2004 and 2005. This change is attributed to the two storm events noted above, which likely increased surface runoff and removal of sediment by waves. Sediment removal from the cliff base may also have led to undercutting of frozen bluffs, and block failure.

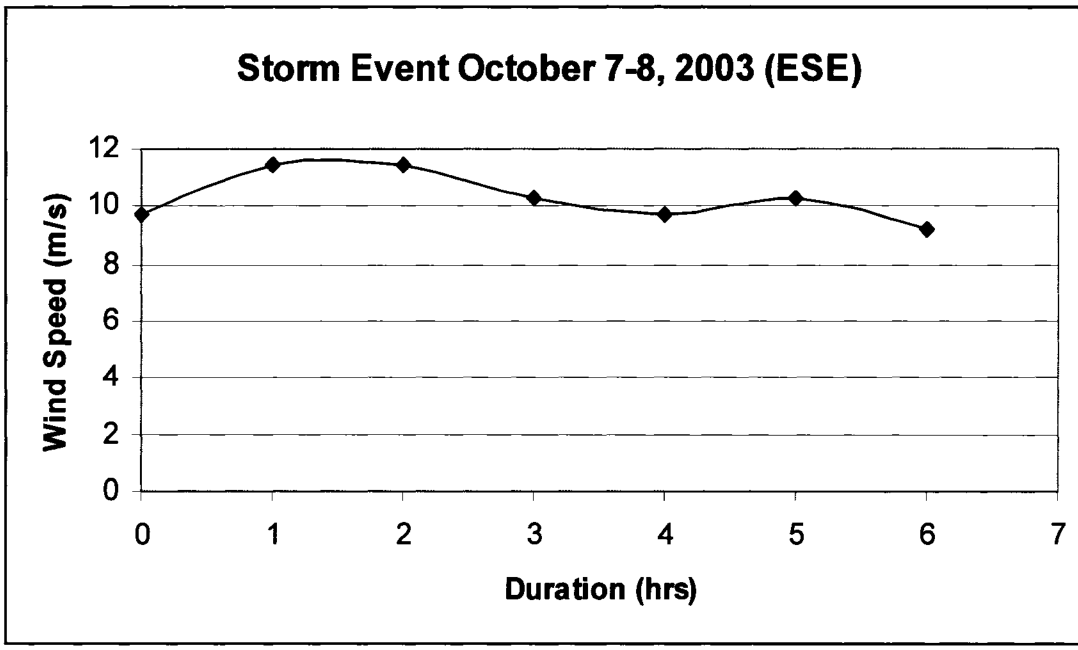


Figure 5.7: October 7-8, 2003, 6 hour event with winds originated from the east-southeast.

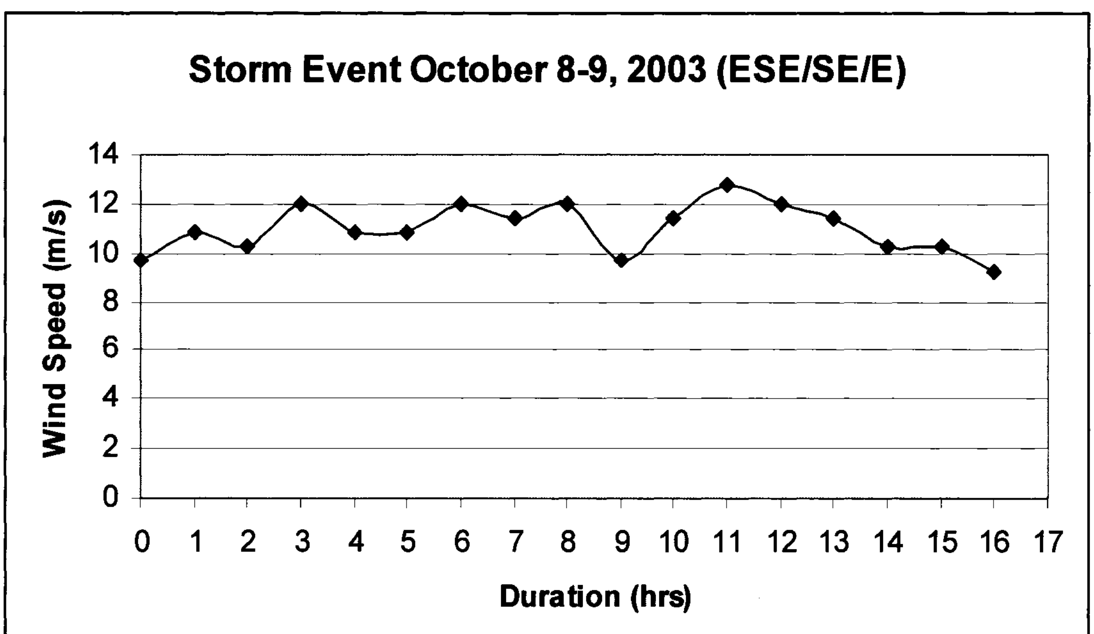


Figure 5.8: October 8-9, 2003, 16 hour event with winds originating from the east-southeast, southeast and east.

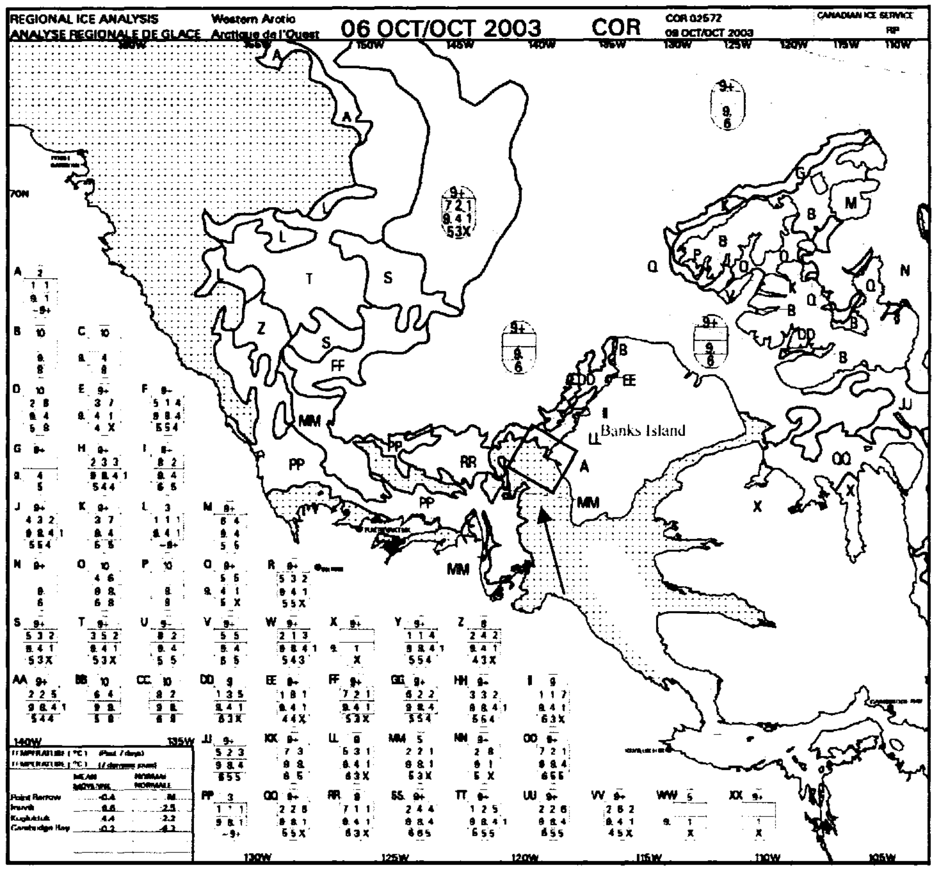


Figure 5.9: Sea-ice conditions for Banks Island and the Beaufort Sea on October 6, 2003. Open-water fetch was limited only by land in the direction the wind was blowing from (to the east, southeast and east-southeast, as indicated by the arrow) (Modified from the Canadian Ice Service, Environment Canada 2006b).

5.2 – Suspended Particulate Matter

On August 8-9, 2005 the onshore wind direction was from the south-southeast in a period of open-water conditions. This event was accompanied by periods of rainfall, and wind speeds up to 39 km/hr, increasing surface runoff along slopes and the shore zone. Plumes of sediment were visible in the nearshore (Figure 5.10). Although this event did not qualify as a storm using the Atkinson (2005) definition, wave interaction with the shoreline was observed causing an increase in sediment removal into the nearshore to the west of the community, in areas of exposed ground ice. During this event surface runoff into the nearshore and re-suspension of fine sediment (sands, silts and clays) occurred.

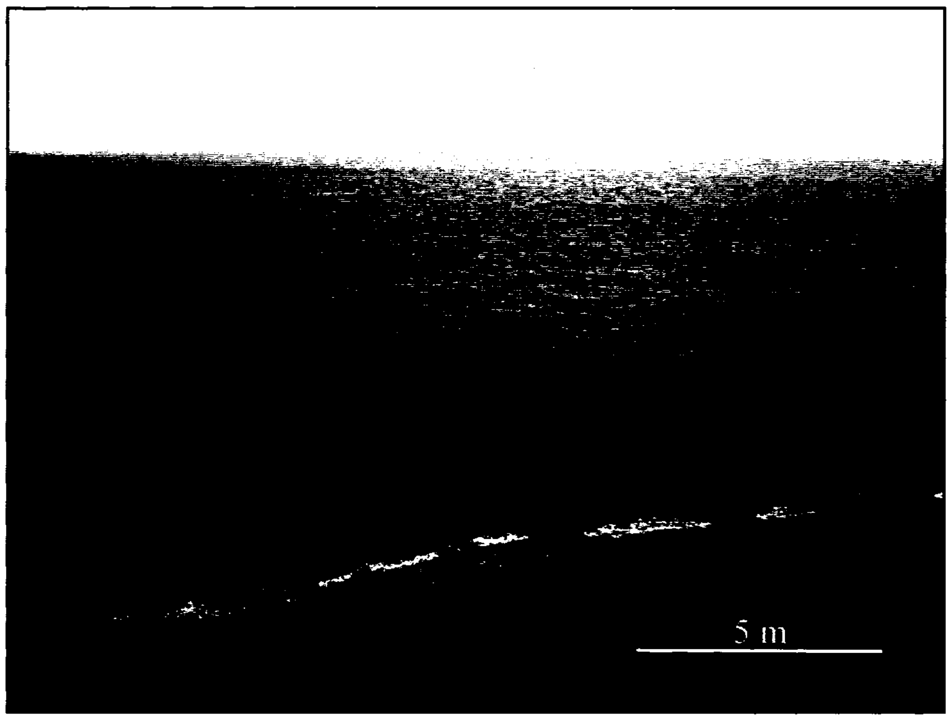


Figure 5.10: Sediment plume visible from the coastline August 9, 2005. UTM Coordinates: 422005 E, 7988670 N.

Suspended particulate matter (SPM) was collected at nine locations approximately 100 m offshore before the wind/rain event. These locations were taken near the community, Sachs Harbour Lines 2 and 8 and locations west of the community Wide Beach Lines 1 and 2, near and at Line 9, the Ground Ice Line, and Line 12 (Figure 5.11). These stations were resampled to determine changes in suspended sediment following the event. A station was also resampled 1 km offshore of the Ground Ice Line where the sediment plume appeared to extend a greater distance offshore.

Seven of the nine locations showed an increase in SPM after the wind/rain event. Sachs Harbour Line 2 (Ln2) 100 m and Wide Beach Line 1 (WB1) 100 m showed small decreases in SPM after the event, which is likely due to the sandy nature of Wide Beach Line 2 and diverted surface runoff in the community near Line 2 (Figure 5.11). Areas west of the community in locations of coastal retreat showed a large increase in SPM after the event, particularly at Sachs Harbour Line 11 (TH 11) with an increase from 24.3 to 49.9 mg/L SPM and the Ground Ice Line (GI) from 29.8 to 75.7 mg/L SPM at 100 metres (Figure 5.11).

The mean SPM for all locations indicates that there was a statistically significant difference in average SPM before and after the rain/wind event, t-test, $t = -2.659$, $p < 0.0289$, $df = 9$ (paired t-test was utilized) (Figure 5.12). There was a higher degree of variability (as indicated by the higher standard deviation) in SPM retested after this event. However, the SPM was not resampled until August 10 and some material which had been re-suspended in the water column or was transported by runoff had already settled out. Sediment plumes were visible in the nearshore near Sachs Harbour on August 9, but were not visible in many locations on August 10. At locations such as the Ground Ice Line the finer materials (fine grained silts) and vegetative debris would have stayed suspended longer in the water column. In contrast, sediment produced from areas of medium to coarse sands such as the Sachs Harbour Wide Beach Line would rapidly settle from suspension. A sediment plume was present to 1 km offshore above the Ground Ice bathymetric survey was visually observed to be reduced up to 1 km offshore on August 10.

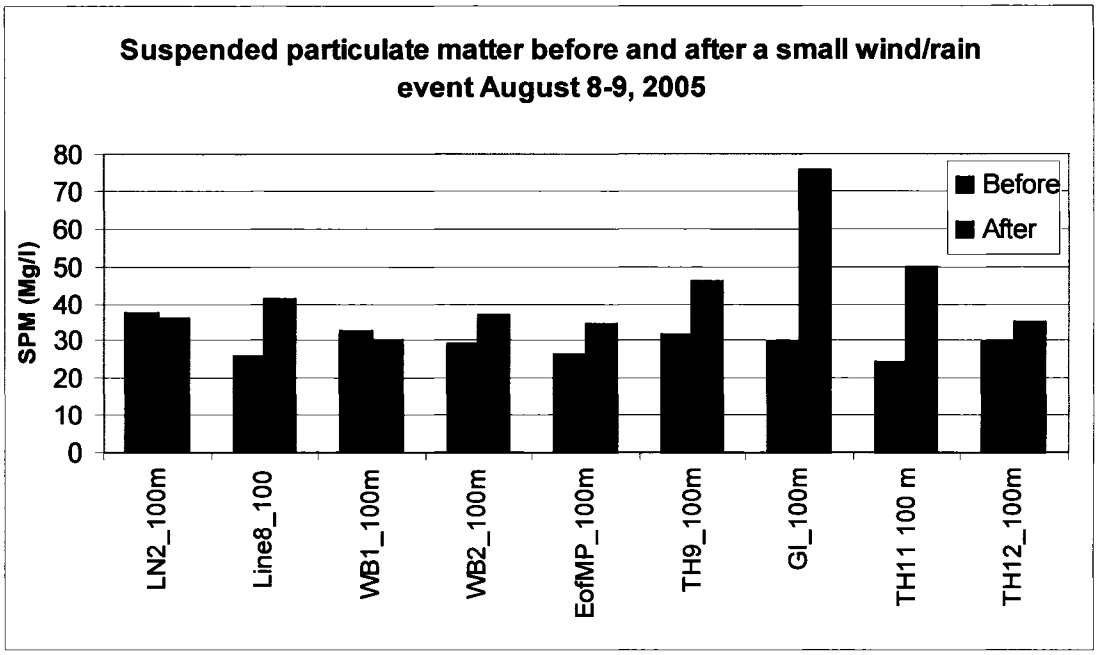


Figure 5.11: Suspended particulate matter at nine locations in the study area.

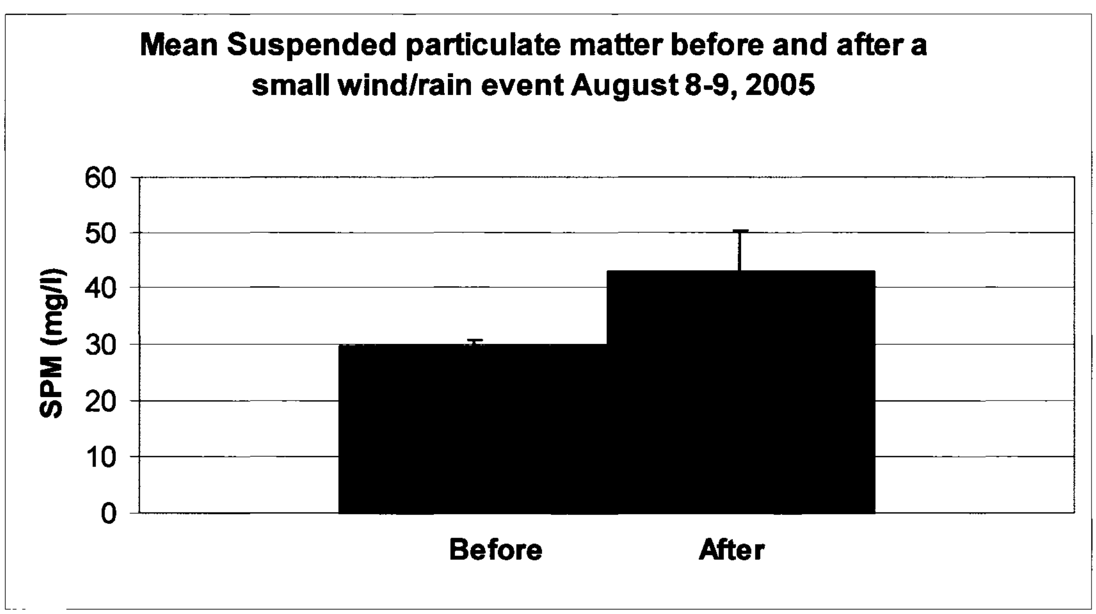


Figure 5.12: Average SPM values in mg/L. t=-2.659-, p = 0.0289, n = 9. Error bars represent the standard error.

Comparison of suspended particulate matter before and after a precipitation event indicates the increase in surficial runoff from the coastal slopes during precipitation events that often accompany open-water events, leads to suspended particulate matter in the nearshore. Surficial runoff along the coastal cliffs leads to an increase in fine grained materials removed from the coastal region to the nearshore environment. During events, increases in surficial runoff combined with removal of sediment from the coastal zone will increase suspended particulate matter, especially in areas such as the Ground Ice Line where ice-rich fine grained sediment dominate the coastal cliffs. Sediment plumes which occur during events lead to increased sedimentation from the coastline. Suspended sediment west of the community is likely transported westward along a large transport cell, while large basins in the community harbour act as a sink for finer grained surface runoff near the community. Increased sedimentation in the nearshore could also affect benthic communities and other higher species.

Chapter 6 – Long-Term Change and Sediment Transport

Analysis of aerial photographs taken over a 53 year period 1950-2003 has revealed four depositional and two erosional areas along the southwest coastline. Beach migration and progradation was evident in four locations within the study area, at Sachs Spit, Sachs Beach, Martha Point and Cape Kellett Spit (Figure 6.1). Long-term coastal retreat over 53 years was evident in two locations: to the west of Martha Point and in the Sachs Lowlands south of the Sachs Spit. Minor erosion was apparent in coastal cliffs within the community of Sachs Harbour with higher retreat rates west of the community. The pattern of shore migration, progradation and erosion indicates that sediment transport in this system is both important and complex.

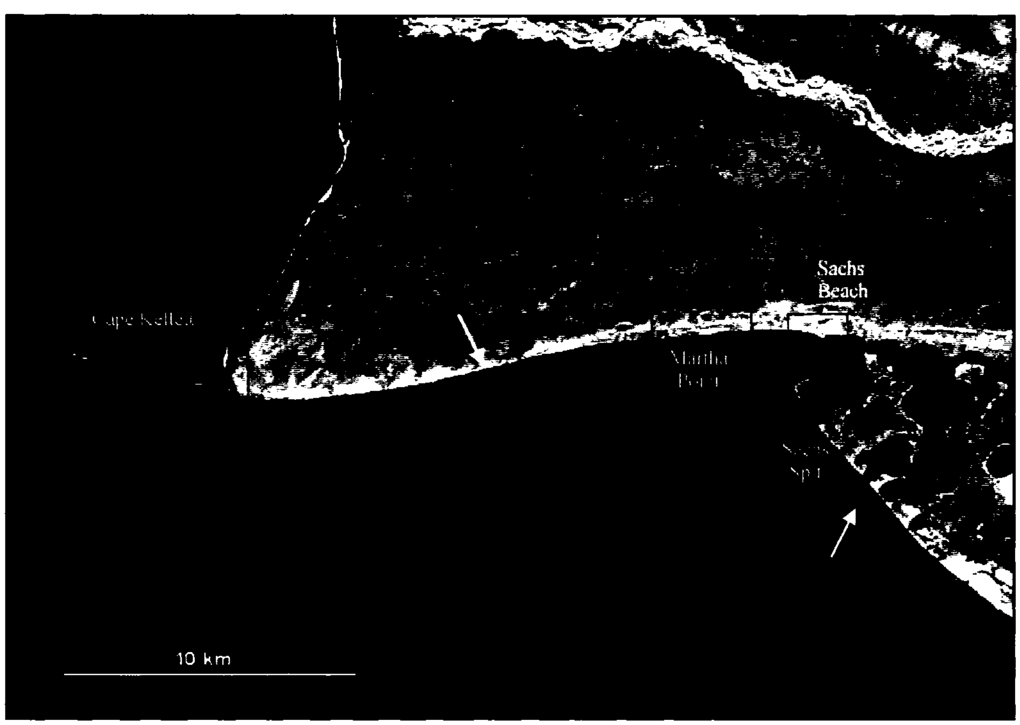


Figure 6.1: Areas of long-term change within in the study area from 1950 – 2005. Red boxes indicate depositional areas and yellow arrows indicate general areas of retreat (modified Landsat from Natural Resources Canada 2000).

6.1 – Sediment Transport Within the Study Area

Previous studies of sediment transport have inferred complex movement of sediment, with three major transport directions along the southwest coast (Harry *et al.* 1983). These include, northward sediment movement from the Sachs Lowlands supplying the Sachs Spit, and westward transport along the Duck Hawk Bluffs to Cape Kellett. Sediment also moves towards Sachs Harbour from the west. The boundary between westward and eastward sediment transport was located near Martha Point Spit. The presence of these depositional features in this low energy environment indicates that sediment transport is an important depositional mechanism. Transport directions determine the migration and development of Sachs Beach and Martha Point Spit towards the east and the configuration of Cape Kellett Spit in the west (Figure 6.2). Fine grained ice rich coastal cliffs to the west of Martha Point are the sediment source for Martha Point Spit.

Transport directions can also be determined by comparison of sediment sorting between survey locations in the study area. Finer, well sorted sediments indicate more distal transport than coarser, poorly sorted sediments in areas with similar sources. Sediments on the Sachs Spit are well sorted and fine grained, indicating distal sediment transport from the Sachs Lowlands to the southeast (Appendix D). In contrast, sediments along the Duck Hawk Bluffs are poorly sorted and coarse grained, indicating short-distance sediment transport, or ice rafting and ice push, or both processes in combination. Sediments from this region also contained greater amounts of feldspars, dolomites and gabbro fragments, not seen in sediments on the Sachs Spit or Sachs Lowlands. Beach sediments from Martha Point, as well as those directly west of Martha Point, are poorly sorted, also indicating transport from proximal areas. Sediments from the shoreline at survey Lines 10 (800 m west of Martha Point), Ground Ice Line (500 m west) and Line 11 (2.6 km west) are very similar in composition to the Martha Point sediments. All are composed of very coarse grained sand to gravel, dominated by gabbro and dolomite fragments (Figure 6.3).

Wave-driven longshore currents from the southeast along the Sachs Lowlands cause a net transport towards the northwest to the Sachs Spit. Sediment is also supplied along the coastline for the maintenance of Cape Kellett at the southwest tip of the island (Figure 6.2). The eastern transport originates west of the Martha Point Spit and provides sediment to that feature and the Sachs Landing Beach. Migration of the Martha Point Spit combined with the nearshore bathymetry indicates that a divergence point of sediment transport exists west of Martha Point Spit, and that it has migrated towards the east over time, visible in successive aerial photographs. The fine well sorted rounded frosted quartz and amphibole derived from sediment of the Sachs Lowlands are not found in beach sediments at Martha Point, where sediments are dominated by lithic fragments and gabbros. This indicates that Martha Point Spit did not originate from sediment transport from the southeast, and that the two sediment transport cells do not connect. Sediment transport from the southeast is deflected towards the northwest by the shallow sill near Sachs Harbour, while sediment maintaining the Sachs Spit moves northeast along the sill within the harbour. Sediment transport in each area, Sachs Lowlands, Cape Kellett, Duck Hawk Bluffs, Martha's Point and the community, will be discussed separately.

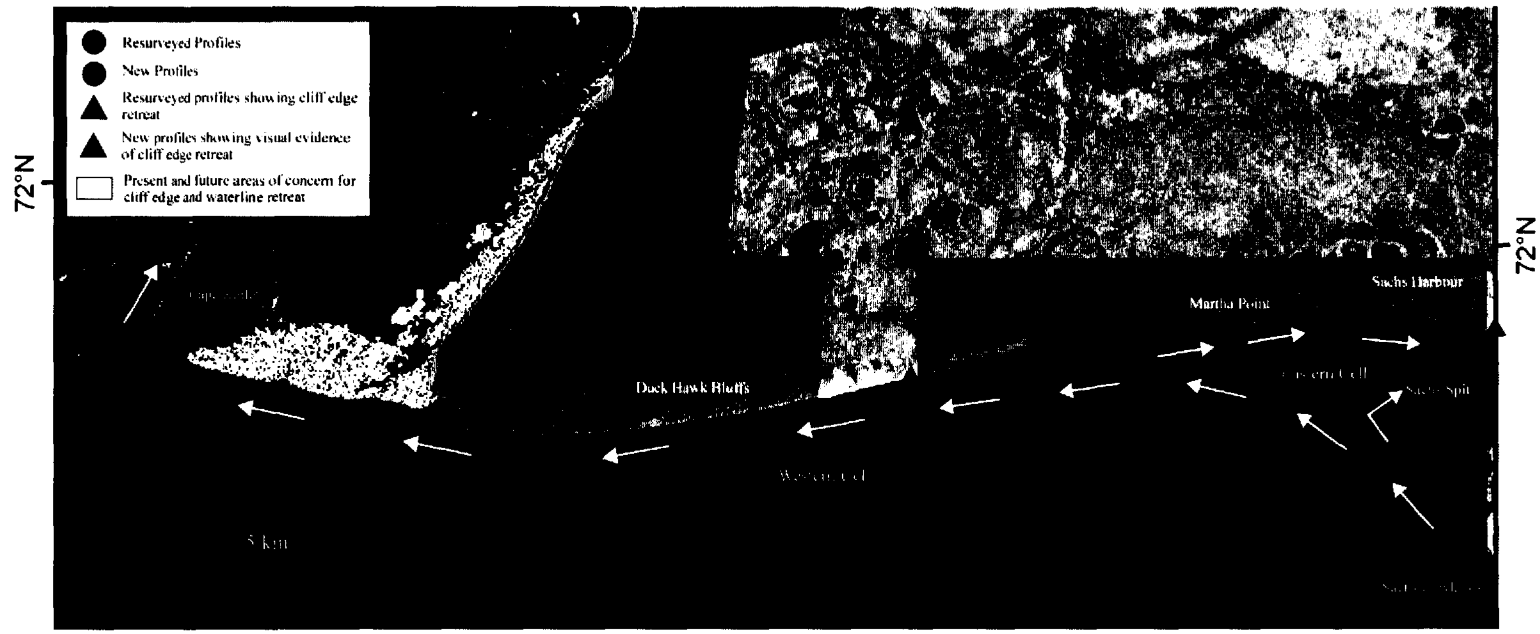


Figure 6.2: Suggested sediment transport diagram for the southwest coastline of Banks Island. A large cell moves sediment from the southeast towards the west where additional material is derived from the Duck Hawk Bluffs and transported to Cape Kellett. An eastward cell brings sediment east toward Martha Point and the Sachs Beach (modified from imagery © Digital Globe).

Figure 6.3: Comparison of sediment from Martha Point (above) and Sachs Harbour Line 10 (below). Both sediment samples were poorly sorted very coarse grain sand to gravel and were dominated by lithic fragments and gabbros.

6.1.1 – Sachs Spit and Sachs Lowlands Shoreline

The growth of Sachs Spit to the south of the community is a result of sediment transport from the southeast along the Sachs Lowlands (Figure 6.2). Sediment supplied from retreat of low-lying coastal cliffs is transported from the southeast. The deposits in this region are composed of glaciomarine sands with high ice content and thermokarst lakes. Exposures of massive ice are common in the coastal bluffs (Figure 6.5). Beaches in this area are less than 3 m in width, with the high water line reaching the base of eroding cliffs. Comparison of aerial photographs from 1950 and satellite images from 2003 indicate a coastal retreat of approximately 80 metres over 53 years (average 1.5 m/a) and a retreat of 78 m at Sachs Spit Line 1 (Figure 6.7). Unfortunately no aerial photographs were available between 1950 and 2003 to enable an analysis of variability in the retreat rates throughout this period (Figure 6.6; Figure 6.7).

The substrate at the waterline of the Sachs Spit and in the nearshore is well sorted to very well sorted fine to medium grained sand. Sorting results from wave reworking in the shore zone and distal sediment transport from the southeast, with the sandy substrate derived from the sandy Carpenter Till and the underlying sandy Beaufort Formation (Vincent 1990). The latter formation is dominated by cherts, quartzites and dolomites (Vincent 1990) while the Carpenter Till is dominated by ice-contact sediments, is bouldery with a silty-clay matrix and dominated by quartz and dolomites (Vincent 1982). Development of the Sachs Spit between 1950 and 2003 indicates progradation, backstepping (migration based on changes in sea level) and extension towards the community harbour (Figure 6.4; Figure 6.8). Since 1950 the trunk of the spit has increased in length from 1560 to 1610 m, while the hook of the spit has increased from approximately 260 to 670 m in length, approximately 7.7 m/a. Spit area has increased from approximately 210,500 m^2 in 1950 to 293,250 m^2 in 2003, an increase of approximately 1560 m^2/a. East of Sachs Spit, coastal bluff retreat due to thermal and wave erosion is visible with approximately 50 m of retreat between 1950 and 2003 (Figure 6.8). A breach in the spit occurred not long before 1950, and is shown on the 1950 aerial photograph (Figure 6.8).

Extension of the spit tip to the northeast and migration is controlled by local bathymetry. Sachs Spit lies on a sill enclosing the harbour basins and its hook has built landward onto the sill between the two main basins of the harbour (Figure 6.4). Further progradation and migration of Sachs Spit could pose problems for marine transport into the community of Sachs Harbour, as the shallow sill region between the lake basins is currently less than 4 m in depth. Although the increase in length of the hooked segment of the Sachs Spit of ca 7.7 m/a, Harry *et al.* (1983) indicated that the hooked segment was approximately 600 m long in 1979. This indicates that an increase of 70 m has occurred since 1979, giving an average extension of *ca.* 2.9 m/a. This decrease in the rate is likely due to migration of the spit curve towards the deep basin, where sediment is being deposited and the water is too deep for rapid spit development.

Although visible rates of sediment transport have decreased since the 1980s, continued migration towards the north-east, and overall transport of sediment from the Sachs Spit and the southeast will continue to infill the shallow sill south of the community (Figure 6.4). This transport leading to infilling may cause the shallow harbour area to require dredging. Dredging would have unknown effects on sediment transport, and may create re-suspension of material causing increased transport and progradation of the Sachs Landing Beach.

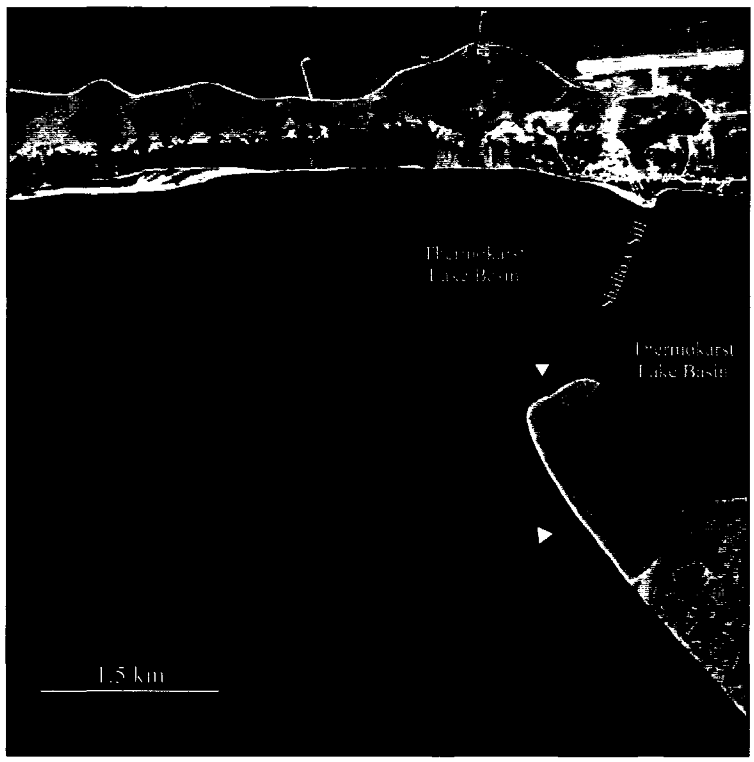


Figure 6.4: Sediment transport direction along the Sachs Lowlands to the Sachs Spit and the migration of the hooked segment. Note the thermokarst lake basins and shallow sill controlling the migration of the spit (modified from images © Digital Globe).

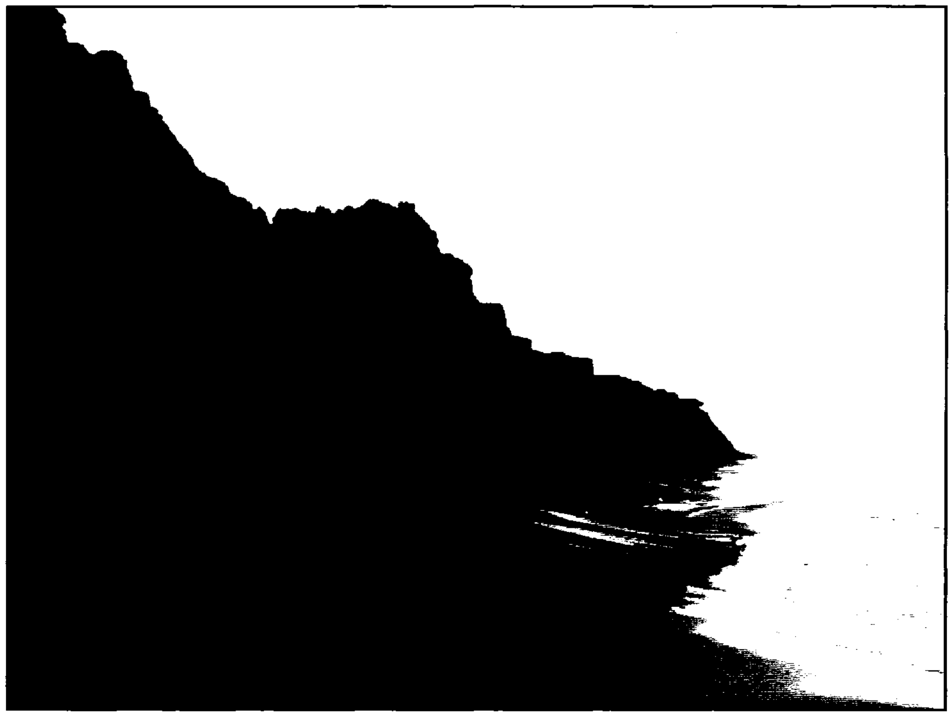


Figure 6.5: Coastal bluff near Sachs Spit Line 1 along the Sachs Lowlands southeast of Sachs Harbour. Note the narrow beach, slumping fine grained material, and exposed ground ice. UTM Coordinates: 422534 E, 7985353 N. Photo taken: July 20, 2005.

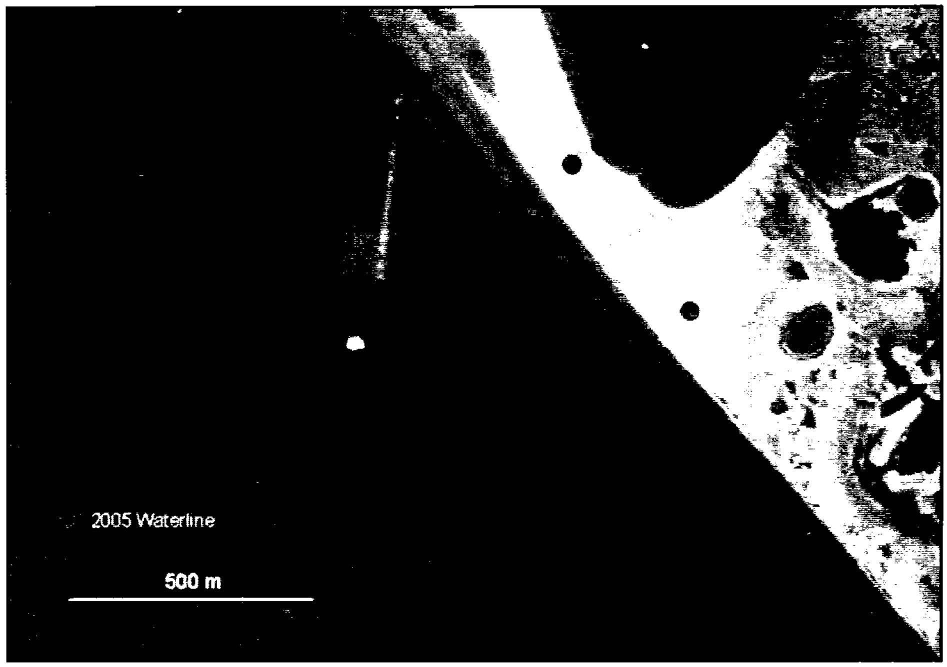


Figure 6.6: The location of the 2005 waterline from Sachs Spit Lines 1 and 2 in 2005 compared to the waterline on the 1950 aerial photograph. Sachs Spit Line 1 showed 78 m of retreat since 1950.

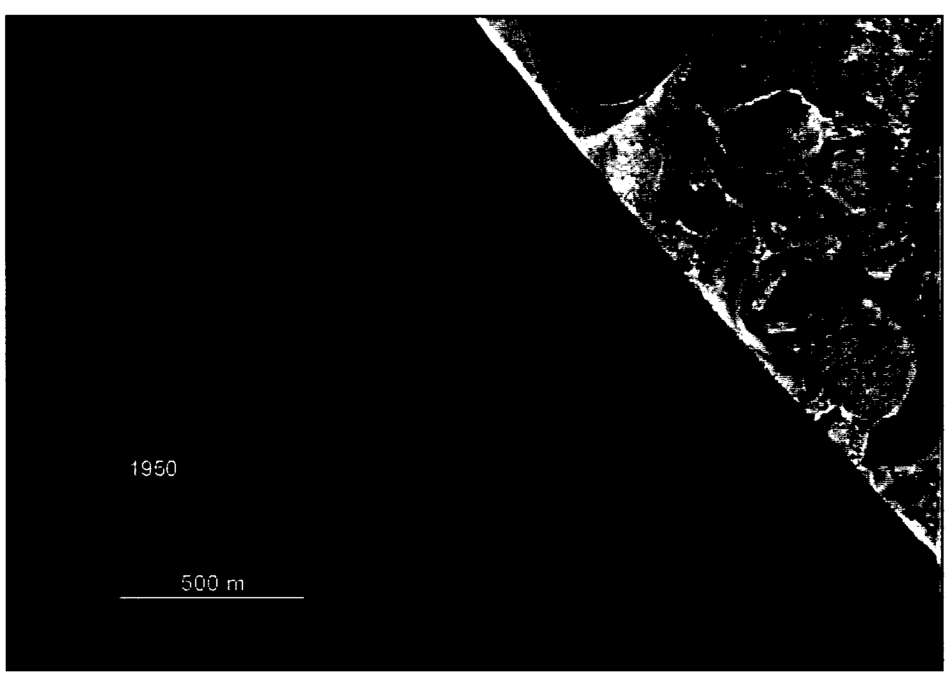


Figure 6.7: 1950 waterline compared to the 2003 waterline. Approximately 80 metres of retreat is evident. The coastline is microtidal throughout with between 0.2 – 0.4 m of variation between high and low tide (modified from imagery © Digital Globe).

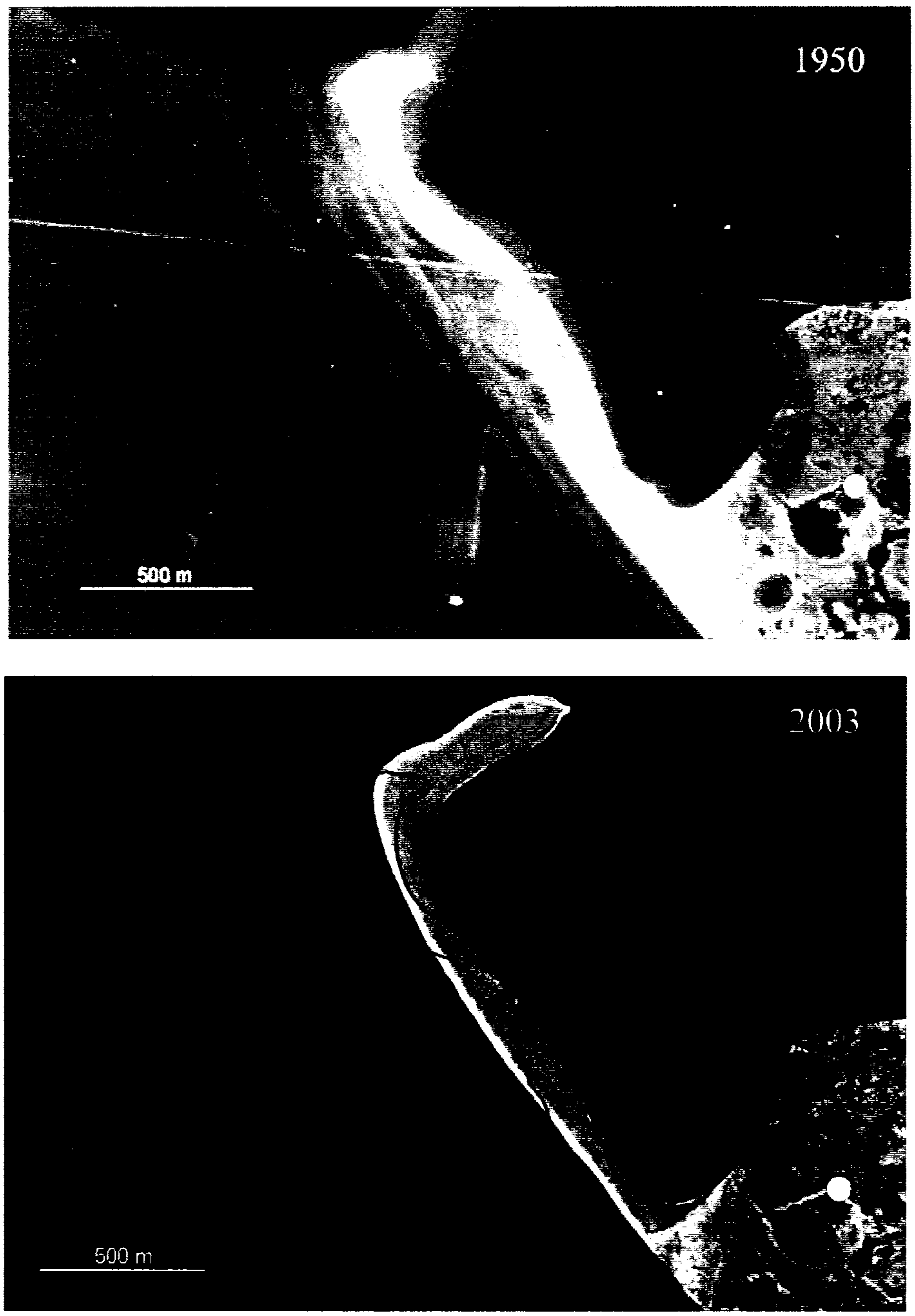


Figure 6.8: Comparison of the Sachs Spit between 1950 and 2003 with the 1950 waterline indicated on the 2003 satellite image. The yellow circle represents a common point on each photograph. Note that the hook of the spit has prograded and migrated towards the north-east. (Bottom diagram modified from image © Digital Globe).

6.1.2 – Cape Kellett

Cape Kellett Spit extends from the southwest point of Banks Island (Figure 6.1). The spit is approximately 10 km in length with a 6.5 km trunk and a 3 km hook. The formation and curvature of this spit indicates that sediment transport is toward the west (Figure 6.2). The age of this spit is unknown. It was named after Captain Henry Kellett, and was discussed in diaries as a base camp area for the ship *Mary Sachs* in 1914 (Canadian Museum of Civilization 2003). The aerial photograph from 1950 indicates that the spit had similar general dimensions to those at present, and that no significant addition to the spit length has occurred since then. Variations in water level are also evident in the comparison of the 1950 and 2000 images. The first major curve of the spit is submerged in the 2000 satellite image, although it was visible during field surveying in 2005, indicating a higher water level in the 2000 image. Small changes in water level would change the appearance of the spit on the aerial photographs, and likely is responsible for the apparent variation along the outer ridges and tip of the spit, as the maximum elevation is less than 2 m asl. Sea ice could also create variations in the images depending on the time of year taken as the spit is open to the Amundsen Gulf. Surveys in 2005 indicated that significant ice shove occurs even during the open-water season (Figure 6.11).

Comparison of aerial photographs from 1950 and a landsat image from 2000, show that Cape Kellett has varied little in the trunk and hooked segment of the spit. The trunk and hook have not migrated significantly since 1950 (Figure 6.9). Changes between 1950 and 2000 are visible along the tip of the spit, near Cape Kellett Survey Line 5. The northeastern tip of the spit appears to have prograded. The width of the tip of the spit has increased from approximately 65 to 170 m between 1950 and 2000 (Figure 6.10). Beach ridges on the tip of the spit are visible and show progradation towards the east (Figure 6.11). Sediment supply originates from the Duck Hawk Bluffs along the southwest coastline and is transported along the spit, causing an increase in the length of the spit tip and a movement towards the east (Figure 6.9).

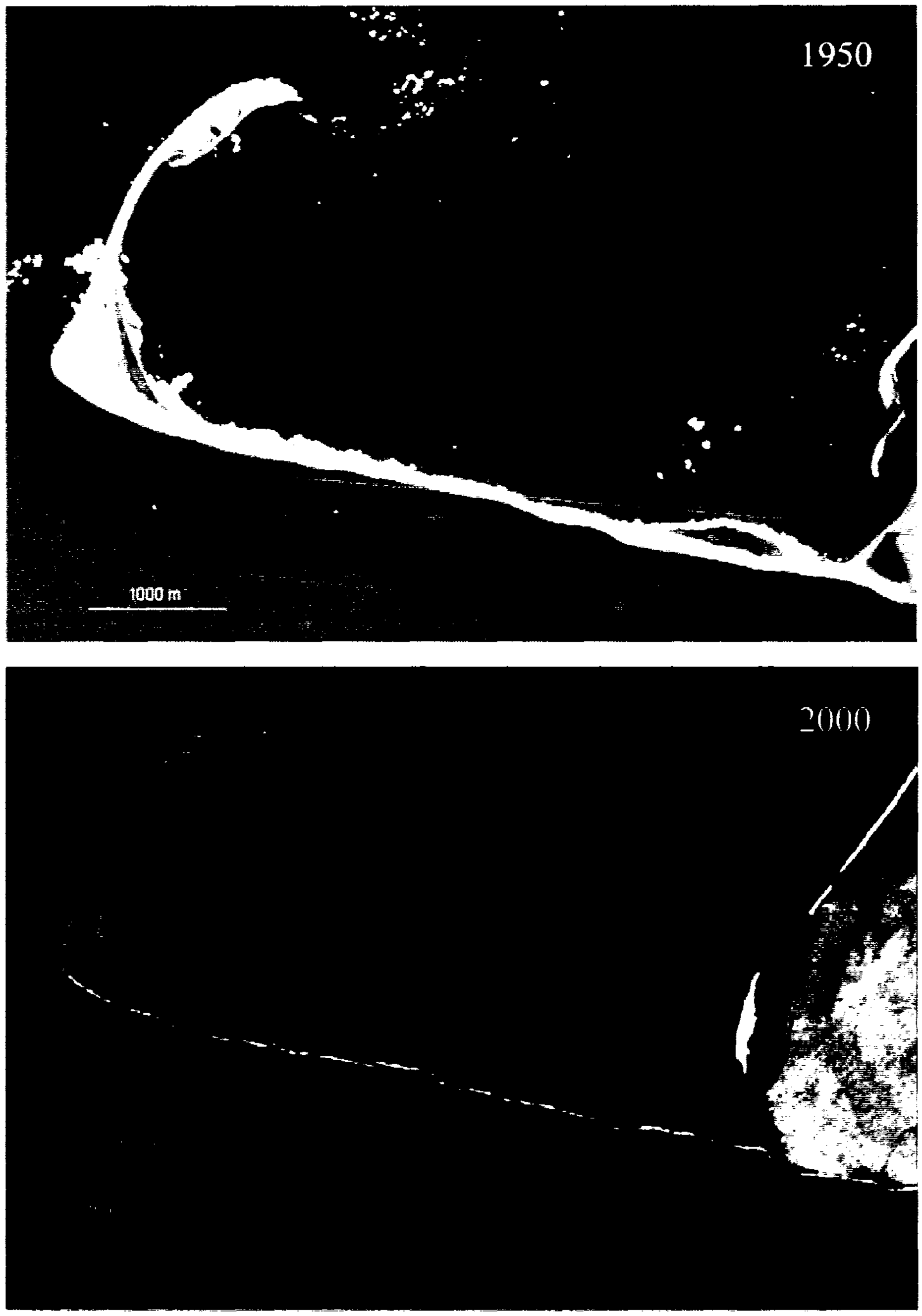


Figure 6.9: Comparison of the Cape Kellett Spit waterlines between 1950 and 2000. Blue line indicates shoreline in 1950. Note changes in the spit tip which indicate progradation. Changes along the inner side of the spit and in ridges along the outer portion of the spit are likely due to water level differences between the images (bottom figure modified Landsat from Natural Resources Canada 2000).

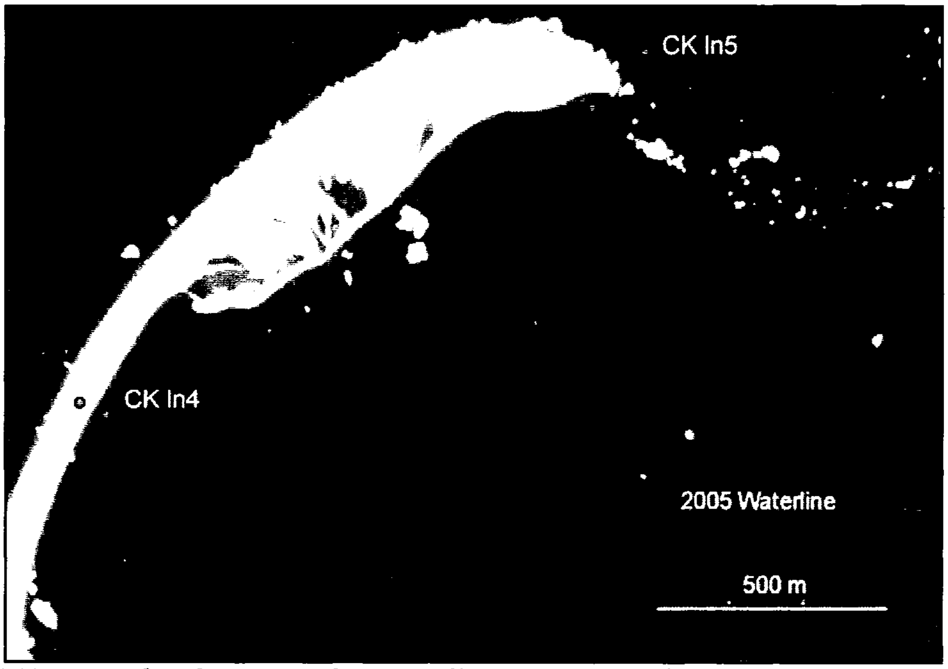


Figure 6.10: Waterline locations of Cape Kellett Surveys 4 and 5 in 2005 superimposed on the 1950 aerial photograph of Cape Kellett. Variation in Cape Kellett Lines 4 and 5 are mainly due to differences in water level between the aerial photograph and the surveys.

Figure 6.11: Beach ridges at the northeastern tip of the Cape Kellett Spit looking towards the south. UTM coordinates: 397980 E, 7990345 N. Photograph taken July 23, 2005.

6.1.3 – The Duck Hawk Bluffs

Between 1950 and 2003, the Duck Hawk Bluffs did not show evidence of overall change. The 2005 surveys noted slumping material along the bluffs. The removal of this material by longshore transport has not caused significant coastal retreat or progradation. Nevertheless, over the long term, sediment from the coastal cliffs slumps onto the beach and is removed by longshore transport providing a sediment source for the Cape Kellett Spit. The rate of influx of terrestrial material appears to approximately balance the rate of removal by coastal transport. Samples show that sediment transport from the southeast does not contribute to beach sediments in the Duck Hawk Bluffs. This is indicated by the large grain sizes of beach sediments dominated by lithic fragments dissimilar to sediments from the southeast and a deep nearshore zone where material from the southeast is likely deposited (Figure 6.2).

6.1.4 – Erosional Area West of Martha Point

Areas of exposed ground ice to the west of Martha Point (near the GI Line and Line 10) showed coastal retreat in successive aerial photographs. Line 10 showed an overall retreat of approximately 70 m between 1950 and 2005, with a greater retreat in the 1950s and 1960s than in more recent years (Figure 6.12). Between 1950 and 1964, the waterline in this location retreated 40 m, at an average of 2.9 m/a. Between 1964 and 1972 the coastline retreated about 22 m, giving an average rate of 1.7 m/a. Between 1972 and 1985 the coastline retreated 56.2 m, 4.3 m/a during a period in the early 1970s when there was an increase in open-water storms. Since 1985 the coastline has retreated 15 m, equivalent to 0.7 m/a, as the number of open-water storms has declined. Similar retreat rates were also measured for the Ground Ice Line from sequential aerial photographs.

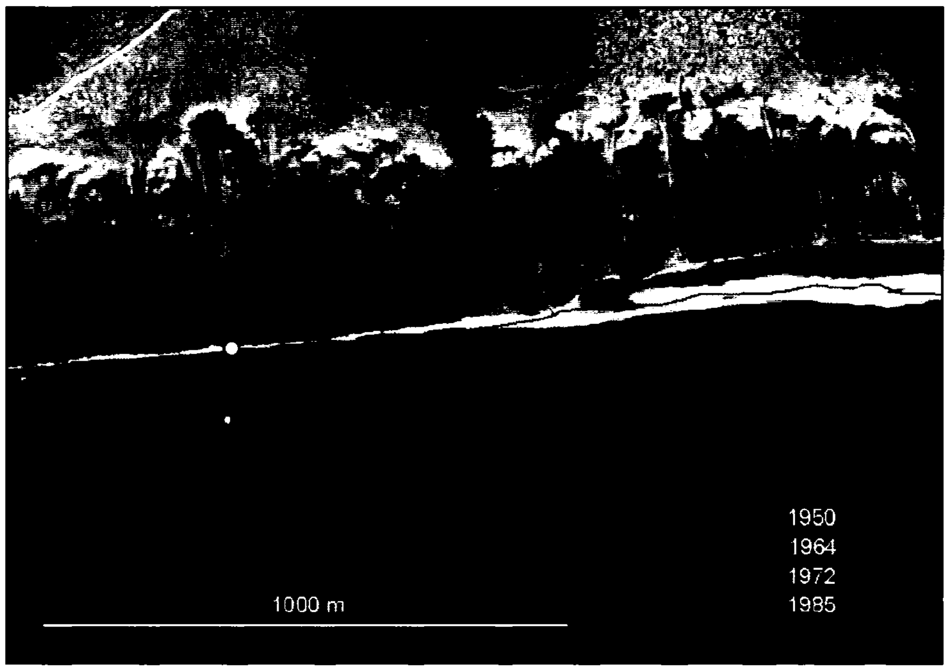
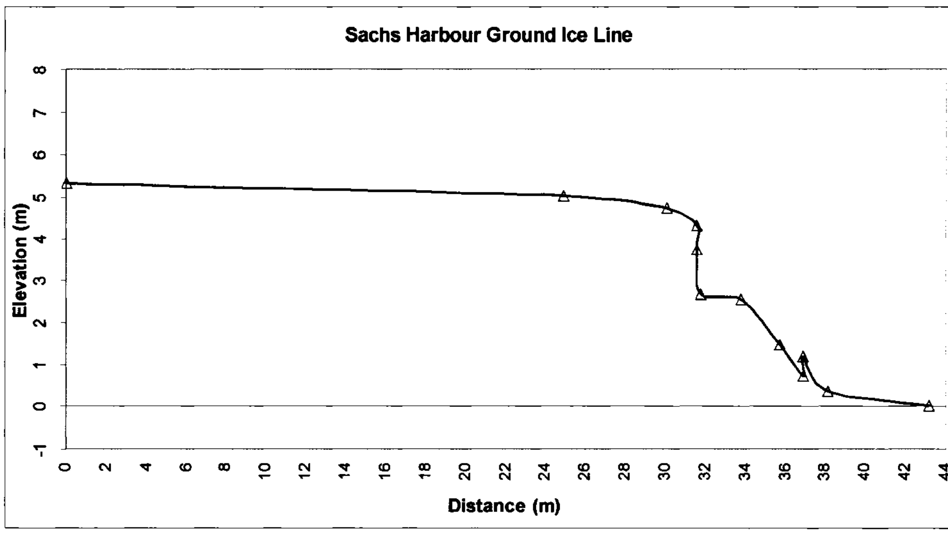


Figure 6.12: Comparison of shorelines between 1950 and 2003 with the locations of the Ground Ice Line (yellow), Sachs Harbour Line 10 (green) and Sachs Harbour Line 9 (purple) (modified from imagery © Digital Globe).

A net retreat of the shoreline west of Martha Point and decreasing beach width shown in successive coastal surveys at Line 10 between 2003 and 2005 indicates removal of sediment from the beach zone (Figure 6.13). This may be due to thermal erosion of coastal bluffs with exposed ground ice slumping onto the beach, with cliff retreat rates of 2.95 m/a between 2003-2005 or about 800 m^3/a of sediment loss from coastal cliff at this location. Material is transported offshore during open-water events, while fine grained material remains in the nearshore. Slumping cliff material and removal of sediment by longshore transport have been the dominant factors in decreasing beach width and shoreline retreat, as storm events have been infrequent since 2002. Sediment transport in this area is towards Martha Point to the east (Figure 6.2).



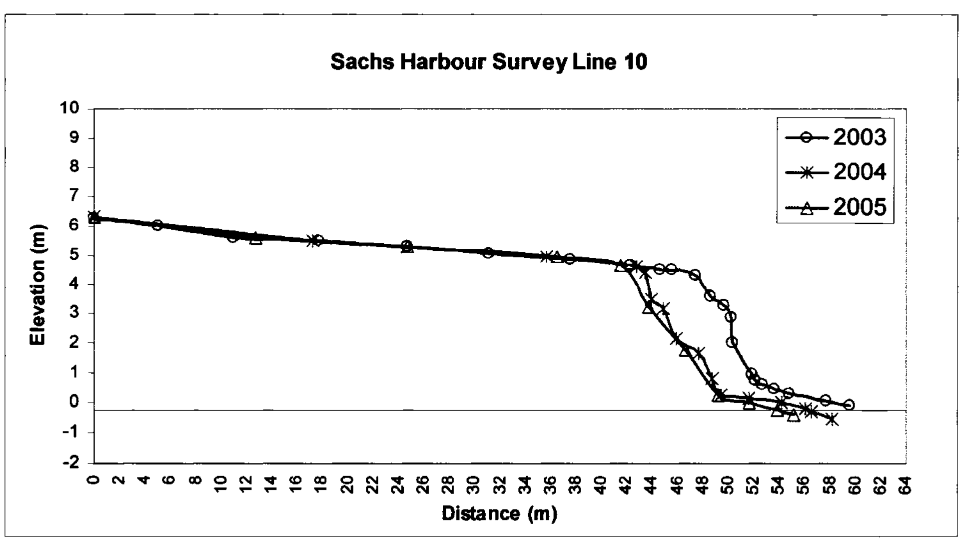


Figure 6.13: Coastal surveys Ground Ice Line (above) and Line 10 (below). The Ground Ice Line indicates a steep cliff face dominated by exposed ground ice and Line indicates retreat over successive survey years of 2.9 m/a.

6.1.5 – Martha Point Spit

Martha Point is a large spit with an approximate age of between 30 and 70 years (Harry *et al.* 1983) and encloses a small lagoon. The spit has prograded and migrated eastwards since 1950 shown in aerial photographs and noted by Harry *et al.* (1983) (Figure 6.14; Figure 6.15). A major breach occurred in the spit *ca.* 1976, which resulted in substantial sediment loss. Development and migration of the spit was slowed during sediment recovery (Harry *et al.* 1983).

Air photo analysis indicates that substantial migration of the spit occurred between 1950 and 1972, with decreased movement between 1985 and 2003, likely due to the decrease in open-water events contributing to sediment loss in cliffs west of the spit, and sediment recovery of the breaching in the late 1970s. Since 1950 the spit has migrated approximately 800 m eastward (Figure 6.14). The spit area has increased from approximately 167 590 m^2 in 1950 to 218 500 m^2 in 2003, an increase of 960.6 m^2/a. All survey years showed an increase in spit area, with the exception of 1985, the result of the loss in area caused by a major breach ca. 1976 (Harry *et al.* 1983).

Migration of Martha Point Spit has been controlled by sediment availability and nearshore bathymetry. Satellite images indicate drowned thermokarst lakes to the east of Martha Point, including one small and one large basin. The larger basin has a maximum depth of 33 m, significantly deeper than the nearshore area to the west. As Martha Point Spit has migrated eastward, the lake basin has been infilled. In 1950 the large basin was approximately 1600 m in width, and has steadily decreased to 870 m in 2003. Future migration and transport of sediment eastward will continue to infill this basin. Other lake basins to the east of Martha Point will act as a control on future migration. These basins are larger (2 km wide) and deeper (over 44 m deep) than that adjacent to the spit. As sediment is transported towards the east, the deep basin will begin to infill, slowing the rate of spit migration (Figure 6.14).

Figure 6.14: Comparison of waterlines between 1950 and 2003 at the Martha Point Spit. The deep basin to the east of the spit is indicated by the arrow. The location of Line 9 is indicated (purple dot).

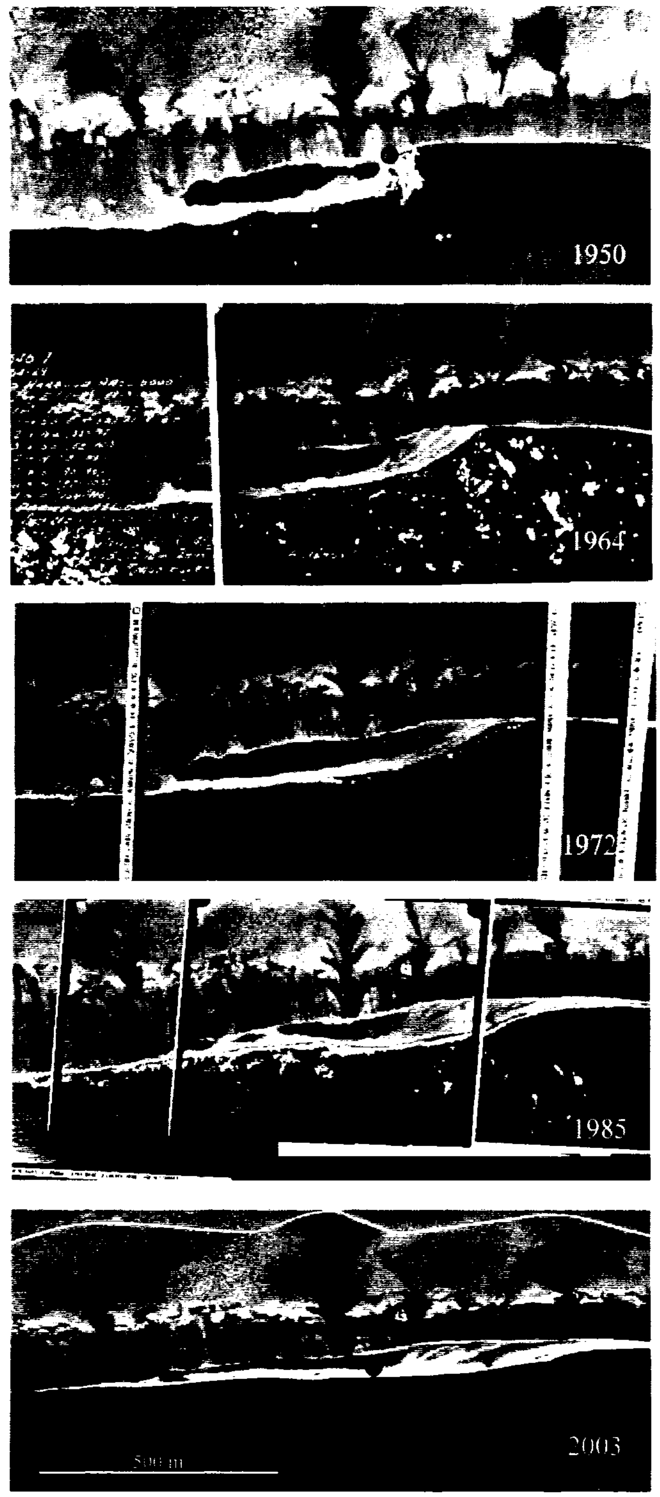


Figure 6.15: Time series of aerial photographs of Martha Point Spit from 1950 to 2003. The scale is the same for the entire series (base image modified from imagery © Digital Globe). Note the elongation and migration of the spit, with the orange dot in the same location in each photo.

6.1.6 – Sachs Landing Beach

Comparison of successive aerial photographs also indicates progradation and eastward migration of the Sachs Landing Beach (Figure 6.16; Figure 6.17). The 1950 air photos indicate that the Sachs Landing Beach was smaller and further west than present, with the waterline approximately 35 m further inland, and the tip of the beach approximately 85 m further west (between Lines 3-6) (Figure 6.17). Progradation on the western side is visible in aerial photographs and little change on the eastern side. The Sachs Landing beach tip has prograded 36 m between 1950-2003, or 0.7 m/a with varying rates of progradation between surveys with an increase in area from 18,100 m^2 in 1950 to 40,790 m^2 in 2003 or 428.1 m^2/a (Figure 6.17). The Sachs Landing Beach has migrated towards the east over the 53 year period with varying rates of migration between surveys (Figure 6.16; Figure 6.17). Between 1950 and 1972 migration rates were less than 0.1 m/a, increasing to 3.7 m/a between 1972-1979, during a period of increased open-water storms, a rate of 2.9 m/a, from 1979-1985 and a rate of 3.3 m/a between 1985 and 2003 (Figure 6.16). Variations in rate of migration of the Sachs Landing Beach between aerial surveys may be related to anthropogenic activity along the beach, including mass movement of sediment to create a dock for the annual barge.

Sachs Landing Beach will continue to migrate eastwards over time with progradation occurring on the western side of the beach as longshore transport moves sediment from the west eastwards. The nearshore bathymetry surrounding Sachs Landing Beach is shallow and will not likely constrain migration, except for the nearshore channel about 100 m offshore. Anthropogenic activity on the beach, such as recreational activity and boat launching, will affect sediment transport over time. Large amounts of sediment are moved each year to build a dock to facilitate unloading of the barge. This movement of sediment has influenced the rates of sediment transport. This is the likely cause of accelerated progradation and migration of the beach. If more sediment is fed into transport by anthropogenic activity, including future dredging, accumulation on beaches in the eastern side of the community will result. Any future development within the community must take into consideration directions of sediment transport and areas of localized retreat.

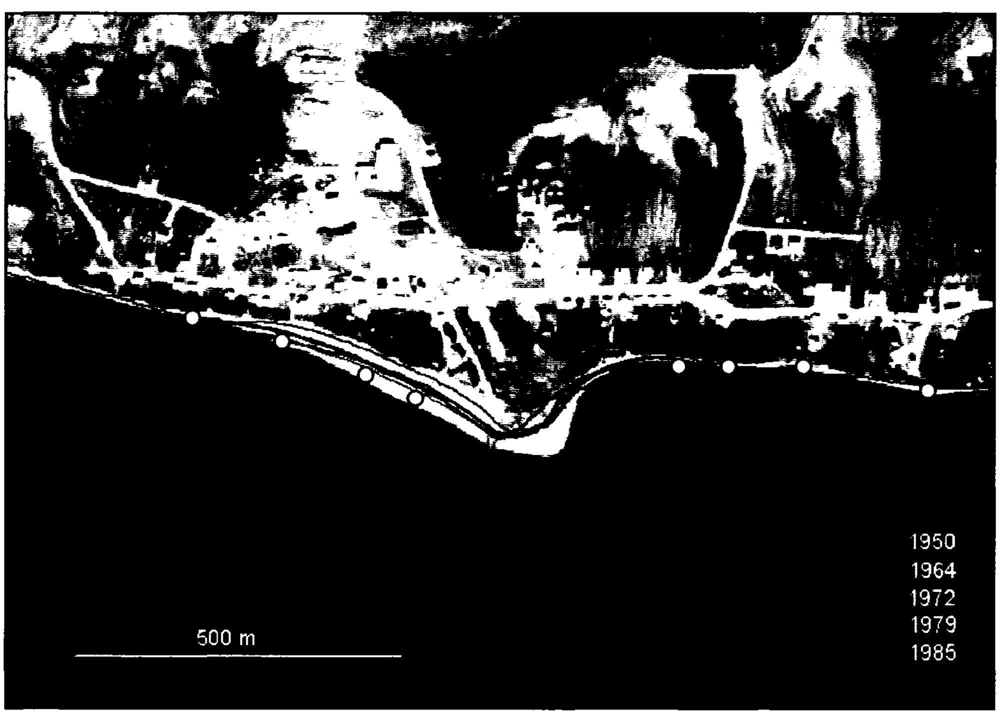


Figure 6.16: Comparison of waterline locations at the Sachs Landing Beach from 1950 to 2003 on a 2003 satellite image with locations of coastal surveys indicated (Surveys start from left to right, with Line 1 on the furthest right) (Modified from material © Digital Globe).

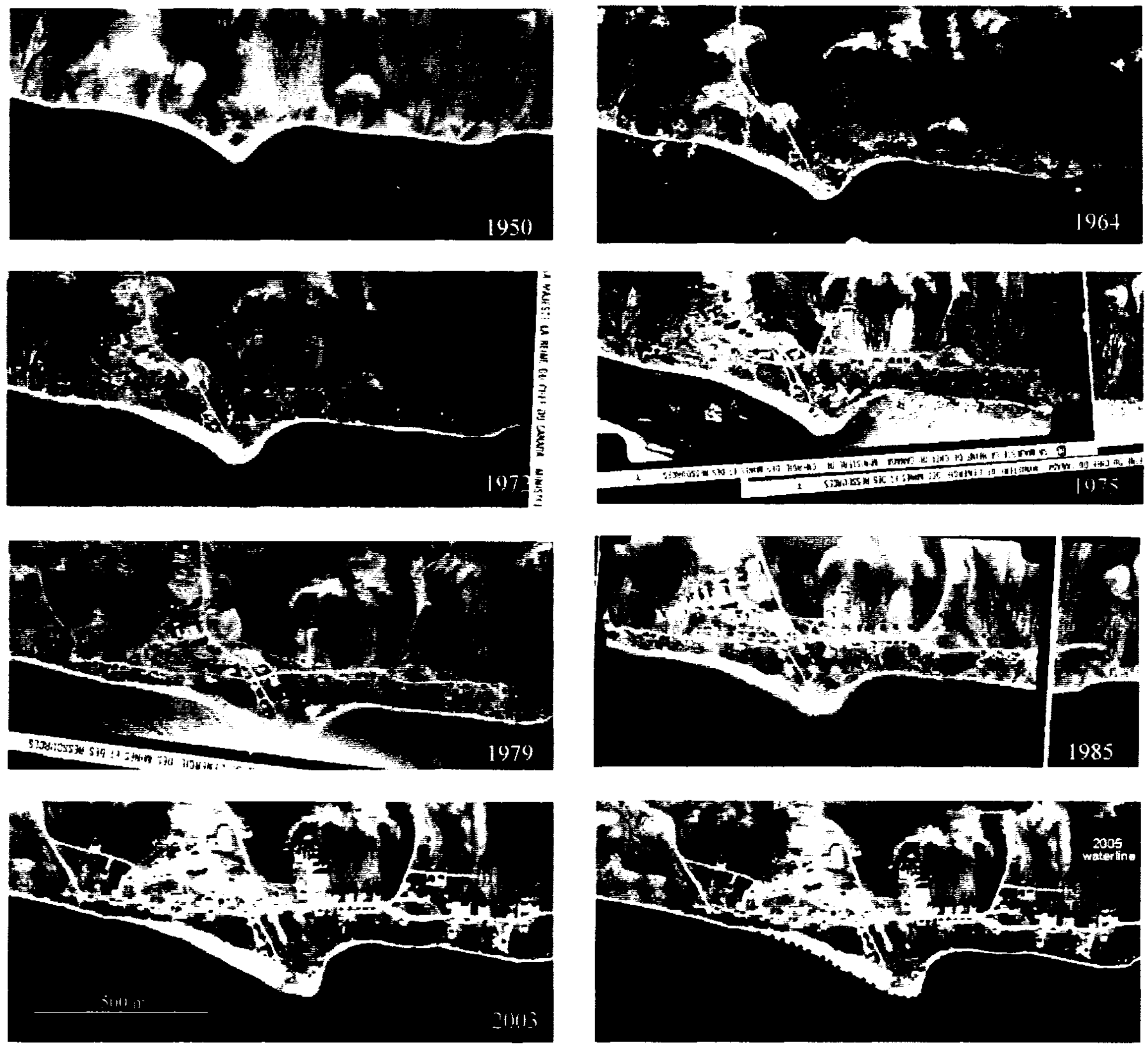


Figure 6.17: Time series of aerial photographs of the Sachs Harbour Beach between 1950 and 2003. The bottom right figure indicates the position of the waterline in 2005. All time series utilize the same scale (Bottom two figures modified from materials © Digital Globe).

6.1.7 - Sachs Harbour Line 2

The eastern side of Sachs Beach near Sachs Harbour Line 2 has shown approximately 27 m of retreat between 1950 and 2003, 0.5 m/a, and appears to be consistent throughout the period. Sediment transport removes material from the western edge of the beach and transports it towards the east. Sediment transport was also visible in the coastal surveys between 2003 and 2005, at 0.4 m/a (Figure 6.19). Retreat of the cliff edge was not accompanied by beach progradation indicating a removal of sediment from the coastal zone. The coastal bluff at Sachs Harbour Line 2 is unvegetated, steeply sloping and retreat has been evident since 2003 from surveying, with retreat rates of 0.4 m/a, corresponding to about 150 m^3/a sediment volume from this exposed cliff approximately 125 m long being added to the coastline, and subsequently removed into the nearshore (Figure 6.18; Figure 6.29).

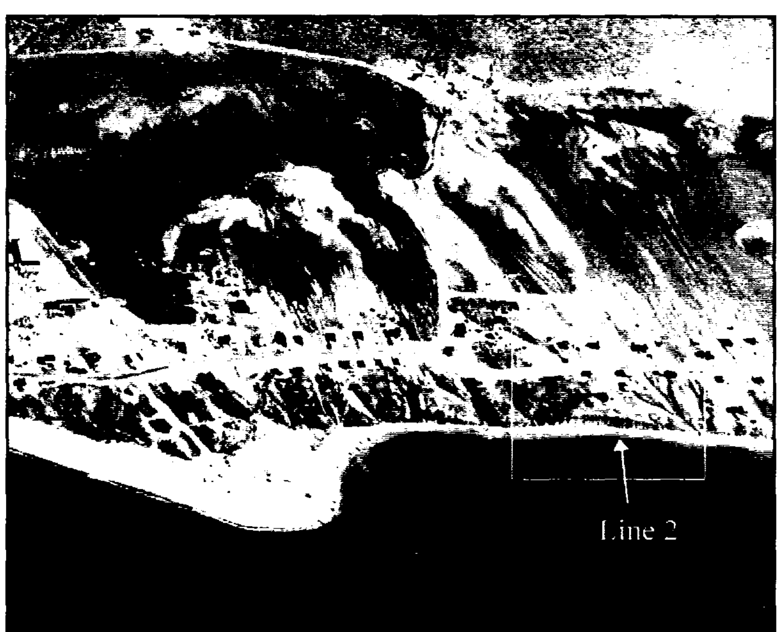


Figure 6.18: Location of Sachs Harbour Line 2 showing the narrow beach and retreating coastal bluff on the eastern side of the Sachs Landing Beach which has lost 150 m^3/a of sediment in recent years.

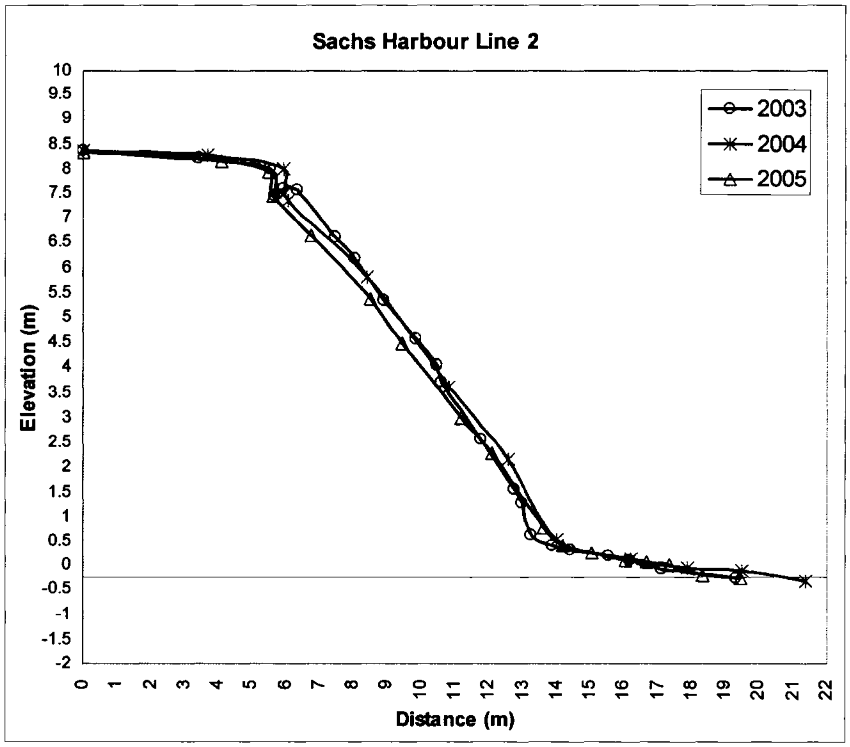


Figure 6.19: Sachs Harbour Line 2 coastal survey indicating retreat of 0.8 m between 2003 and 2005, 0.4 m/a.

6.1.8 – Spit East of Sachs Harbour

Approximately 1 km east of Sachs Harbour near the Sachs River is an approximately 47 000 m^2 cuspate spit (Figure 6.20). The spit is relatively symmetrical on its eastern and western sides, indicating that sediment supply from both the east and west has contributed to its formation and growth. Although the Sachs River supplies sediment to spit growth, aerial photographs indicate an overall migration towards the east, suggesting that longshore transport dominates over river sediment supply. Wave action does not likely effects the spit as the area is protected by the Sachs Spit to the south. This spit has not shown significant progradation between 1950 and 2005.

Figure 6.20: Cuspate spit east of the community of Sachs Harbour near the mouth of the Sachs River (indicated by the yellow arrow). UTM Coordinates: 422541 E, 7989251 N. Photo taken July 18, 2005.

6.2 – Cliff Retreat and Thermal Erosion

Coastal surveys completed from 2002 – 2005 indicate that although cliff retreat occurs in several locations in the study area, it is dominated by thermal erosion and slumping (Figure 6.21; Figure 6.22). Unlithified sediments with high ground ice concentrations between 40 and 90% (French 1976a) and overall warming temperatures in the region cause increased melting and instability in coastal bluffs (Comiso 2003). Coastal retreat occurs in areas with fine grained substrate and exposures of ground ice. These areas indicating cliff retreat show limited retreat at the shoreline over time or a decrease in beach width indicating that although bluffs are retreating, there is no net removal of material from the coastline except during open-water events. Studies of aerial photographs show evidence of significant erosion of waterline locations such as the Sachs Lowlands, where beaches are less than 3 m in width, the area west of Martha Point where ground ice is exposed in coastal cliffs along the waterline, and on the eastern side of the Sachs Landing Beach at Line 2.

Sachs Harbour Lines 2, 4, 10, and 12 show cliff edge retreat associated with thermal erosion as indicated by slumping block retreat, retrogressive thaw flow at Line 12 and exposed ground ice. Several newly surveyed locations appeared to be actively retreating such as, Sachs Harbour Line 0, the Beacon Line, GI Line, both Duck Hawk bluff Lines and Sachs Spit Line 1 (Figure 6.23). These locations are areas with either exposed ground ice, slumping due to thermal melting, retrogressive thaw, and/or areas heavily utilized by the community. Areas within the study area not considered to be susceptible to cliff edge retreat are those with no large ground ice lenses and where the bluffs had lower proportions of fine grained sediment. These slopes are commonly vegetated with wide flanking beaches, such as Lines 3, 5, 9, and Wide Beach Lines 1 and 2. These areas do not show evidence of rapid thermal or mechanical erosion (Figure 6.23; Figure 6.24).

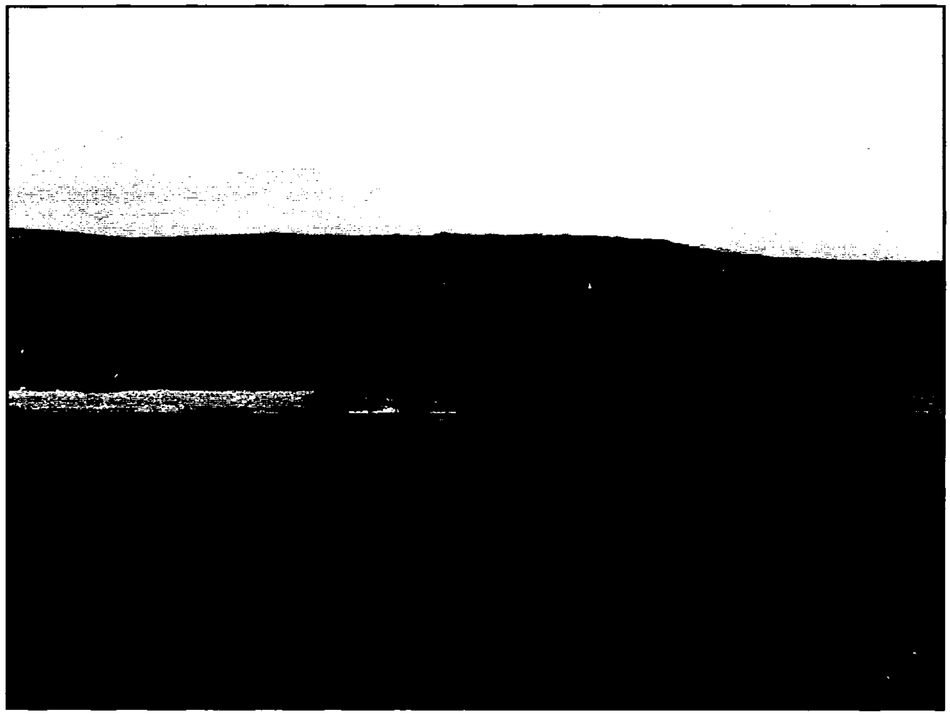


Figure 6.21: New slump and retrogressive failure between Lines 10 -11, which occurred in late July 2005. UTM coordinates: 415616 E, 7988381 N. Photo taken August 1, 2005.

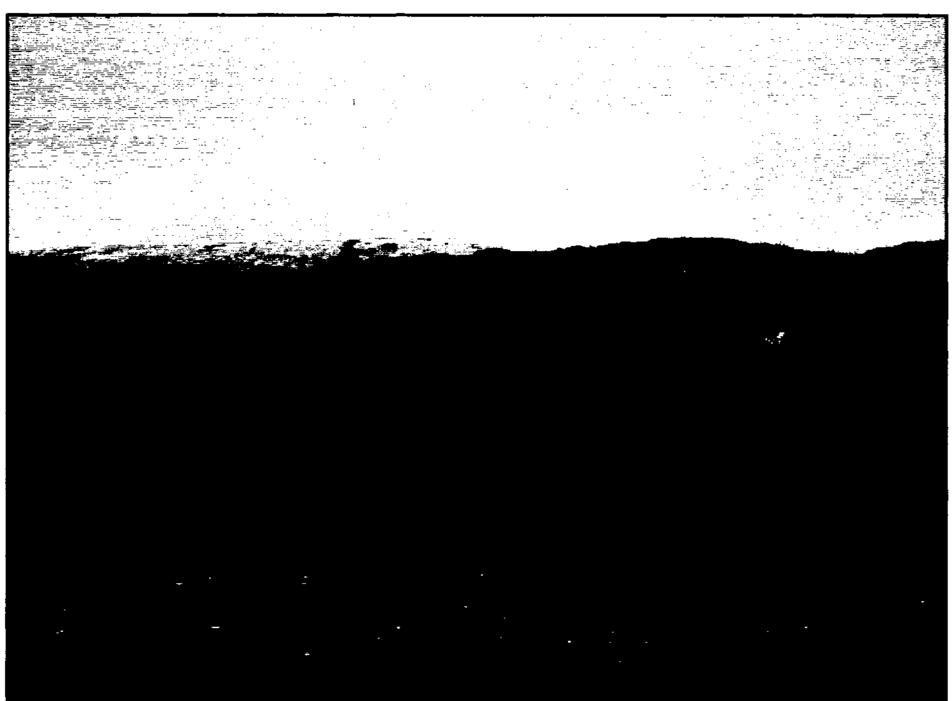


Figure 6.22 Block slumping near Sachs Harbour Line 11. UTM coordinates: 413011 E, 7988279 N. Photo taken August 1, 2005.

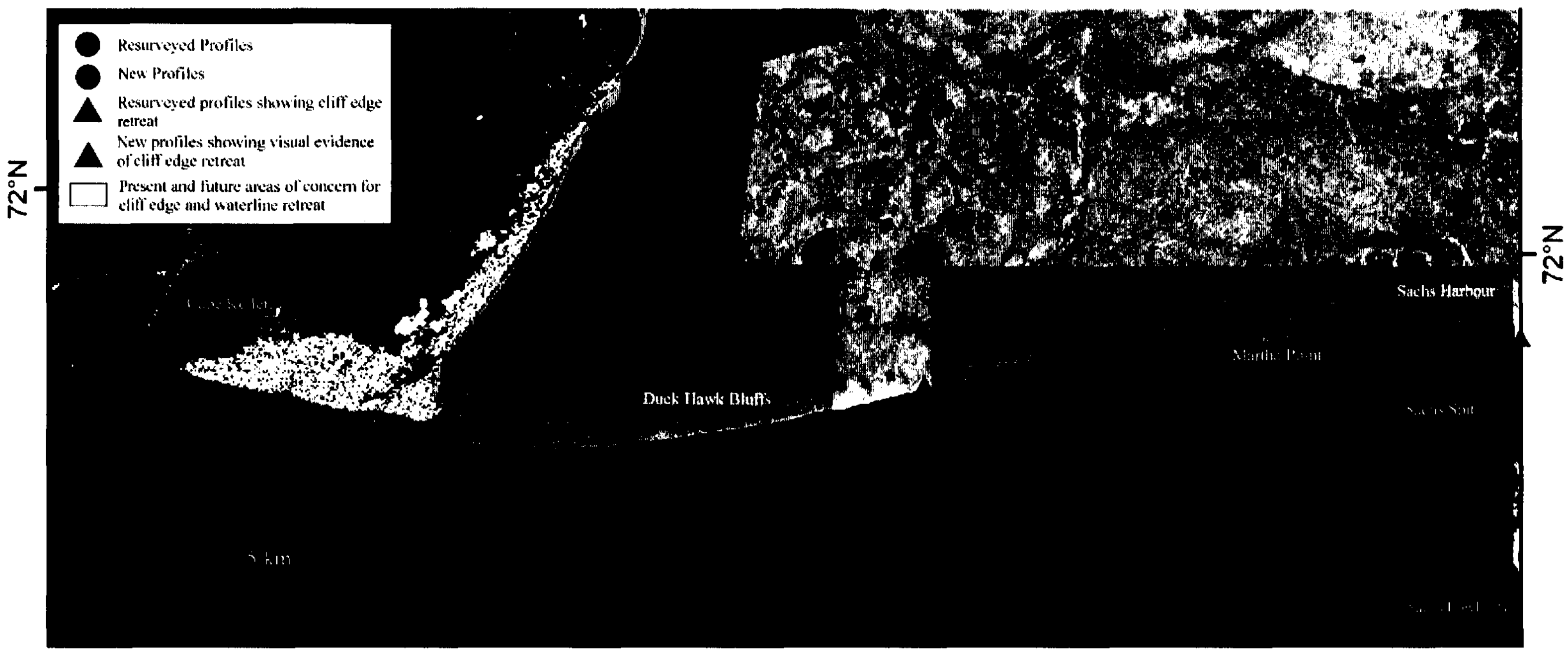


Figure 6.23: Location of all coastal surveys completed along the Southwest coast of Banks Island including new and resurveyed locations and locations which indicated cliff edge retreat. Areas of present and future concern for cliff edge retreat, waterline retreat, and sensitivity to sea-level rise are indicated

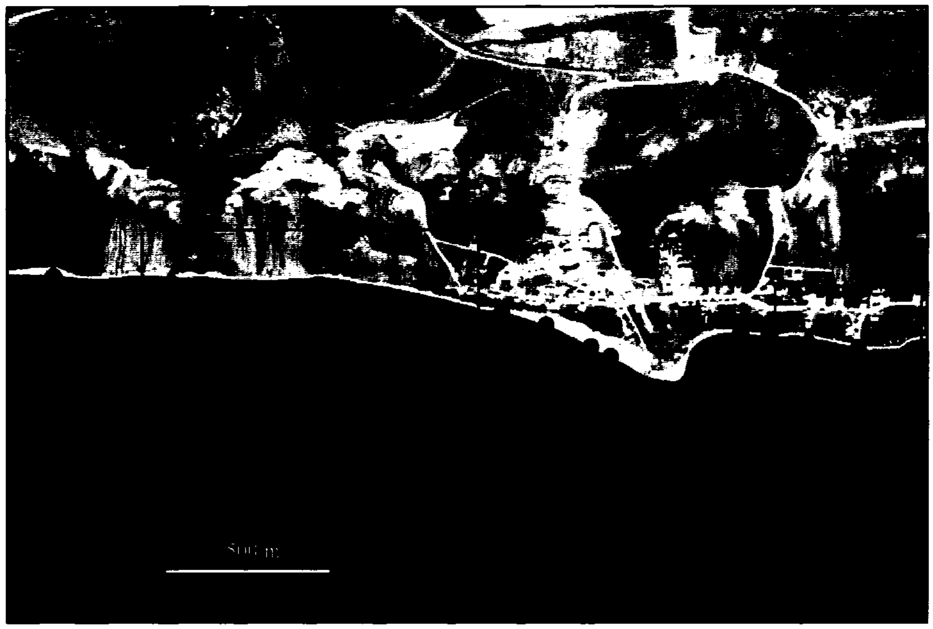


Figure 6.24: Magnified view of the community of Sachs Harbour and resurveyed coastal surveys (Line 1 is on the far right of the diagram). The purple boxes indicate areas of current and future concern for cliff edge retreat (modified from imagery © Digital Globe).

6.3 – Long-Term Impacts of Storm Events

The southwest coastline of Banks Island is a low wave energy environment with little wave interaction with coastal cliffs except during periods of high waves and water levels associated with storm events. Although storm events occur in the region, only the strongest storms appear to have the ability to remove sediment directly from the cliff slope or cause slope instability. Smaller wind/rain events increase surface runoff, thereby increasing thermal erosion. However, significant mechanical erosion by wave action does not occur. Larger storm events occurring with the greatest frequency from August and October with winds out of the south and southeast over Amundsen Gulf or Beaufort Sea can impact the coastline if there is significant open-water during the event. Drifting sea ice in the Amundsen Gulf often limits the open-water fetch, suppressing the generation of waves decreasing the effectiveness of these events.

Within the study area, coastal bluffs to the west of Martha Point are susceptible to thermal erosion and have shown retreat through successive surveys. Melting of segregated ground ice lenses or exposures of massive ice causes material to slump and flow into the shore zone in areas where beach widths are less than 10 m and slope is less than 7° (Figure 6.25; Figure 6.26). These cliffs are directly open to the Amundsen Gulf and highly susceptible to mechanical erosion (wave action eroding and removing slumped material) and thermal (relatively warm ocean water interacting with frozen sediment) erosion during storm events. Aerial photographs show an overall retreat of the waterline in this area since 1950, indicating removal of sediment from past storm events and movement of material into the nearshore.

Figure 6.25: Ground ice actively melting along the southwest coastline near Martha Point. UTM coordinates: 415128 E, 7988482 N. Photo taken July 24, 2005.

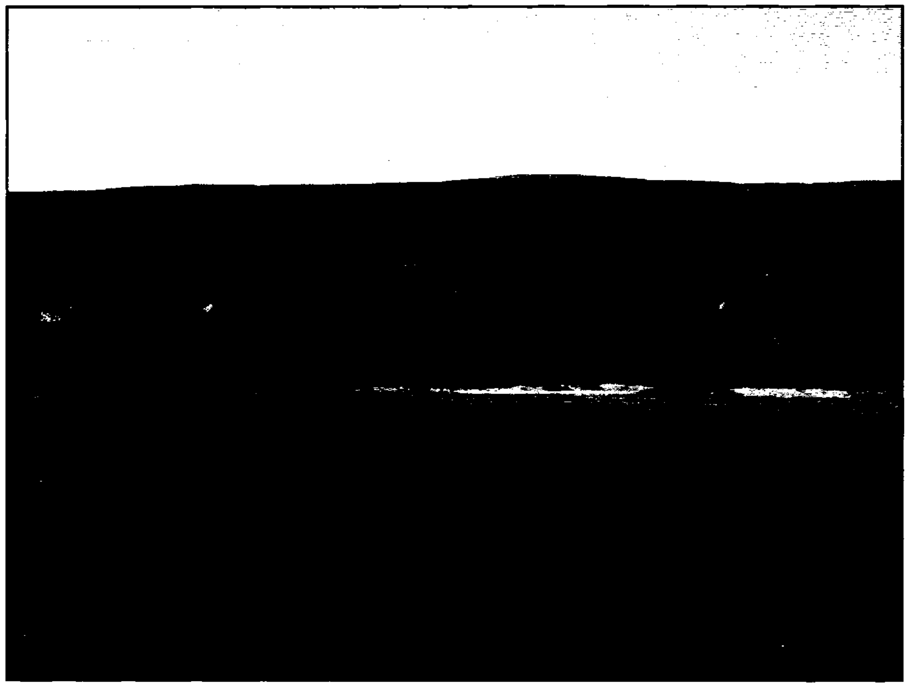


Figure 6.26: Exposed ground ice in coastal cliffs near Sachs Harbour Line 10. UTM Coordinates: 416692 E, 7988457 N. Photo taken July 24, 2005.

Warming temperatures regionally will lead to continued erosion, as high concentrations of ground ice will be susceptible to thermal erosion (Comiso 2003; Manson *et al.* 2005b). Coastal erosion will only result, however, if waves remove sediments from the shore zone and will be dependent on open-water events. The low wave energy regime in the region is not sufficient to mechanically erode the coastal bluffs. Material in the shore zone is only removed by waves in areas such as the Sachs Lowlands where beach widths are less than 3 m.

Chapter 7 – Conclusions

7.1 – Summary of Results

The southwest coastline of Banks Island near the community of Sachs Harbour is dominated by low-lying coastal bluffs and large depositional features in a low-energy microtidal coastal environment. Coastal cliff top and shoreline retreat within the area, determined through coastal surveys and aerial photographs is dominated by thermal retreat, with subsequent removal of material from the shoreline by sediment transport or storms. Areas along the coastline with high ground ice contents and fine-grained substrates are more susceptible to retreat, including areas to the west of the Martha Point Spit, the eastern side of Sachs Harbour and the Sachs Lowlands to the southeast. Four major depositional areas occur along the coastline where sediment transport has maintained wider beaches and large spits. In these areas, cliff sediment is sandier with lower ice content and less susceptible to thermal erosion. Longshore transport is an important mechanism within the system for movement of sediment, with migration of depositional features occurring in the order of metres annually.

During the open-water season wind directions vary with dominant wind directions from the NNW, the SSE and ESE, with winds from the SSE and ESE originating from offshore. Storm winds occur most frequently in this region in September and October. With a substrate of ground ice-rich unlithified sediments, storm events can be effective at eroding coastal bluffs and beaches and removing this material into the nearshore. Sea ice, often present in Amundsen Gulf, limits the impact of these storm events. Past sea ice has been variable: breakup has occurred early in the season in some years, although in other years the harbour was ice covered throughout the entire open-water season, even though the Amundsen Gulf was ice free (K. Parewick, personal communication, based on community interviews 2006). Smaller storm and precipitation events in the area increase the runoff along coastal slopes and thermal erosion. However, material which slumps into the shore zone is commonly not removed for some time, until a storm raises water level and generates waves to rework the slumped sediment. Sediment plumes which are visible in the nearshore after precipitation events are due primarily to surface runoff from the slopes, rather than originating from sediment eroded from the cliff base. Storm events with open-water fetch with wind directions blowing onshore (ESE through SSW) have the ability to erode the coastline in the exposed areas west of Martha Point and the Sachs Lowlands. At these locations, thermal retreat has slumped material into the shoreline, and where beaches are less than 10 m in width and material is removed by waves.

7.2 – Coastal Processes

Past studies of coastal processes of the southwest coast of Banks Island indicated a coastline of poorly consolidated and ice-rich permafrost sediments with cliff heights ranging from 6-8 m, and cliff morphology related to lithology (Harry *et al.* 1983). Coastal erosion noted by previous study occurred in the area southeast of Sachs Harbour and that directly west of the Martha Point Spit. Two mechanisms were considered to dominate: summer thaw releasing ice bonded sediments and removal of sediment from the coastline during late-season storm events (Harry *et al.* 1983). Using results and background data of the Harry *et al.* (1983) study, combined with satellite images and fieldwork, a comprehensive analysis of sediment transport, depositional features and erosional areas was conducted. Discussion of depositional environments and long-term sediment transport on the southwest coast focused on the Sachs Spit region and the Martha Point (Allen Creek) Spit, their development, and sediment supply for these depositional features (Harry *et al.* 1983).

This current discussion of coastal retreat areas and mechanisms are similar to the results of the previous study, with erosion west of Martha Point and to the southeast of the community, and with thermal retreat as a mechanism of cliff retreat. In contrast to the 1983 study, loss of sediment from the coastline during storm events was not observed. However, in the late 1970s and early 1980s the frequency of open-water events was greater than present.

Inferred expansion and migration rates of the Martha Point Spit in the 1983 study are consistent with aerial photographs and satellite images, showing progradation of approximately 400 m from 1950-1979, consistent with a total growth of approximately 800 m from 1950-2003.

The development of the Sachs Spit from erosion to the southeast is consistent with satellite images and aerial surveys. However, the mechanisms and future growth of this spit did not take local bathymetry into consideration. Recent satellite imagery of the Sachs Spit shows that spit growth is controlled and constrained by two deep drowned thermokarst lake basins within the community harbour. The growth and development of this spit has been along the shallow sill separating the two basins, and migration of the spit has been along this sill.

Inferred sediment transport in the region in earlier studies suggested a bifurcation in sediment transport near the eastern side of Martha Point Spit. This suggestion, however, does not provide an adequate explanation of sediment supply for the spit. The current investigations indicate that the Martha Point Spit is thought to be supplied by eroding coastal cliffs to the west, where a transport cell moves sediment eastward. The main transport cell moves sediment from the southeast of Sachs Harbour to the Cape Kellett Spit, as suggested by the 1983 study.

7.3 – Sensitivity to Sea-Level Rise

The assessment by Shaw *et al.* (1998) indicated that the southwest coastline of Banks Island was highly sensitive to sea-level rise based on seven criteria: relief, geology, coastal landforms, sea-level tendency, shoreline displacement, tidal range, and wave height. This assessment was based on a blanket assessment of the 1:50,000 topographic map of the region. Assessment of coastal geomorphology in 2005 has shown that within the southwest coastline of Banks Island, some areas have higher sensitivities than others, based on shoreline displacement, relief, wave height and geology. Most of the length of this coastline is moderately sensitive to sea-level rise, due to the unlithified nature of the substrate and rates of current sea-level rise in the region. Based on recent surveying and longer-term changes, the southwest coast should be divided into the following distinctive areas: Cape Kellett, the Duck Hawk Bluffs, bluffs west of the

Martha Point Spit, the Martha Point Spit, the western and eastern sides of Sachs Harbour, and the Sachs Spit with associated lowlands to the southeast of the community.

Although the Cape Kellett Spit is directly exposed to sea ice and storm events from the Amundsen Gulf and Beaufort Sea, it is only moderately sensitive to sea-level rise. It is composed of coarse grained material, mainly cobbles, and has shown some progradation along the recurved tip. The Duck Hawk Bluffs are also moderately sensitive to sea-level rise due to higher elevations (nearly 20 m in height) and the coarser grained substrate of the Beaufort Formation with lower ground ice concentrations (less susceptible to thermal erosion). This area also has wider beaches which have not shown long-term erosion through aerial photograph studies.

In areas to the west of Martha Point, high concentrations of ground ice within the sediments and retreat rates of approximately 3 m/a (with coastal bluff elevation less than 10 m in elevation) in an area directly open to wave attack suggest that this location is highly sensitive to change (based on Shaw *et al.* 1998 criteria). Long-term studies have indicated that melting of ground ice and subsequent slumping has been ongoing and has led to approximately to 80 m of retreat since 1950.

Other areas along the southwest coastline with depositional features that do not show evidence of retreat or high ground ice contents and are not directly open to wave attack are moderately sensitive. This includes the area directly west of the community (near Wide Beach Lines 1 and 2) as well as Martha Point Spit. These areas have shown deposition and widening of beaches through the long term.

The western and eastern slopes of the community have both shown gullying and thermal erosion. However, with the exception of one location, the coastal bluffs have not evidence of short or long term retreat. As the community slopes are fronted by Sachs Landing Beach and have shown little evidence of retreat, the community is assessed as moderately sensitive to sea-level rise.

Southeast of Sachs Harbour, the Sachs Lowlands are highly susceptible to sea-level rise based on present shoreline displacement of approximately 1.5 m/a, high ground-ice contents in fine grained material, and narrow beaches (<3 m) directly exposed to wave action and sea ice. With these retreat rates in fine grained ice-rich sediments and exposure to wave action, this region should be classified as highly sensitive to sea-level rise. The Sachs Spit itself is composed of fine sands and is exposed to storm events from the southeast and south-southeast, increasing its sensitivity to sea-level rise.

Although the overall region is considered highly sensitive to sea-level rise, specific areas along the coastline are more sensitive mainly based on the proportion of ground ice present within the substrate and the fine grained nature of the sediments. As thermal erosion plays a major role in coastal retreat within the region, ground ice concentrations within the unlithified sediments should be given greater consideration when assessing sensitivity to sea-level rise. Areas with coarser grained substrates that are not showing current retreat, depositional areas, and the bluffs in the community of Sachs Harbour are moderately sensitive to sea-level rise, while areas of sandier substrates with high ground ice concentrations which are currently retreating are highly sensitive to sea-level rise.

7.4 – Implications of Climate Change for the Southwest Coast of Banks Island

Thermal erosion and storm events are not a major concern for infrastructure in the community at present. However rising sea level, decreased sea ice and the increased effectiveness of storm events (Johannessen *et al.* 2004) may lead to increased thermal and mechanical erosion along coastal bluffs and increased runoff along slopes within the community.

With increased storm frequency in the past, particularly during the late 1970s, aerial photograph analysis and previous studies indicated an increase in deposition at Martha Point Spit and an increase in shoreline retreat rates west of the spit, with undercutting and slumping of bluffs from storm events (Harry *et al.* 1983). This area is susceptible to attack from storm events because it is open to the Amundsen Gulf and deepens in the offshore. As storm frequency in the region varies throughout the record, an increase in storm events in the future with diminished sea ice in the Amundsen Gulf may increase the effectiveness of storms to impact the coastline. This will lead to undercutting of bluffs, block failure and increased runoff, leading to suspension and loss of sediment to the nearshore. Rates of coastal retreat may increase to rates similar to those along the mainland Beaufort Sea coast during storm events with warming temperatures, decreased sea ice during the open-water season, and increased storm events.

As thermal erosion is the current dominant mechanism of coastal erosion along this coastline, high concentrations of ground ice in the unlithified sediments will continue to increase erosion in coastal bluffs. Warming temperatures throughout the region will lead to increased active layer thickness and melting of massive ice and ice lenses, increasing erosion throughout the study area. Specifically in the community of Sachs Harbour, thermal erosion has been an issue on the eastern and western edges of the community where gullying along the slopes makes these areas poor locations for community expansion. Increased precipitation in the region will assist in increasing thermal processes along the coastline. The precipitation record (1956 – present) has shown an increase in precipitation, with most of the precipitation occurring in the summer and fall. Erosion at culverts and improper drainage are considered hazardous for community members (K. Parewick 2006, personal communication) and will continue to pose a problem for infrastructure with warming temperatures and increased precipitation.

7.5 –Concerns in the Community of Sachs Harbour

Land claims, location and community limits in Sachs Harbour has led to concerns for adequate space for new housing development. The hillside location of the community makes planning for housing and industry locations difficult, as the current land claim agreement limits contain infrastructure (K. Parewick 2006, personal communication). Future expansion of the community is constrained to changes in land claims and other political issues.

Several dwellings within the community were abandoned and scheduled for destruction due to the age of the dwellings and their proximity to the shore, as there has been concern within the community of the hazards of retreating bluffs. A dwelling owned by Parks Canada is threatened, as the house edge sits approximately 5.5 m from the cliff edge in an area that has shown 0.3 m of retreat since 2003 (Sachs Harbour Line 2). Associated with this cliff edge are deep tension cracks up to 1 m above the cliff edge. This rate of retreat indicates that the house will likely have to be relocated or abandoned and demolished. Other coastal cliffs within the community, with the exception of that crossed by Sachs Harbour Line 2, have not shown retreat over successive coastal surveys, but the time base of the ground surveys is no more than four years.

The eastern slopes within community boundaries show evidence of gullying and potential for retreat in the future, and are therefore not recommended as a suggested potential area for community expansion. Similarly, at the western edge of the community, gullying within the slopes is evident through aerial photography, indicating that thermal retreat is ongoing, and this is also unsuitable for community expansion. Slides and thermokarst failures have occurred in the community in the past in the western slopes, and evidence of a large failure is still visible in an area directly adjacent to the school. Gullying and slope movement along roads and culverts within Sachs Harbour are potential hazards within the community. Improper maintenance of culverts by inexperienced workers within the community also results in poor drainage, leading to erosion along all culverts.

The community location, with the Sachs River directly east and the Sachs Spit to the south, is protected from wave action during storm events. Mechanical erosion from wave action during events does not pose a great risk to infrastructure within the community as it is not directly adjacent to the coastal zone. The coastal cliffs within the slopes of the community are composed of interbedded silty sand, fine sand, and gravel with up to 25% excess ice and thin lenses and icy layers with excess ice from 40 to 95% (French 1976a). Coastal retreat within the community is due to thermal erosion combined with longshore transport of material towards the east removing slumped material from the waterline. As the community is fronted by a large beach, the coastal bluffs within the community have not shown active retreat between 2002 and 2005 with the exception of Sachs Harbour Line 2. Retreat along this survey line is also accelerated by children playing along the unvegetated slope, causing sediment to slump and fall into the coastal zone.

A shallow sill separates two deep basins in the nearshore to the southeast of the community. Although most marine transport is limited to small boats, annual barge shipments are difficult due to the shallow nature of the nearshore. With complex sediment transport eastwards and the growth of the Sachs Spit towards the southeast, infilling of this shallow sill (less than 4 m) may lead to problems for the docking of the barge (currently this takes several hours, and the barge must follow a specific path to enter and dock the community beach). Dredging and a permanent dock have been considered to allow easier access of boats to the community (K. Parewick 2006, personal communication). However, disruption of the complex sediment transport pattern along the Sachs Landing Beach is ill advised.

7.6 - Future Work and Other Studies

The 2005 coastal surveys, both new and resurveyed locations, should be resurveyed on an annual basis. Particularly, areas that have shown cliff edge retreat in past surveys and new survey locations should be closely monitored. Although open-water storms have not impacted the community since 2002, any future events should be monitored and the impacts photographed along the coastline and within the community. As these events often occur in August and October, photographs and written observations by community members would be instrumental in determining the impacts of these events. Continued analysis of storm data in the region and comparison of the frequency of storms to larger scale atmospheric mechanisms is necessary. With changing climatic conditions in the region it is important to understand past and present variables associated with storm events, as decreasing sea-ice extents in the area may increase the effectiveness of open-water events.

Increased sedimentation into the nearshore from thermal erosion and surface runoff associated with storm events also has negative consequences on benthic communities (Brown *et al.* 2005). The most diverse benthic communities along the southwest coastline of Banks Island are associated with the large deep basins of the harbour (Brown *et al.* 2005). With increased runoff during storm and rain events (as indicated by a wind/rain event in August 2005) and high rates of sediment transport, these lake basins are highly susceptible to future change. Infilling of these lake basins with migration of the Martha Point and Sachs Spit may impact benthic communities and subsequently other predator species. A project within the study area focuses on determining benthic communities in the study area and the impacts of erosion and sedimentation into the nearshore and how sedimentation causes changes in grain size distribution, nutrient availability and organic content within benthic habitats (Brown *et al.* 2005). These benthic habitats are necessary for predator species consumed by community members within the community of Sachs Harbour.

A community based planning process is being undertaken in the community of Sachs Harbour to enhance development of adaptive strategies and community resilience. This study combines the current bio-physical studies of the region to form recommendations of potential physical hazards in the community and areas of potential community expansion (Parewick *et al.* 2005). Community based planning in Sachs Harbour will attempt to decrease the negative social and economic impacts of climate change while building a foundation of participatory action, traditional knowledge and the adaptive capacity of residents in Sachs Harbour and other northern coastal communities (Parewick *et al.* 2005).

7.7 – Recommendations

Although there is concern within the community of coastal retreat and changing climate conditions within the community of Sachs Harbour, the community is much less sensitive to coastal retreat than mainland Beaufort Sea Coast communities, such as Tuktoyaktuk. The Sachs Spit to the south, the slope location of the community, and the large beach fronting the community leave it protected from open-water events. Currently there is only one location that is experiencing retreat, and other coastal infrastructure located near the coastline is scheduled for demolition. Although coastal retreat is an issue for future community planning, it is of much lesser magnitude to other coastal communities (retreat rates of less than 1 m/a in only one location) and does not pose a serious threat for community relocation, as is the case in Tuktoyaktuk, where the modal retreat rate is 0.6 m/a and retreat rates as high as 22.5 m during storm events.

While no retreat is evident in coastal bluffs within the community of Sachs Harbour, except at one location, coastal erosion is an issue within the community. Housing and other community infrastructure should not be placed in coastal sites that show gullying or near the edge of coastal cliffs. The eastern side of the community specifically appears more susceptible to erosion with transport of material towards the east removing material from the coastal zone. Infrastructure which is currently near a cliff edge, such as the Parks Canada house (Sachs Harbour Line 2) should be relocated to avoid loss in future years. Coastal cliffs within the community are often sparsely vegetated, and use of these slopes by the community should be minimized to avoid accelerating retreat. Dredging of the community harbour should be avoided as this would introduce sediment into transport and increase the rate of progradation of the Sachs Landing Beach.

Specific recommendations for the community of Sachs Harbour are:

1. No community expansion along the coastal cliffs in the community boundaries, especially in the eastern slopes,
2. Removal or relocation of infrastructure in proximity to cliff edges, particularly the Parks Canada House,

3. Resurveying of coastal cliffs that have shown retreat in the past, such as the cliffs to the west of Martha Point, southeast of the Sachs Spit, and the eastern slopes of the community,
4. No dredging of the community harbour, as sediment transport is complex and dredging will likely re-suspend sediment in the transport cell,
5. No armouring structures to be placed along the coastline as these will disrupt sediment transport, and
6. No community infrastructure to be placed on or in proximity to the Sachs Landing Beach.

References

Aiken, S.G., Dallwitz, M.J., Consaul, L.L., McJannet, C.L., Gillespie L.J., Boles, R.L., Argus, G.W., Gillett, J.M., Scott, P.J., Hansen, K.T. and Elven, R. 1999 onwards. Flora of the Canadian Arctic Archipelago: descriptions, illustrations, identification and information retrieval. Accessed August 14, 2006. URL: http://www.mun.ca/biology/delta/arcticf/

Anderson, John R. 2004. Laboratory 6: Sand Sieve Analysis. Department of Geology, Georgia Perimeter College. Dunwoody, GA. (Accessed September 20, 2005). URL: http://gpc.edu/~janderso/historic/labman/sievean.htm

Andrews, J.T., Peltier, W.R. 1989. Quaternary Geodynamics in Canada. In: Fulton, R.J (Ed.), Quaternary Geology of Canada and Greenland: 543 – 572.

Arctic Climate Impacts Assessment. 2005a. Technical Report: Chapter 2, Arctic Climate, Past and Present. Lead Author: Gordon McBean. Cambridge University Press. pp 30-31; 36-39.

Arctic Climate Impacts Assessment. 2005b. Technical Report: Chapter 9, Marine Systems. Lead Author: Loeng, H. Cambridge University Press. pp 456-461.

Arctic Climate Impacts Assessment. 2005c. Technical Report: Chapter 6, Cryosphere and Hydrology. Lead Author: Walsh, J.E.. Cambridge University Press. pp 209-215.

Are, F.E. 1988. Thermal Abrasion of Sea Coasts (Part II). Polar Geography and Geology, 12 (2): 87-157.

Are, F.E., Grigoriev, M.N., Hubberten, H.W., Rachold, V. 2004. Using Thermoterrace Dimensions to Calculate the Coastal Erosion Rate. Geo-Marine Letters, 25, 2-3 121-126.

Ashford, G., and Castleden, J. 2001. Inuit Observations on Climate Change: Final Report. International Institute for Sustainable Development.

Atkinson, D.E. 2005. Observed Storminess Patterns and Trends in the Circum-Arctic Coastal Regime. Geo-Marine Letters 25: 98-109.

Aveco Infrastructure Consultants. July 1986. Tuktoyaktuk Shore Erosion Protection.

Ballard, K., and Pullen, S. 2004. The Tundra Biome. The Biomes Group. University of California Berkley, CA. Accessed September 26, 2005
URL: http://www.ucmp.berkeley.edu/glossary/gloss5/biome/tundra.html

Bailey, R.G. 1998. Ecoregions: The Ecosystem Geography of the Oceans and Continents. Spring-Verlag New York, Inc. New York, USA.

Barber, D.G., Hanesiak, J.H. 2004. Meteorological Forcing of Sea Ice Concentrations in the Southern Beaufort Sea Over the Period 1979 to 2000. Journal of Geophysical Research, 109.

Berkes, F. and Jolly, D. 2001. Adapting to Climate Change: Social-Ecological Resilience in a Canadian Western Arctic Community. Conservation Ecology 5(2): 18.

Bird, E.C.F. 1969. *Coasts.* An Introduction to Systematic Geomorphology Volume 4. The Massachusetts Institute of Technology.

Bouchard, M., Rampton, V.N. 1972. Environmental Geology Tuktoyaktuk, District of Mackenzie (107C). Geological Survey of Canada Paper 72-1A: 141-143.

Brown, R.J.E. 1960. The Distribution of Permafrost and Its Relation to Air Temperature in Canada and the USSR. Arctic, 13, 163-177.

Brown, R.J.E. 1967. Comparison of Permafrost Conditions in Canada and the USSR. Polar Record, 13, 741-741-751.

Brown, T., Edinger, E., Hooper, R. 2005. Marine Biological Survey of Rapidly Eroding Coastal Environments, Sachs Harbour, NWT. Proceedings from ArcticNet annual scientific meeting posters. Accessed July 2006.
URL: http://www.arcticnet-ulaval.ca/pdf/posters_2005/brown_et_al.pdf

Burn, C.R., Michel, F.A., and Smith, M.W. 1986. Stratigraphic, Isotopic and Mineralogical Evidence for an Early Holocene Thaw Unconformity at Mayo, Yukon Territory. Canadian Journal of Earth Sciences 23, 794-803.

Canadian Ice Service. 2002. Sea Ice Climate Atlas, Northern Canadian Waters 1971-2000. Department of Public Works and Government Services. Government of Canada.

Canadian Museum of Civilization. 2003. New Lands: Explorations of the Northern Party: The First Ice Drift, 1914. In Northern People Northern Knowledge: The Story of the Canadian Arctic Expedition 1913 – 1918. Canadian Museum of Civilization Corporation. Government of Canada. Accessed July, 2006. URL: http://www.civilization.ca/hist/cae/exp32e.html

Canadell, J., Jackson, R.B., Ehleringer, J.B., Mooney, H.A., Sala, O.E., Schulze, E-D. 1996. Maximum Rooting Depth of Vegetation Types at the Global Scale. Oecologia 108, 55-595.

Catto, N.R. and Quaternary Research Group. 1989. Geology 482: Field and Laboratory Manual, Appendix A: Textural Analysis of Sediments. Quaternary Research Group. University of Alberta, Edmonton, AB.

Cavalieri, D.J., P., Gloersen, C.L., Parkinson, J.C. Comiso and H.J. Zwally. 1997. Observed hemispheric asymmetry in global sea ice changes. Science, 278: 1104–1106.

Clark, M.J. 1988 ed. Advances in Periglacial Geomorphology. New York: John Wiley and Sons.

Church, J.A., White, N.J., Coleman, R., Lambeck, K., Mitrovica, J.X. 2004. Estimates of the Regional Distribution of Sea Level Rise over the 1950-2000 Period. Journal of Climate, 17 (13), 2609-2625.

Comiso, J., 2003. Warming Trends in the Arctic From Clear Sky Satellite Observations. Journal of Climate, 16, 3498–3510

Couture R, Robinson S, Burgess M, and Solomon S. 2002. Climate Change, Permafrost, and Community Infrastructure: A Compilation of Background Material From a Pilot Study of Tuktoyaktuk, Northwest Territories. Geological Survey of Canada Open File D3867, 89pp

Couture, R., S. Smith, S.D. Robinson, M.M. Burgess and S. Solomon. 2003. On the Hazards to Infrastructure in the Canadian North Associated With Thawing of Permafrost. Proceedings of Geohazards 2003, Third Canadian Conference on Geotechnique and Natural Hazards, 97–104. Canadian Geotechnical Society

Dallimore, S.R., Wolfe, S. 1988. Massive Ground Ice Associated with Glacio-Fluvial Sediments, Richards Island, N.W.T. In Proceedings, Fifth International Permafrost Conference, Trondheim, Norway, Vol 1, Trondheim: Tapir Publishers, 132-137.

Dallimore, S.R., Wolfe, S.A., Solomon, S.M. 1996. Influence of Ground Ice and Permafrost on Coastal Evolution, Richards Island, Beaufort Sea Coast, N.W.T. Canadian Journal of Earth Sciences. 33, 664-675.

De Krom, V. 1990. Retrogressive Thaw Slumps and Active Layer Slides on Herschel Island, Yukon. MSc Thesis, McGill University, Montreal, Quebec, 157.

Department of Fisheries and Oceans Canada. 2006. Tides, Currents and Water Levels: Sachs Harbour (Station # 6424). Government of Canada. Accessed April, 2006. URL: http://www.waterlevels.gc.ca/

Douglas, R.J.W. 1969. Geological Map of Canada. Geological Survey of Canada. Map 1250A, Scale 1:5,000,000.

Dyke, A.S. 1987. A Reinterpretation of Glacial and Marine Limits Around the Northwestern Laurentide Ice Sheet. Canadian Journal of Earth Sciences, 24, 591-601.

Emery, K.O. 1961. A Simple Method of Measuring Beach Surveys. Limnology and Oceanography, 6, 90-93

Environment Canada. 2004. Canadian Climate Normals 1971-2000: Sachs Harbour A, Northwest Territories. Government of Canada.

Environment Canada. 2006a. Hourly Data Report: Weather station: Sachs Harbour A, Northwest Territories. Government of Canada.

Environment Canada. 2006b. Weekly Regional Ice Chart – Western Arctic 1968 – 2005. Canadian Ice Service

Environment Canada. 2006c. Precipitation Data 1956-2005: Sachs Harbour A, Northwest Territories. Government of Canada.

ESRI. 2004. ArcGIS 9: Using ArcMap. ArcGIS by Environmental Systems Research Institute. Redlands, CA. USA.

Folk, R., Ward, W. 1957. Brazos River Bar: A Study in the Significance of Grain-Size Parameters. Journal of Sedimentary Petrology, 45, 651-668.

Folk, R. 1966. A Review of Grain Size Parameters. Sedimentology, 6, 73-93.

Forbes, D.L. 1980. Late-Quaternary Sea Levels in the Southern Beaufort Sea. Geological Survey of Canada, Current Research, Paper 80-1B, 75-87.

Forbes, D.L., Frobel, D. 1985. Coastal Erosion and Sedimentation in the Canadian Beaufort Sea. Geological Survey of Canada, Current Research Paper, 85 (1B), 69-80.

Forbes, D.L., Taylor, R.B. 1994. Ice in the Shore Zone and the Geomorphology of Cold Coasts. Progress in Physical Geography 18, 1, pp 59-89.

Forbes, D.L. 2000. Earth Science and Coastal Management: Natural Hazards and Climate Change in the Coastal Zone. Canadian Society of Exploratory Geophysics Conference.

Forbes, D.L., Craymer, M., Solomon, S.M., Manson, G.K. 2004. Defining Submergence and Erosion Hazards in the Canadian Arctic. Arctic Coastal Dynamics: Report of the 4th International Workshop, St. Petersburg, Russia, November 2003. Berichte zur Polar und Meeresforschung, 482, 196-202.

French, H.M. 1974. Mass-Wasting At Sachs Harbour, Banks Island, N.W.T. Canada. Arctic and Alpine Research 6 (1), 71-78.

French, H.M. 1975. Man-Induced Thermokarst, Sachs Harbour Airstrip, Banks Island, Northwest Territories. Canadian Journal of Earth Sciences, 12, 132-144

French H.M. 1976a. Geomorphological processes and terrain disturbance studies, Banks Island, District of Franklin. Geological Survey of Canada Paper 76-1A: 289-292.

French, H.M. 1976b. The Periglacial Environment. London and New York: Longman.

French H.M., Harry, D.G., Clark, M.J. 1982. Ground-Ice Stratigraphy and Late-Quaternary Events, South-west Banks Island, Canadian Arctic. In: French HM (Ed.), Proceedings of Fourth Canadian Permafrost Conference, National Research Council of Canada: 81-90

French, H.M., Harry, D.G. 1988. Nature and Origin of Ground Ice, Sandhills Moraine, Southwest Banks Island, Western Canadian Arctic. Journal of Quaternary Science 3: 19-30.

French, H.M., Harry, D.G. 1990. Observations on Buried Glacier Ice and Massive Segregated Ice, Western Arctic Coast, Canada. Permafrost and Periglacial Processes 1: 31-43.

French, H.M. 1996. The Periglacial Environment 2nd Edition. Addison Wesley Longman Limited. Harlow Essex, England, UK.

Gulliver, F.P. 1899. Shoreline Topography. Proceedings of the American Academy of Arts and Science, 34, 151-258.

Gurney, S.D., Worsley, P. 1997. Genetically Complex and Morphologically Diverse Pingos in the Fish Lake Area of South West Banks Island, N.W.T, Canada. Geografiska Annaler, 79A 1-2.

Harper, J.R, Reimer, P.D., Collins, A.D. 1985. Canadian Beaufort Sea: Physical Shore-Zone Analysis. Dobrocky-Seatech Ltd, Sidney. Contract Report to Indian and Northern Affairs Canada and Atlantic Geoscience Centre. Geological Survey of Canada, Open File 1689, 105 p.

Harper, J.R., Henry, R.F., Stewart, G.G. 1988. Maximum Storm Surge Elevations in the Tuktoyaktuk Region of the Canadian Beaufort Sea. Arctic 41 (1), p 48-52.

Harper, J.R. 1990. Morphology of the Canadian Beaufort Sea Coast. Marine Geology, 91, 75-91.

Harry, D.G., French, H.M., and Clark, M.J. 1983. Coastal Conditions and Processes, Sachs Harbour, Banks Island, Western Canadian Arctic. Zeitschrift für Geomorphologie (Annals of Geomorphology), Supplementband 47: Coastal and Inland Periglacial Processes, Canadian Arctic, 1-26.

Harry, D.G. 1988. Ground Ice and Permafrost. In M.J. Clark, ed. Advances in Periglacial Geomorphology, New York: John Wiley and Sons, 113-149.

Hequette, A., Ruz, M-H. 1991. Spit and Barrier Migration in the Southeastern Canadian Beaufort Sea. Journal of Coastal Research, 7 (3), 677-698.

Hequette, A., Ruz, M-H., Hill, P.R. 1995. The Effects of the Holocene Sea Level Rise on the Evolution of the Southeastern Coast of the Canadian Beaufort Sea. Journal of Coastal Research 11(2), 494-507.

Herbert, PDN. 2002. Canada's Polar Environments. CyberNatural Software, University of Guelph. Internet. Accessed April 2006.
URL: http://www.arctic.uoguelph.ca/cpe/

Hill, P.R., Mudie, P.J., Moran, K., Blasco, S.M. 1985. A Sea Level Curve for the Canadian Beaufort Sea Shelf. Canadian Journal of Earth Sciences, 22, 1383-1393.

Hill, P.R., Hequette, A., Ruz, M-H. 1993. Holocene Sea-Level History of the Canadian Beaufort Shelf. Canadian Journal of Earth Sciences. 30, 103-108.

Hill, P.R., Solomon, S.M. 1999. Geomorphic and Sedimentary Evolution of a Transgressive Thermokarst Coast, Mackenzie Delta Region, Canadian Beaufort Sea. Journal of Coastal Research, 15 (4), 1011-1029.

Hudson, R.D. 1987. Multiyear Sea Ice Floe Distribution in the Canadian Arctic Ocean. Journal of Geophysical Research, 92: 14, 633-639.

Huscroft, C.A., Lipovsky, P. and Bond, J.D., 2004. Permafrost and Landslide Activity: Case Studies from Southwestern Yukon Territory. In: Yukon Exploration and Geology 2003, D.S. Emond and L.L. Lewis (eds.), Yukon Geological Survey, p. 107-119.

Indian and Northern Affairs. 2005. Communities – A Guide to Mineral Exploration and Development in the NWT, Sachs Harbour. Government of Canada. (Accessed April 27, 2005).
URL: http://nwt-tno.inac-ainc.gc.ca/mpf/communit/com_e.asp?ID=23

International Panel on Climate Change. 2001a. Climate Change 2001: Impacts, Adaptations, and Vulnerability. World Meteorology Organization and the United Nations Environment Programme.

Johannessen, O. M., Shalina, E. V. and Miles, M. W. 1999. Satellite evidence for an Arctic Sea Ice Coverage in Transformation. Science 286, 1937–1939.

Johannessen, O., Bengtsson, L., Miles, M.W., Kuzmin, S.I, Semenov, V.A., Alekseev, G.V., Nagurnyi, A.P., Zakharov, V.F., Bobylev, L.P., Petterson, L.H., Hasselman, K., Cattle, H.P. 2004. Arctic Climate Change: Observed and Modelled Temperature and Sea-Ice Variability. Tellus, 46 (4), 328-341.

Johnson, D.W. 1965. Shore Processes and Shoreline Development. Hafner Publishing Company. Columbia University.

Johnson, K., Solomon, S.; Berry, D.; and Graham, P. 2003. Erosion Progression and Adaptation Strategy in a Northern Coastal Community. Proceedings - 8th International Conference on Permafrost, Zurich, Switzerland, July 20-25, 2003. Edited by. Phillips, S.M. Springman and L.U. Arenson; International Permafrost Association 8, 489-494.

Kobayashi, N., Vidrine, J.C., Nairn, R.B., Solomon, S.M. 1999. Erosion of Frozen Cliffs Due to Storm Surge on Beaufort Sea Coast. Journal of Coastal Research, 15 (2), 332-344.

Kokelj, S.V., Smith, C.A.S., Burn, C.R. 2002. Physical and Chemical Characteristics of the Active Layer and Permafrost, Herschel Island, Western Arctic Coast, Canada. Permafrost and Periglacial Processes, 13 (2), 171-185.

Krause, G. 2004. The "Emery Method" Revisited – Performance of an Inexpensive Method of Measuring Beach Surveys and Modifications. Journal of Coastal Research, 20, 340-346.

Krumbein, W. 1934. Size Frequency Distribution in Sediments. Journal of Sedimentary Petrology, 4, 65-77.

Lambeck, K. 1995. Late Devensian and Holocene Shorelines of the British Isles and North Sea From Models of Glacio-Hydroisostatic Rebound. Journal of the Geological Society, London 152, 437–448

Lane, L. S., and Dietrich, J. R. 1996. Bedrock Geology and Offshore structural trends: In Geological Atlas of the Beaufort-Mackenzie Area, edited by J. Dixon, Geological Survey of Canada, Miscellaneous Report 59, p. 10-12.

Lantuit, H., Pollard, W.H. 2004. A Volumetric Analysis of Long-Term Coastal Erosion On Herschel Island, Yukon Territory: First Results. Geophysical Research Abstracts, 6, 00186.

Lantuit, H., Pollard, W.H. 2005. Temporal Sterophotogrammetric Analysis of Retrogressive Thaw Slumps on Herschel Island, Yukon Territory. Natural Hazards and Earth System Sciences, 5, 413-423.

Liverman, D.G.E., Forbes, D.L., and Boger, R.A.. 1994. Coastal Monitoring on the Avalon Peninsula. Newfoundland Department of Mines and Energy, Current Research, Geological Survey Branch Report 94-1, p. 17-27.

Liverman, DGE, 1994. Relative Sea-level History and Isostatic Rebound in Newfoundland, Canada. Boreas, 23, 217-230

Lewis, C.P., Forbes, D.L. 1974. Sediments and Sedimentary Processes, Yukon Beaufort Sea Coast. Environmental and Social Comm. Northern Pipelines Task Force on Northern Oil Development, Report 74-29, 40 pp.

Lewis, C.P., Forbes, D.L. 1975. Coastal Sedimentary Processes and Sediments, Southern Beaufort Sea. Fisheries and Oceans Canada, Sidney BC. Beaufort Sea Project Technical Report, 24, 68 pp.

MacDonald, B.C., Lewis, C.P. 1973. Geomorphic and Sedimentologic Processes of Rivers and Coasts, Yukon Coastal Plain. Environmental and Social Comm. Northern Pipelines Task Force on Northern Oil Development., Report 73-79 245 pp.

Magellan Corporation. 1999. Practical GPS Surveying. Ashtech Precision Products. Santa Clara, California, U.S.A.

Manson, G.K., Forbes, D.L., Armenakis, C., Savopol, F. 2005a. Remote Measurements of Coastal Change Using Quickbird, Ikonos and Aerial Photography, Sachs Harbour, Northwest Territories, Canada. Eighth International Conference on Remote Sensing for Marine and Coastal Environments, Halifax, Nova Scotia, Canada.

Manson, G.K., Solomon, S.M., Forbes, D.L., Atkinson, D.E., Craymer, M. 2005b. Spatial Variability of Factors Influencing Coastal Change in the Western Canadian Arctic. Geo-marine Letters, 25, 138-145.

McCann, S.B., Owens, E.H. 1969. The Size and Shape of Sediments in Three Arctic Beaches, Southwest Devon Island, NWT, Canada. Arctic and Alpine Research 1, 267-278.

McCann, S.B. 1973. Beach Processes in an Arctic Environment. Coastal Geomorphology: A Proceedings Volume of the Third Annual Geomorphology Symposia Series, Held at Binghamtom New York, September 28-30, 1972. State University of New York Binghamton, N.Y. pp 141-155.

MacKay, J.R. 1962. The World of Underground Ice. Annals of the American Association of Geographers, 62, 1-22.

MacKay, J.R. 1963. Notes on the Shoreline Recession Along the Coast of the Yukon Territory. Arctic, 16 (3), 195-197.

Mackay, J.R. 1966. Segregated Epigenetic Ice and Slumps in Permafrost, Mackenzie Delta, N.W.T. Geographical Bulletin, 8, 59-80.

Mackay, J.R. 1989. Massive Ice: Some Field Criteria for the Identification of Ice Types. In, Current Research Part G, Geological Survey of Canada, Paper 89-1G, pp 5-11.

Miall, A. 1974. Bedrock Geology of Banks Island, *District of Franklin.* Report of Activities part A. April to October 1973; by Blackadar, R G; Geological Survey of Canada, Paper 74-01A, 1974; pages 336-342.

Miall, A. 1975. Geology of Banks Island. Report of Activities part A, April to October 1974; by Geological Survey of Canada; Geological Survey of Canada, Paper , 75-01A, 1975; pages 559-563.

Miall, A. 1976. Proterozoic and Paleozoic Geology of Banks Island, Arctic Canada. Geological Survey of Canada Bulletin 258. Natural Resources Canada.

Miall, A. 1979. Mesozoic and Tertiary Geology of Banks Island, Arctic Canada; The History of an Unstable Craton Margin. Geological Survey of Canada, Memoir, no 387, 235 pp.

Murton, J.B. 2001. Thermokarst Sediments and Sedimentary Structures, Tuktoyaktuk Coastlands, Western Arctic Canada. Global and Planetary Change, 28, 175-192.

National Snow and Ice Data Centre. 2005a. Sea Ice. State of the Cryosphere. University of Colorado, Boulder. Accessed May 2006. URL: http://nsidc.org/sotc/sea_ice.html

National Snow and Ice Data Centre. 2005b. Sea Ice Decline Intensifies. Joint Press Release between the National Snow and Ice Data Centre (University of Colorado, Boulder) and the University of Washington.

Nichols, T., Berkes, F., Jolly, D., Snow, N., and the Community of Sachs Harbour. 2004. Climate Change and Sea Ice: Local Observations from the Western Canadian Arctic. Arctic; March 2004; 57, 1.

Parewick, K., Catto, N., Forbes, D.L., Bell, T., Pollard, W., Edinger, E., Couture, N. 2005. Integrating Coastal Science Into Regional Impact Assessment and Local Decision-Making to Build Community Resilience in the Canadian Arctic. Proceedings from ArcticNet annual scientific meeting.

Parkinson, C.L., Comiso, J.C., Zwally, H.J., Cavalieri, D.J., Gloerson, P., W.J, Campbell. 1987. Arctic Sea Ice, 1973-1976: Satellite Passive-Microwave Observations. Washington, DC: NASA.

Parkinson, C.L., D.J. Cavalieri, P. Gloersen, H.J. Zwally and J.C.Comiso. 1999. Arctic Sea Ice Extents, Areas, and Trends, 1978–1996. Journal of Geophysical Research, 104 (C9), 20837–20856.

Peltier W.R. 1994. Ice age paleotopography. Science 265, 195-201

Pewe, T.L. 1966. Permafrost and its Effect on Life in the North. Arctic Biology, 2nd Edition. Oregon State University Press. Corvallis, 27-66.

Pielou, E.C. 1994. The Naturalist's Guide to the Arctic. The University of Chicago Press. U.S.A

Pollard, W.H. 1990. The Nature and Origin of Ground Ice in the Herschel Island Area, Yukon Terrritory. Fifth Canadian Permafrost Conference, Quebec. 23-30.

Pollard, W., C. Omelon, N. Couture, S. Solomon and P. Bukdewitsch. 2002. Ice Content and Sensitivity Analysis Based on Landscape Interpretation for Several Sites Along the Beaufort Sea coast. Berichte zur Polarforschung und Meeresforschung, 413, 48-52.

Quinlan, G., Beaumont, C. 1981. A Comparison of Observed and Theoretical Postglacial Relative Sea Level in Atlantic Canada. Canadian Journal of Earth Sciences, 18, 1146-1163.

Rampton, V.N, Bouchard, M. 1975. Surficial Geology of Tuktoyaktuk, District of Mackenzie. Geological Survey of Canada, Paper 74-53. 18 p.

Rampton, V.N. 1982. Quaternary Geology of the Yukon Coastal Plain. Geological Survey of Canada Bulletin, 317, 49.

Rampton, V.N. 1988. Quaternary Geology of the Tuktoyaktuk Coastlands, Northwest Territories. Geological Survey of Canada, Memoir 423, 98 p.

Reimnitz, E., Maurer D.K. 1979. Effects of Storm Surges on the Beaufort Sea Coast, Northern Alaska. Arctic 32: 329-344.

Reimnitz, E., Barnes, P.W., Harper, J.R. 1990. A Review of Beach Nourishment From Ice Transport of Shoreface Materials, Beaufort Sea, Alaska. Journal of Coastal Research, 6, 439-470.

Romanovsky, V.E. 2006. How Rapidly is Permafrost Changing and What Are the Impacts of These Changes?. Arctic Theme Page: National Oceanic and Atmospheric Administration: Arctic Research Office. Accessed May 2006. URL: http://www.arctic.noaa.gov/essay_romanovsky.html

Serreze, M. C., Maslanik, J. A., Scambos, T. A., Fetterer, F., Stroeve, J., Knowles, K., Fowler, C., Drobot, S., Barry, R. G., and Haran, T. M. 2003. A Record Minimum Arctic Sea Ice Extent and Area in 2002. Geophysical Research Letters. 30, 1110.

Shaw, J., Taylor, R.B., Forbes, D.L., Ruz, M.-H., Solomon S. 1998. Sensitivity of the Coasts of Canada to Sea-Level Rise. Geological Survey of Canada Bulletin 505. Natural Resources Canada.

Smith, M., Rigby, B. 1981. Distribution of Polynyas in the Canadian Arctic. In I. Stirling and H. Cleator, eds., Polynyas in the Canadian Arctic. Occasional Paper No. 45, Canadian Wildlife Service, Ottawa, 7-28.

Smith, S., Burgess, M. 2006a. Permafrost: Permafrost and Climate Change. Geological Survey of Canada, Earth Sciences Sector. Natural Resources Canada. Accessed May 2006. URL: http://gsc.nrcan.gc.ca/permafrost/climate_e.php

Smith, S., Burgess, M. 2006b. The Sensitivity of Canadian Permafrost to Climate Warming. Terrain Sciences Division, Geological Survey of Canada. Natural Resources Canada. Poster. Accessed May 2006. URL: http://gsc.nrcan.gc.ca/permafrost/pdf/wkshpsensitivityposter2.pdf

Solomon, S.M., Forbes, D.L., Kierstead, B. 1994. Coastal Impacts of Climate Change: Beaufort Sea Erosion Study. Geological Survey of Canada. Open File 2890, p 85.

Solomon, S.M. 2005. Spatial and Temporal Variability of Shoreline Change in the Beaufort-Mackenzie Region, Northwest Territories, Canada. Geo-Marine Letters 25, 127-137.

Squire VA, Dugan JP, Wadhams P, Rottier PJ, and Liu, AK. 1995. Of Ocean Waves and Sea Ice. Annual Review of Fluid Mechanics 27, 15-168

Stroeve, J. C., Serreze, M. C., Fetterer, F., Arbetter, T., Meier, M., Maslanik, J., Knowles, K. 2005. Tracking the Arctic's Shrinking Ice Cover: Another Extreme September Minimum in 2004. Geophysical Research Letters. 32, L04501, 10.1029/2004GL021810.

The Community of Sachs Harbour, Wildlife Management Advisory Council, and Joint Secretariat. 2000. Inuvialuit Settlement Region: Sachs Harbour Community Conservation Plan. Beaufort-Mackenzie Mineral Development Area.

Taylor, R.B., McCann, S.B. 1983. Coastal Depositional Landforms in Northern Canada. In J.T. Lowe and A. Dawson, eds, Shorelines and Isostacy, 53 – 75. London: Academic Press. Institute of British Geographers, Special Publication 16.

Usher, P.J. 1970. The Bankslanders: Economy and Ecology of a Frontier Trapping Community. 2 Vols. Ottawa: Department of Indian Affairs and Northern Development.

Vasiliev, A., Kanevskiy, M., Firsov, Y. 2003. The Mechanism of the Sea Coast Destruction in Marre-Sale, Western Yamal. Report on Polar Marine Research, 443: 110-113.

Vincent, Jean-Serge. 1982. The Quaternary History of Banks Island, N.W.T., Canada Géographie physique et Quaternaire. Vol XXXVI, No 1-2, 209-232.

Vincent, Jean-Serge. 1983. La Géologie du Quaternaire et la Géomorphologie de L'île de Banks, Arctique Canadien. Geological Survey of Canada, Memoir 405.

Vincent, J-S., Occhietti, S., Rutter, N., Lortie, G., Guilbault, J-P., de Boutray, B. 1983. The Late Tertiary – Quaternary Stratigraphic Record of the Duck Hawk Bluffs, Banks Island, Canadian Arctic Archipelago. Canadian Journal of Earth Sciences, 20, 1694-1712.

Vincent, J-S. 1990. Late Tertiary and Early Pleistocene Deposits and History of Banks Island, Southwestern Canadian Arctic Archipelago. Arctic, 43 (4), 339-363.

Wadhams, P., 2000. Ice in the Ocean. Gordon and Breach Science Publishers, Amsterdam, 351pp.

Washburn, A.L. 1980. Geocryology: A Survey of Periglacial Processes and Environments. New York: J. Wiley.

Wendler, G., Moore, B., Curtis, J., Stuefer, M. 2002. Beaufort Sea Ice Concentration and the Climate of the Alaskan North Slope. Ice in the Environment: Proceedingsof the 16th IAHR International Symposium on Ice. Dunedin, New Zealand, 2nd–6th December 2002. International Association of Hydraulic Engineering and Research.

Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., Roest, W.R. 1997. Geological Map of Canada, Geological Survey of Canada. Map D1860A.

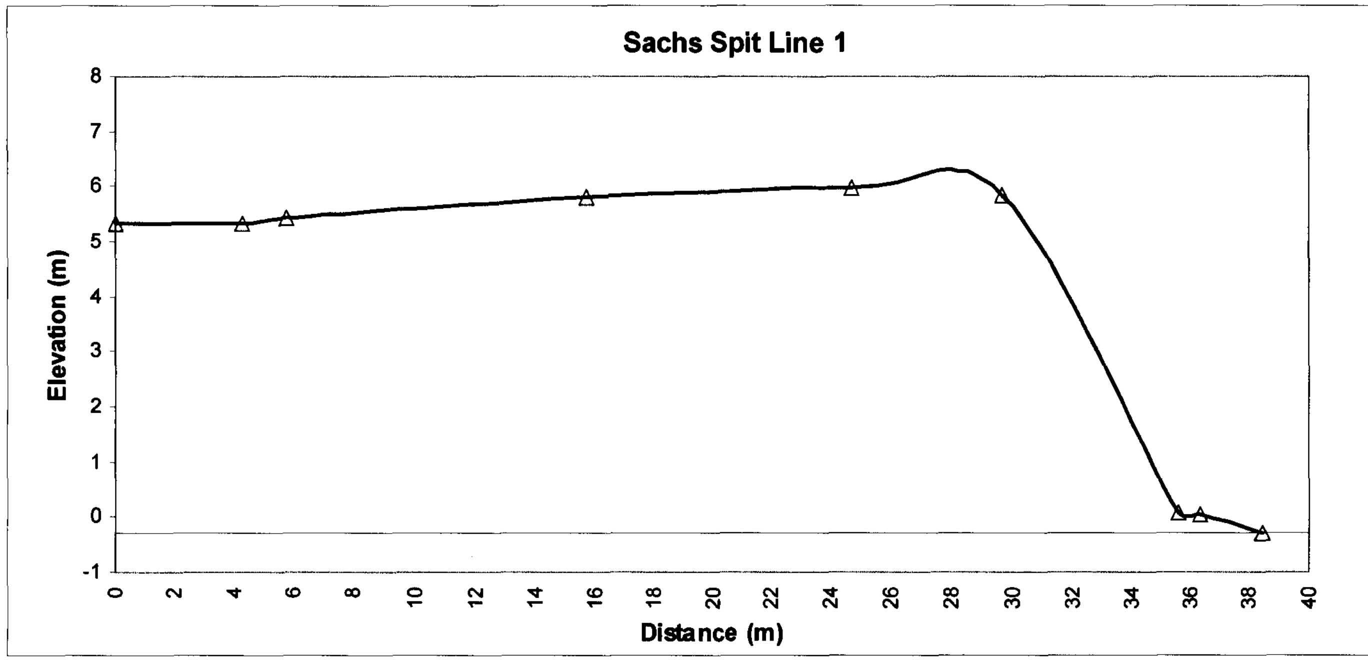
Willams, P.J., Smith, M.W. 1989. The Frozen Earth: Fundamentals of Geocryology. Cambridge: Cambidge University Press.

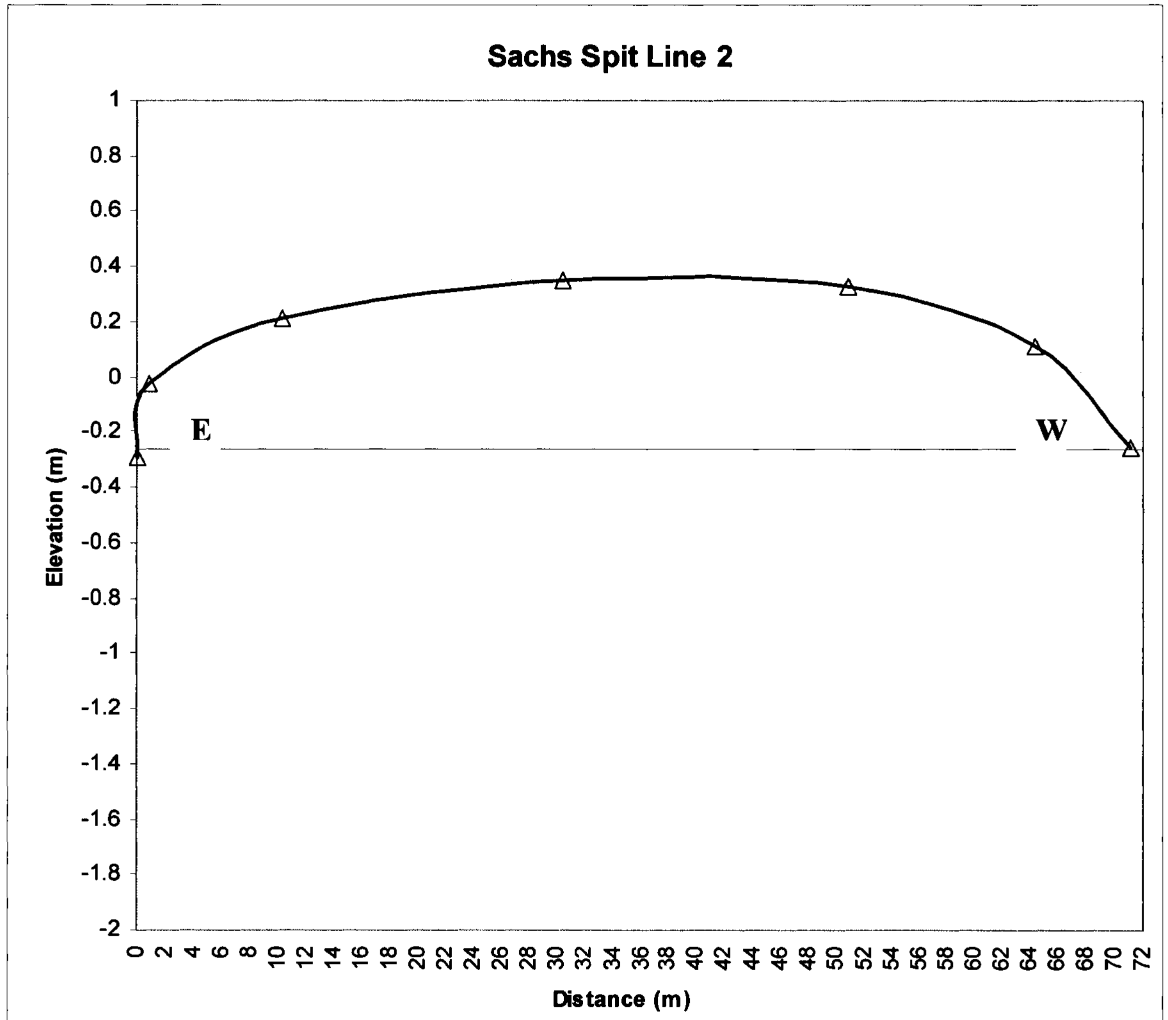
Wolfe, S.A., Dallimore, S.R., Solomon, S.M. 1998. Coastal Permafrost Investigations Along a Rapidly Eroding Shoreline, Tuktoyaktuk, N.W.T. Permafrost; seventh international conference, proceedings. Collection Nordicana, 57, 1125-1131.

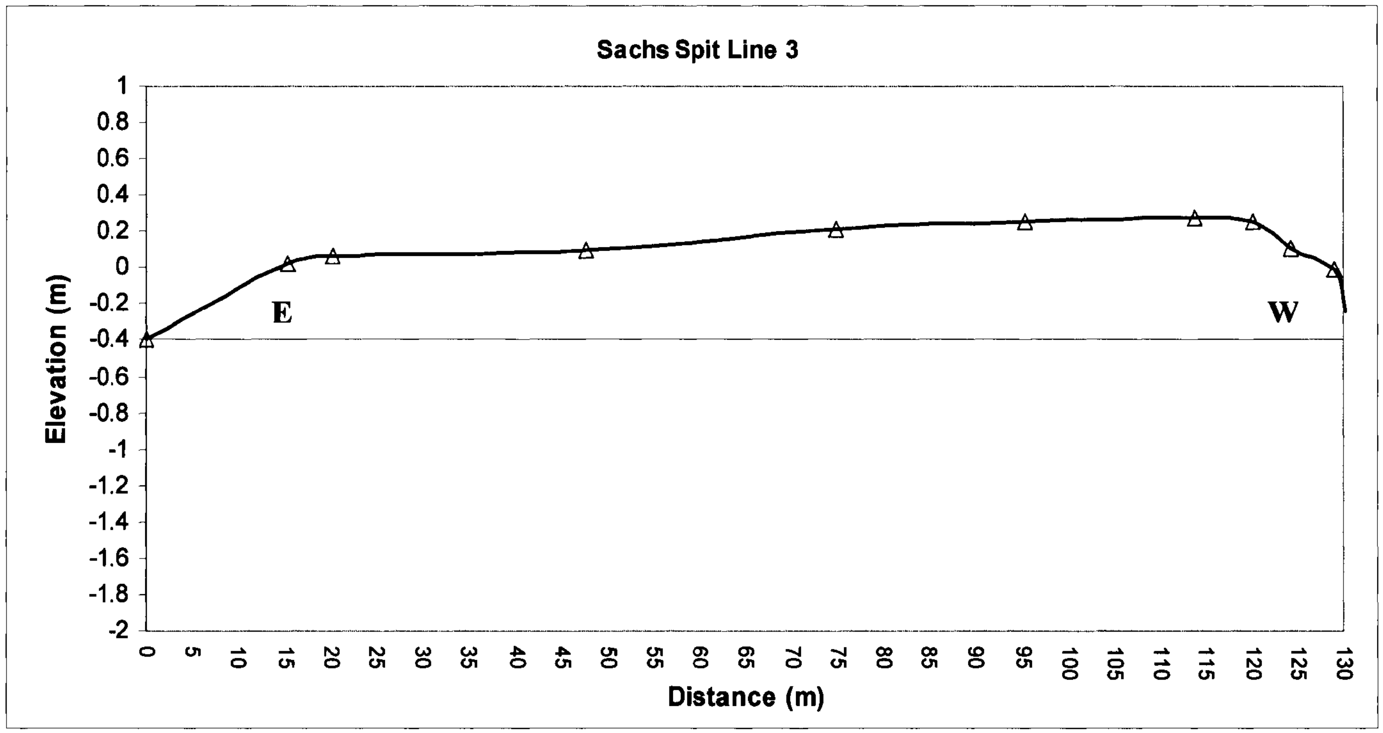
Wolfe, S.A., Kotler, E., Dallimore, S.R. 2001. Surficial Characteristics and the Distribution of Thaw Landforms (1970-1999), Shingle Point to Kay Point, Yukon Territory. Geological Survey of Canada, Open File 4088.

Worsley, P. 2000. Late-Quaternary Cryostratigraphy of a Coastal Cliff at Martha Point, Southwest Banks Island, Western Canadian Arctic. The Holocene, 10 (3), 395-400.

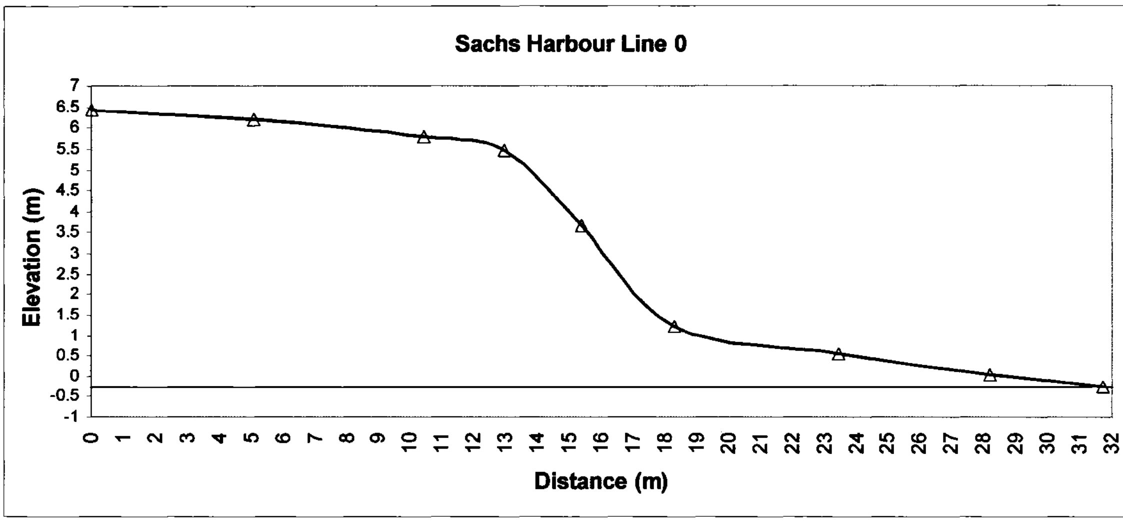
Appendix A – New Coastal Surveys

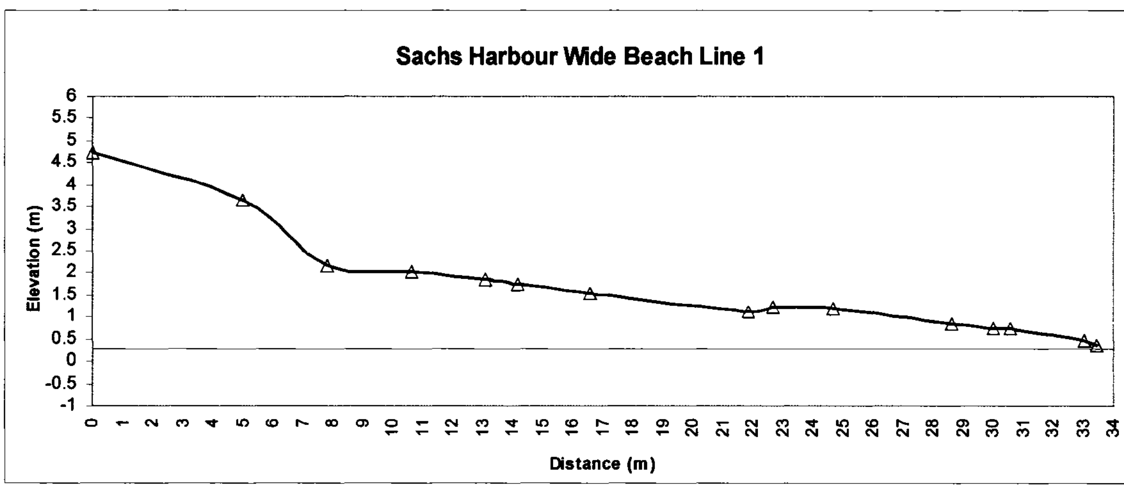


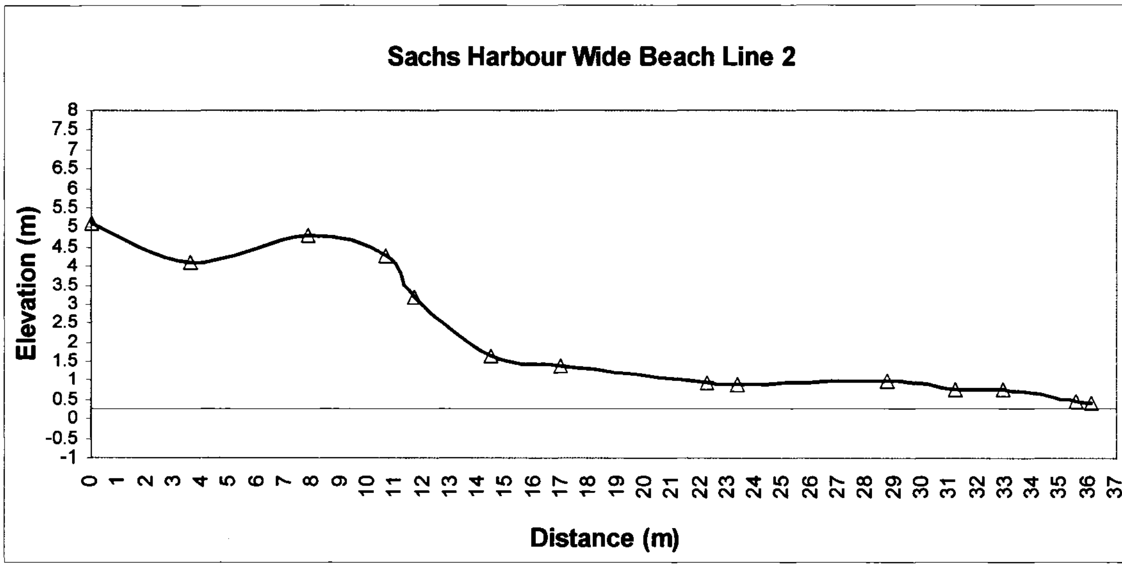

Sachs Spit Line 2
Elevation (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
E
W
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72
Distance (m)

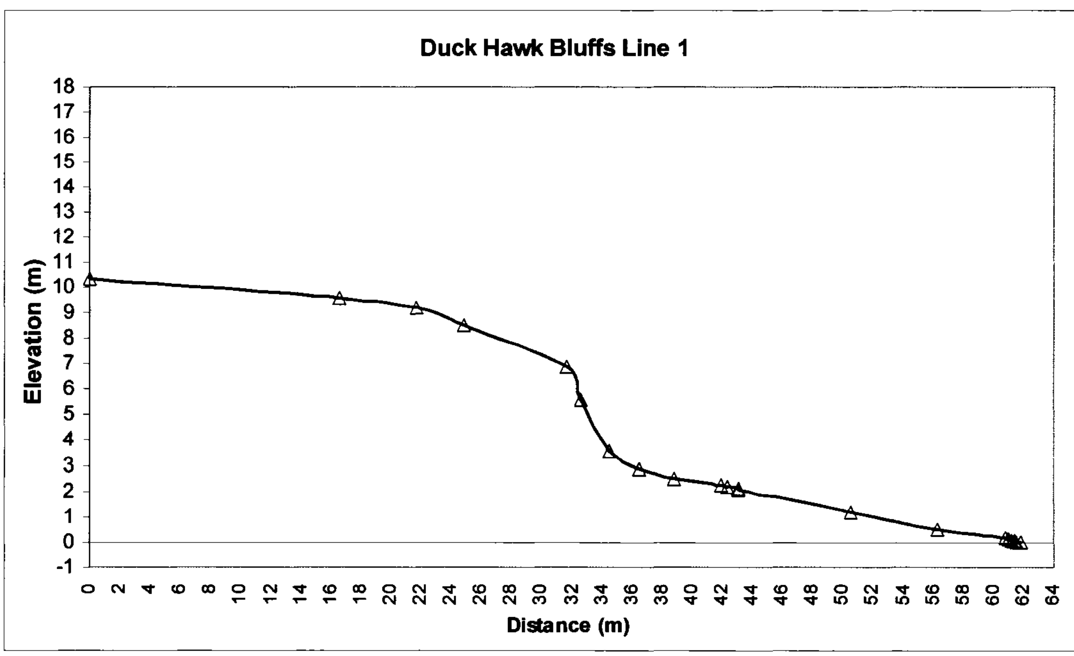


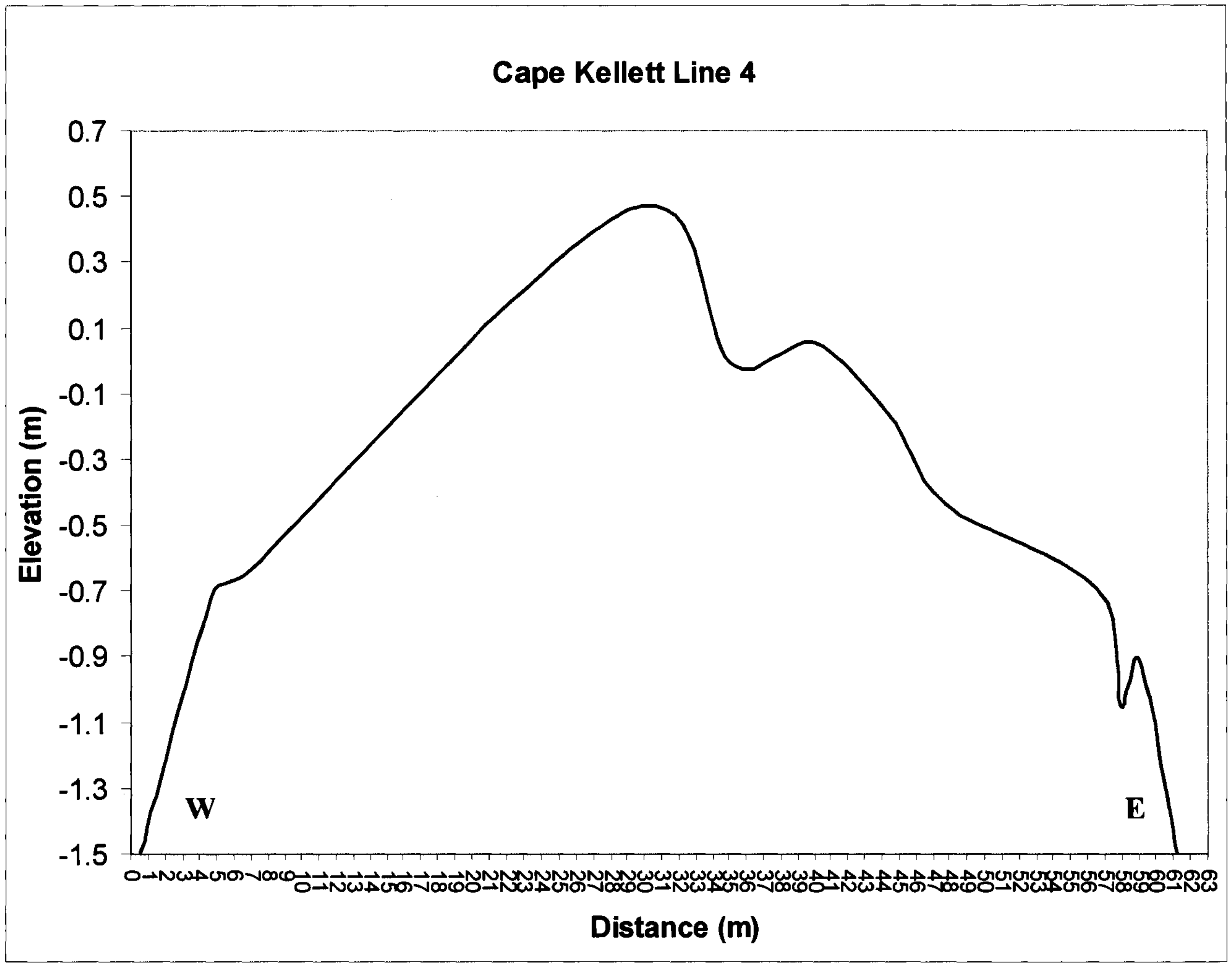
Sachs Spit Line 3
Elevation (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
E
W
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130
Distance (m)


Sachs Harbour Line 0
Elevation (m)
Distance (m)

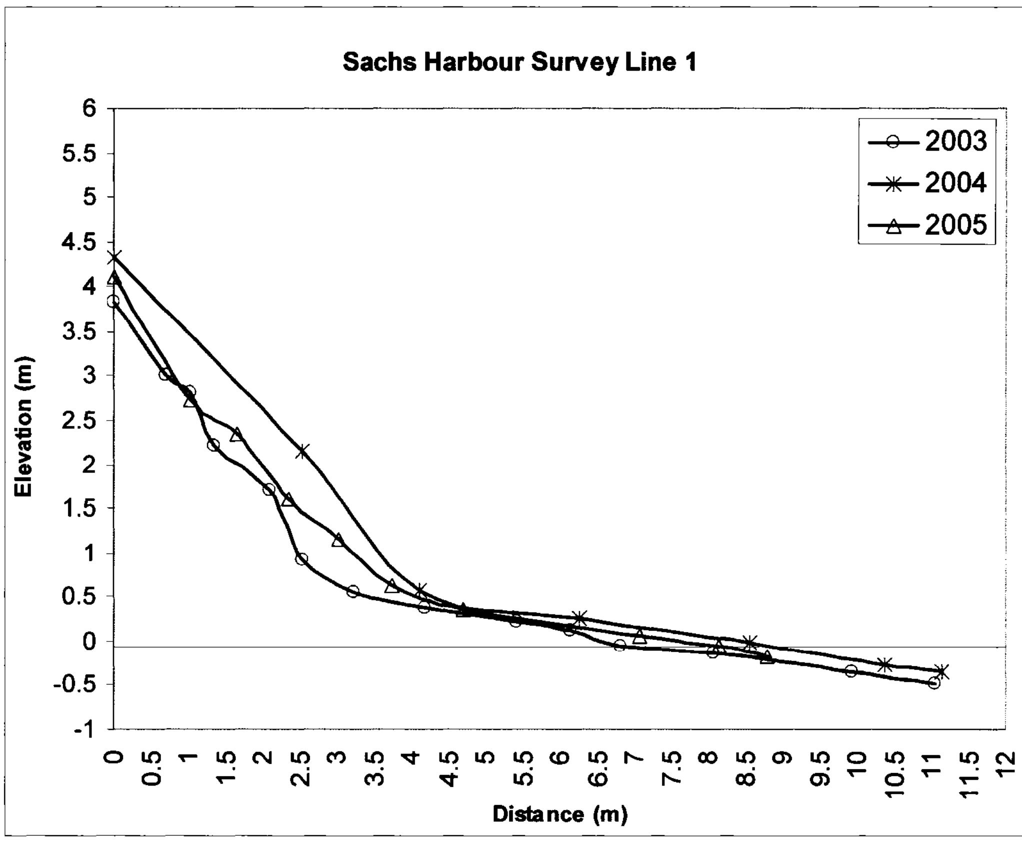

Sachs Harbour Wide Beach Line 1
Elevation (m)
Distance (m)

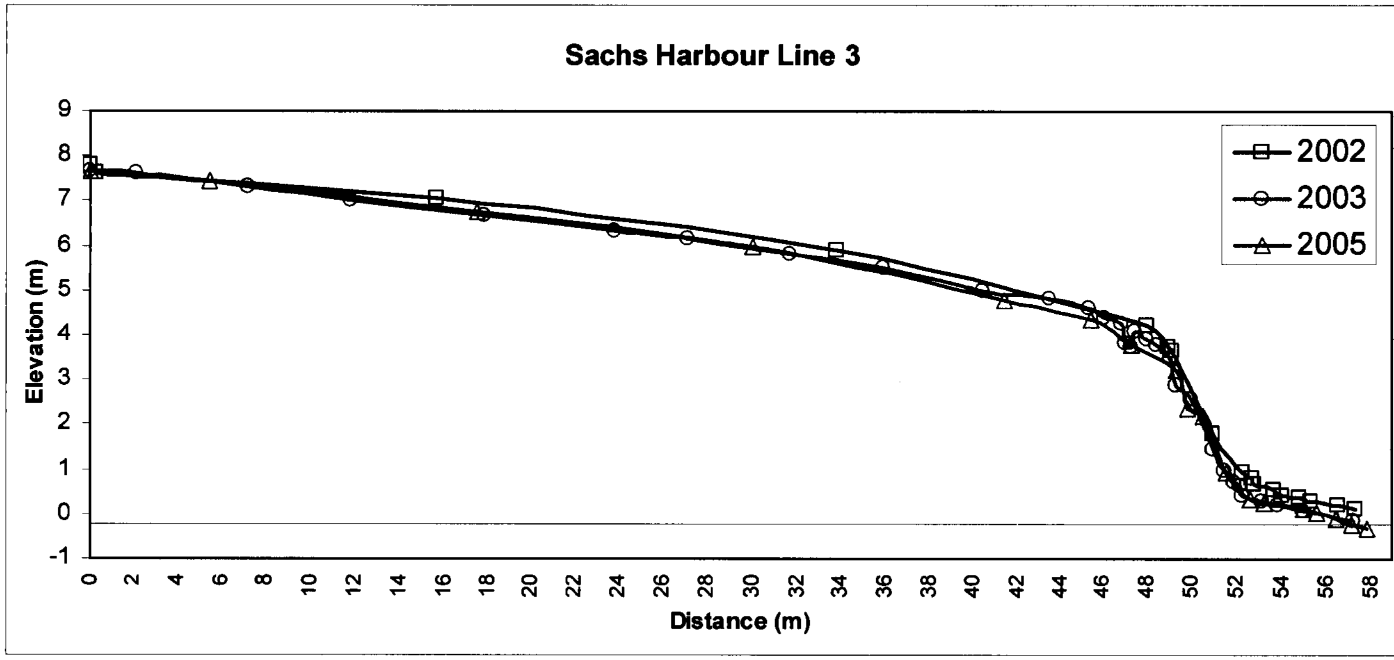

Sachs Harbour Wide Beach Line 2
Elevation (m)
Distance (m)

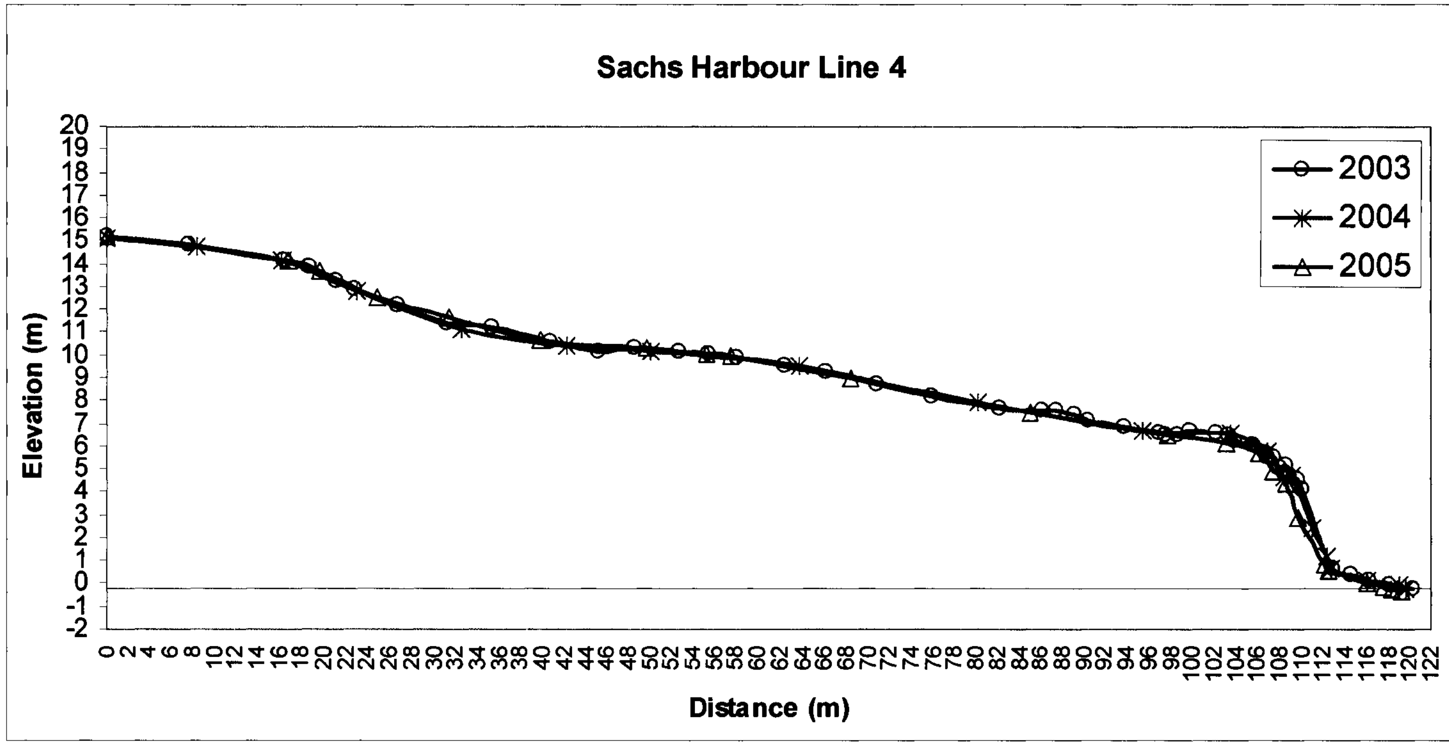

Duck Hawk Bluffs Line 1
Elevation (m)
Distance (m)

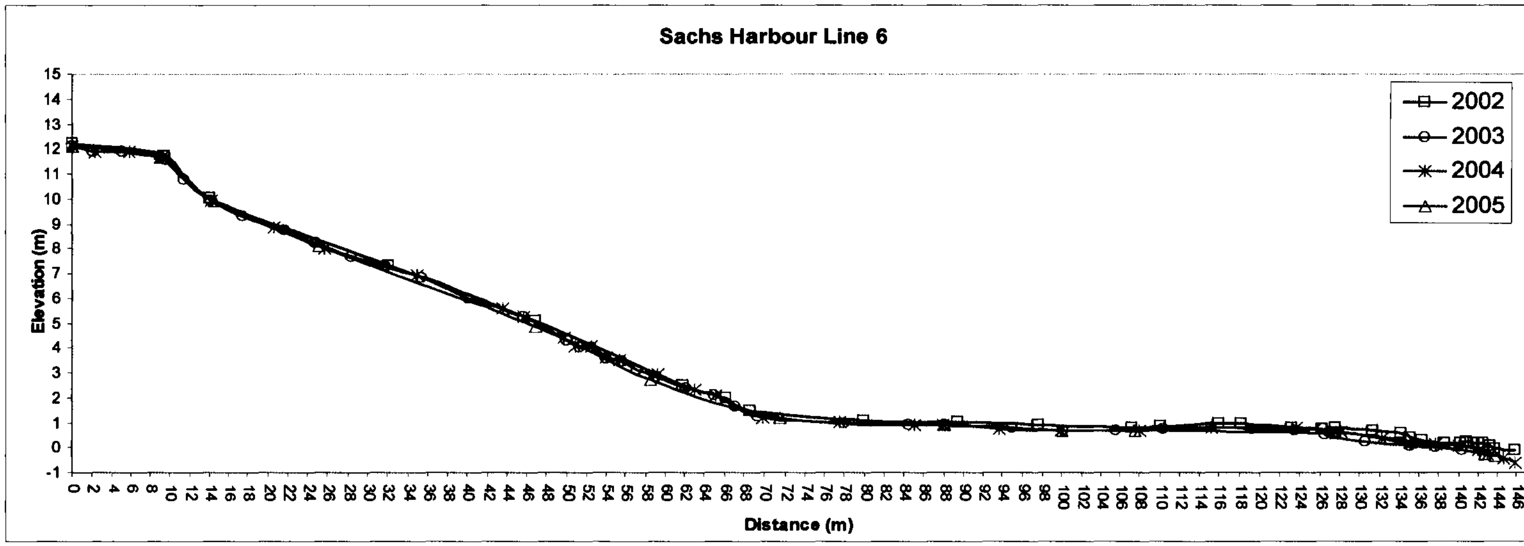

Cape Kellett Line 4
Elevation (m)
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
-0.9
-1.1
-1.3
-1.5
W
E
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63
Distance (m)

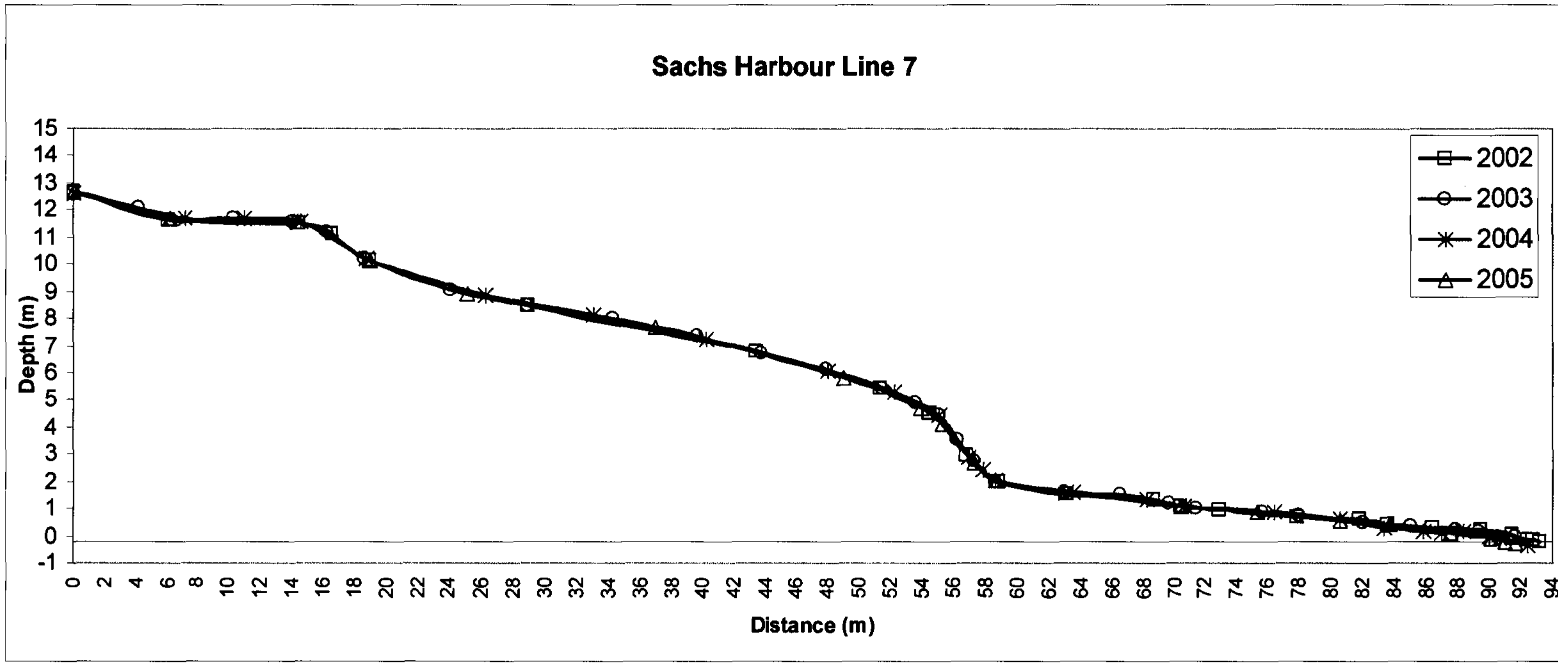
Appendix B – Resurveyed Coastal Surveys

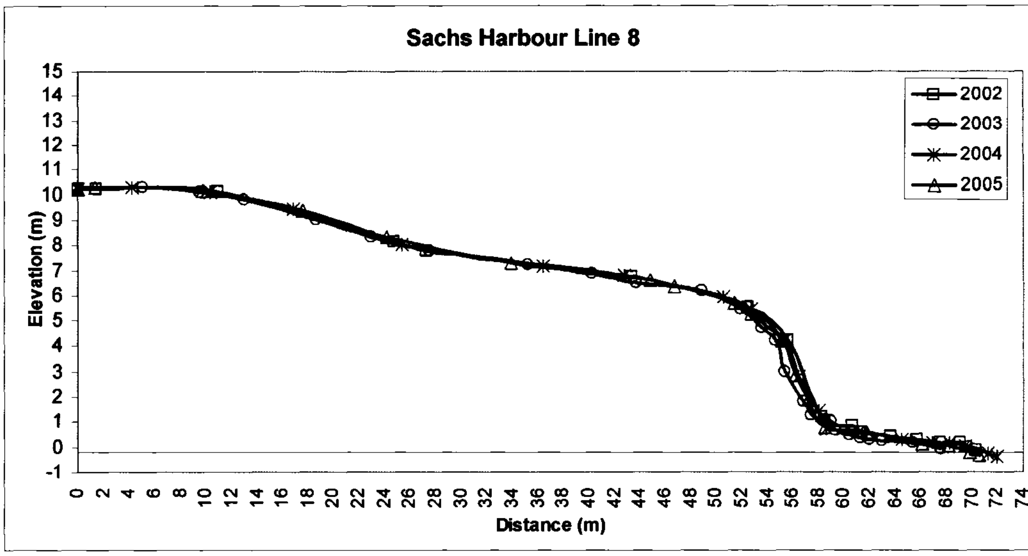


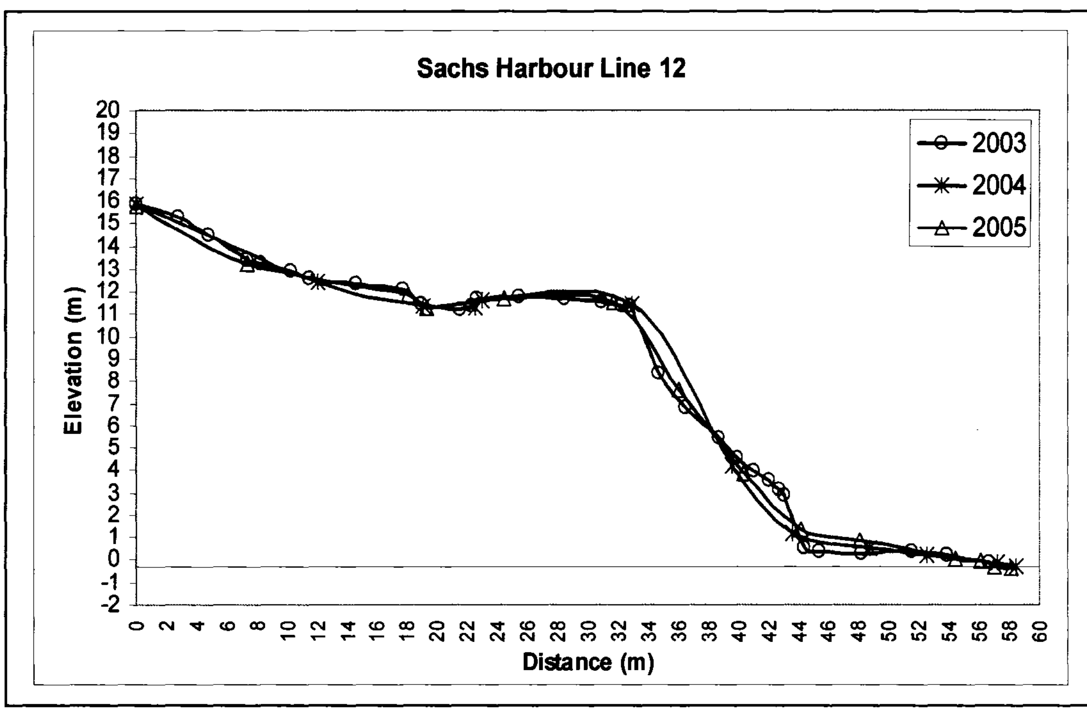

Sachs Harbour Line 3
Elevation (m)
9
8
7
6
5
4
3
2
1
0
-1
Distance (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
2002
2003
2005

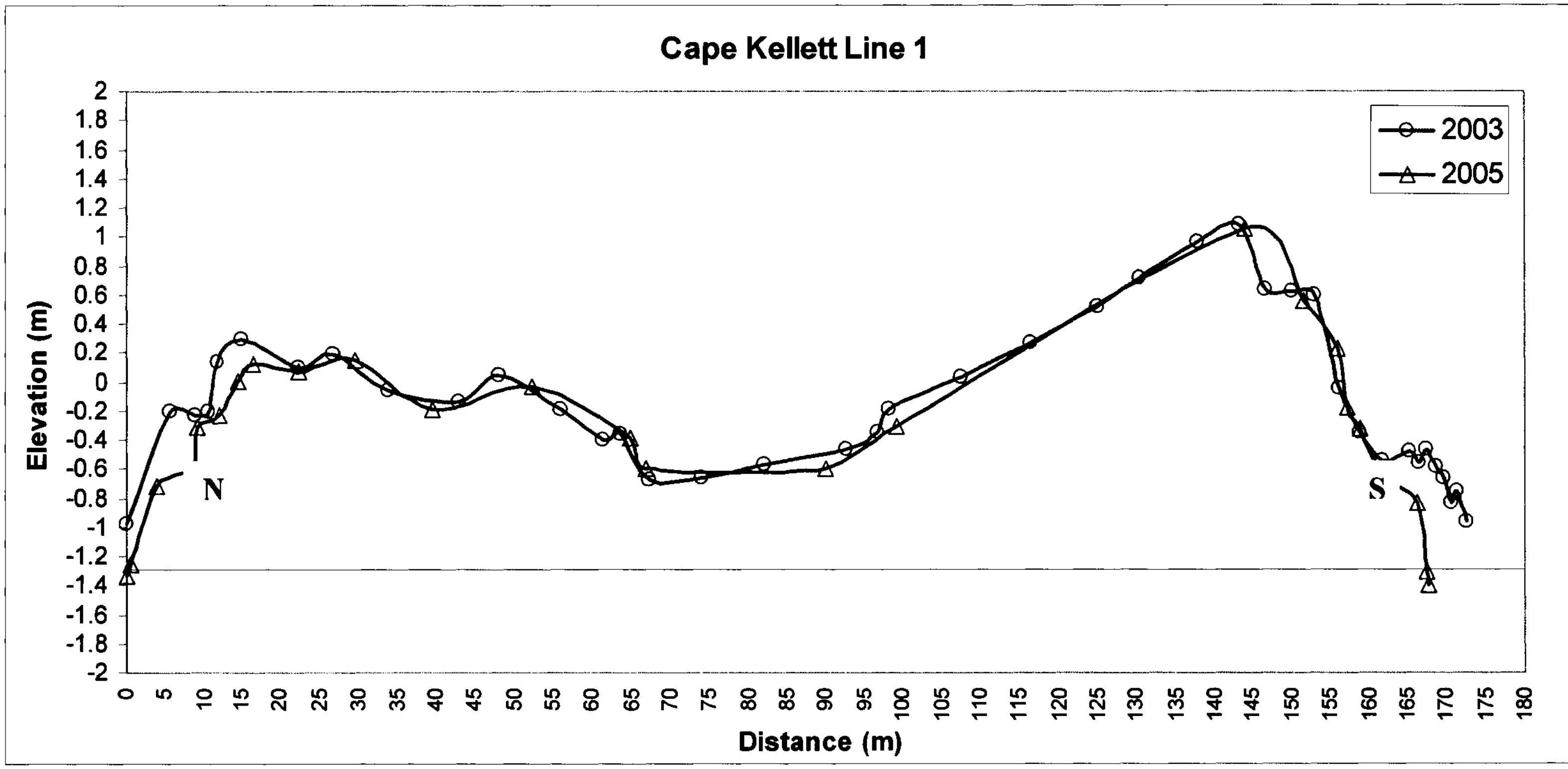

Sachs Harbour Line 4
Elevation (m)
Distance (m)
2003
2004
2005
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100 102 104 106 108 110 112 114 116 118 120 122


Sachs Harbour Line 6
Elevation (m)
Distance (m)
2002
2003
2004
2005

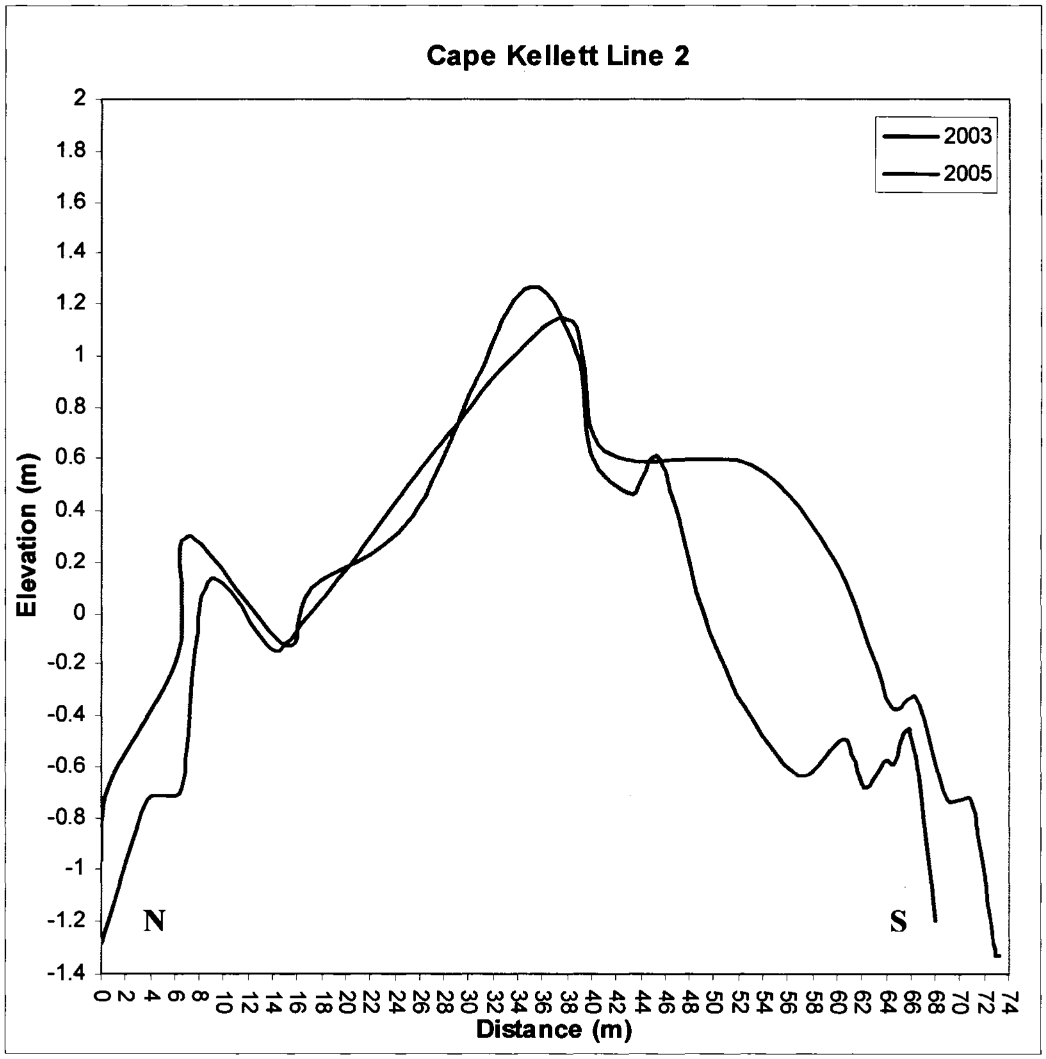

Sachs Harbour Line 7
Depth (m)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82
84
86
88
90
92
94
Distance (m)
2002
2003
2004
2005

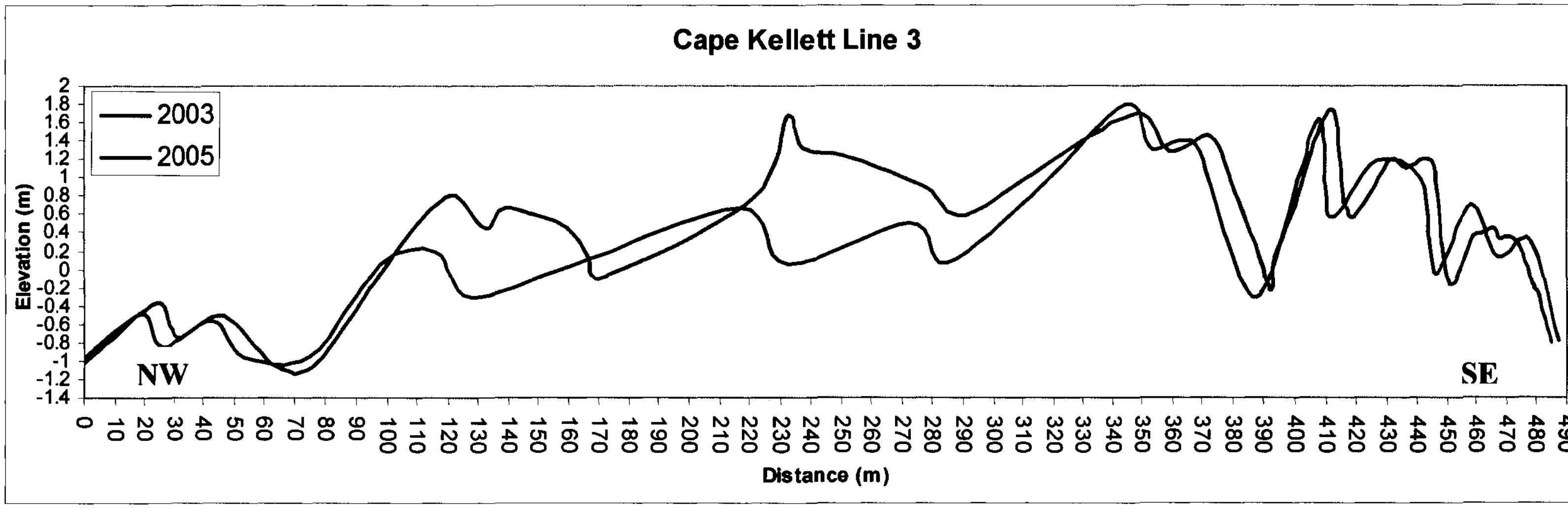

Sachs Harbour Line 8
Elevation (m)
Distance (m)
2002
2003
2004
2005


Sachs Harbour Line 12
Elevation (m)
Distance (m)
2003
2004
2005



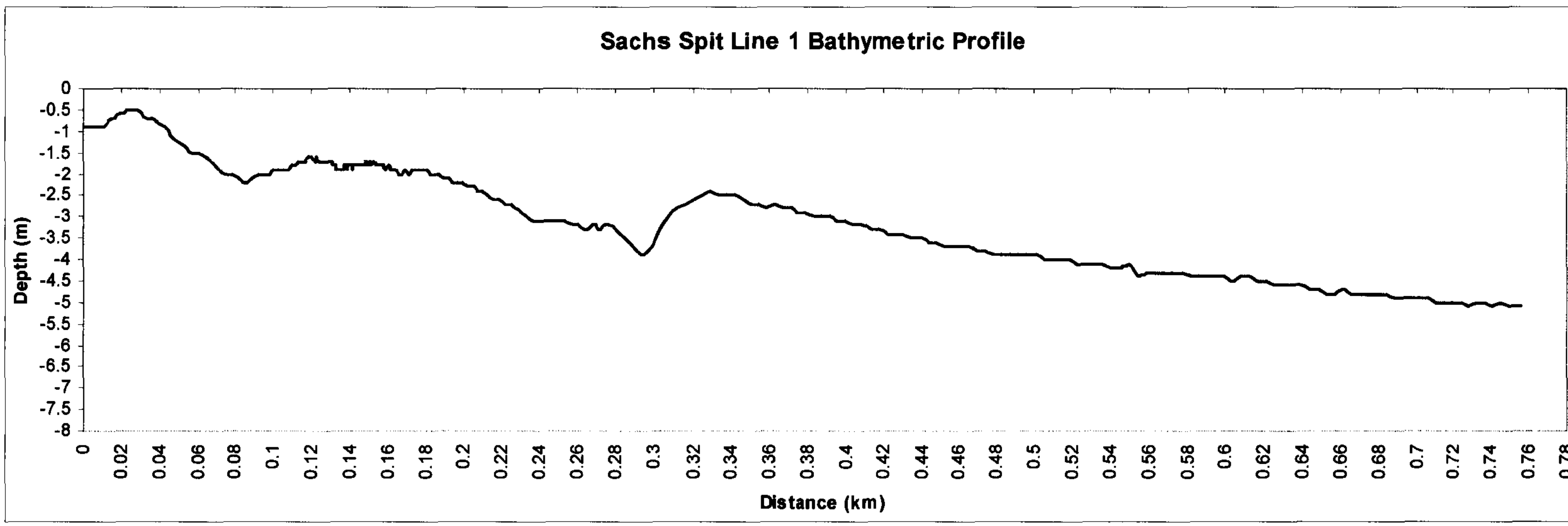
Cape Kellett Line 1
2003
2005
Elevation (m)
Distance (m)
N
S

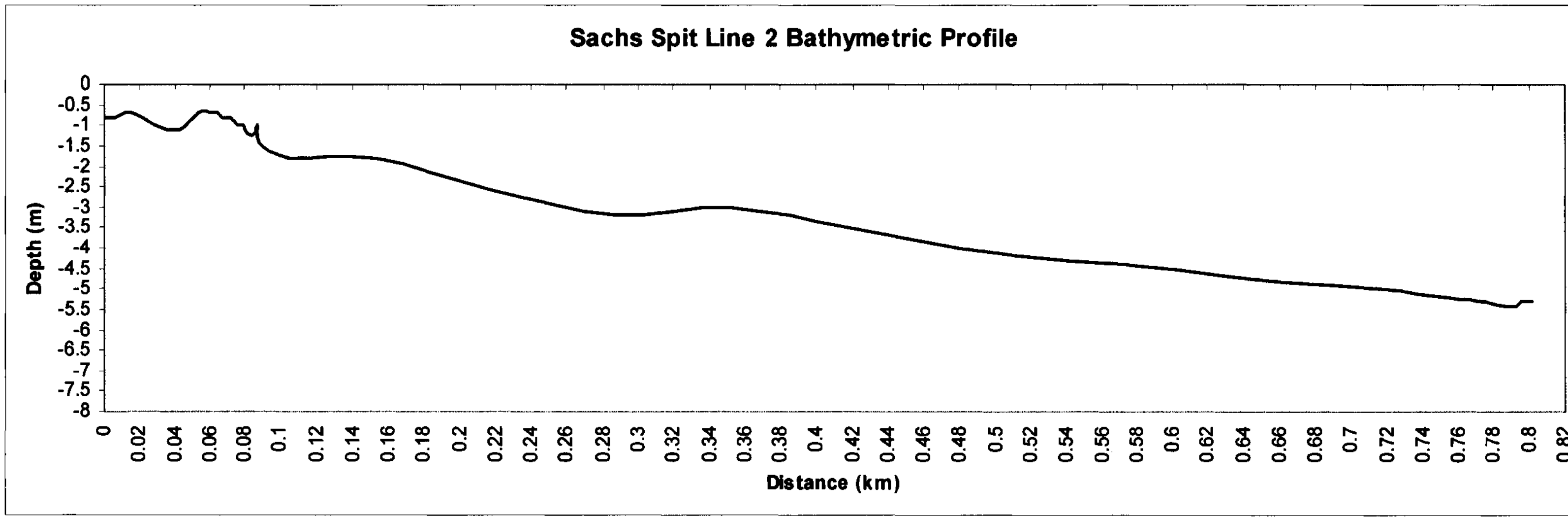

Cape Kellett Line 2
2003
2005
Elevation (m)
Distance (m)
N
S
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74



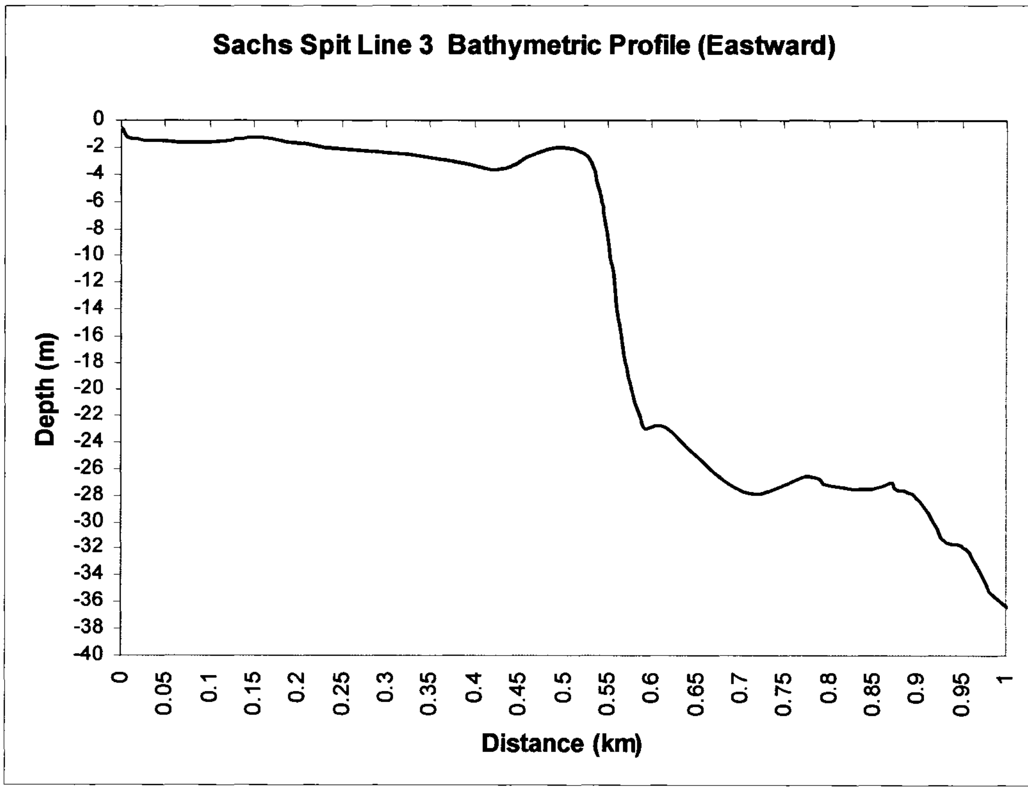
Cape Kellett Line 3
2003
2005
NW
SE
Elevation (m)
Distance (m)

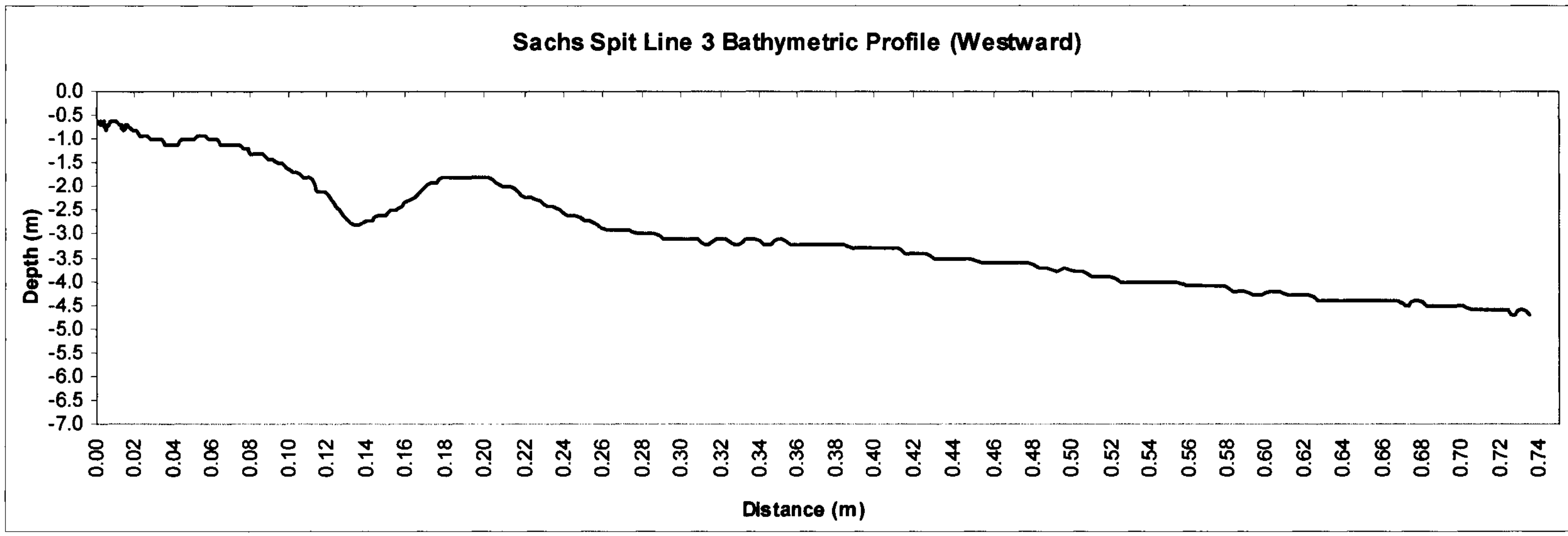
Appendix C – Bathymetric Surveys

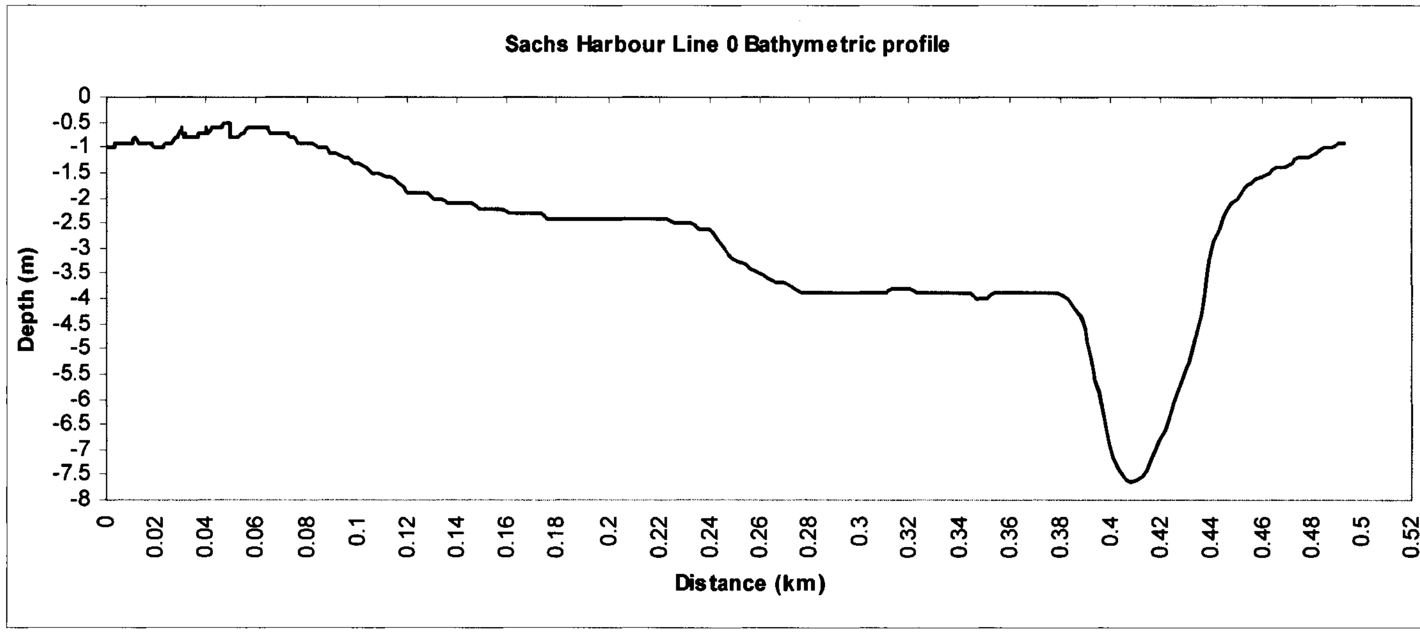


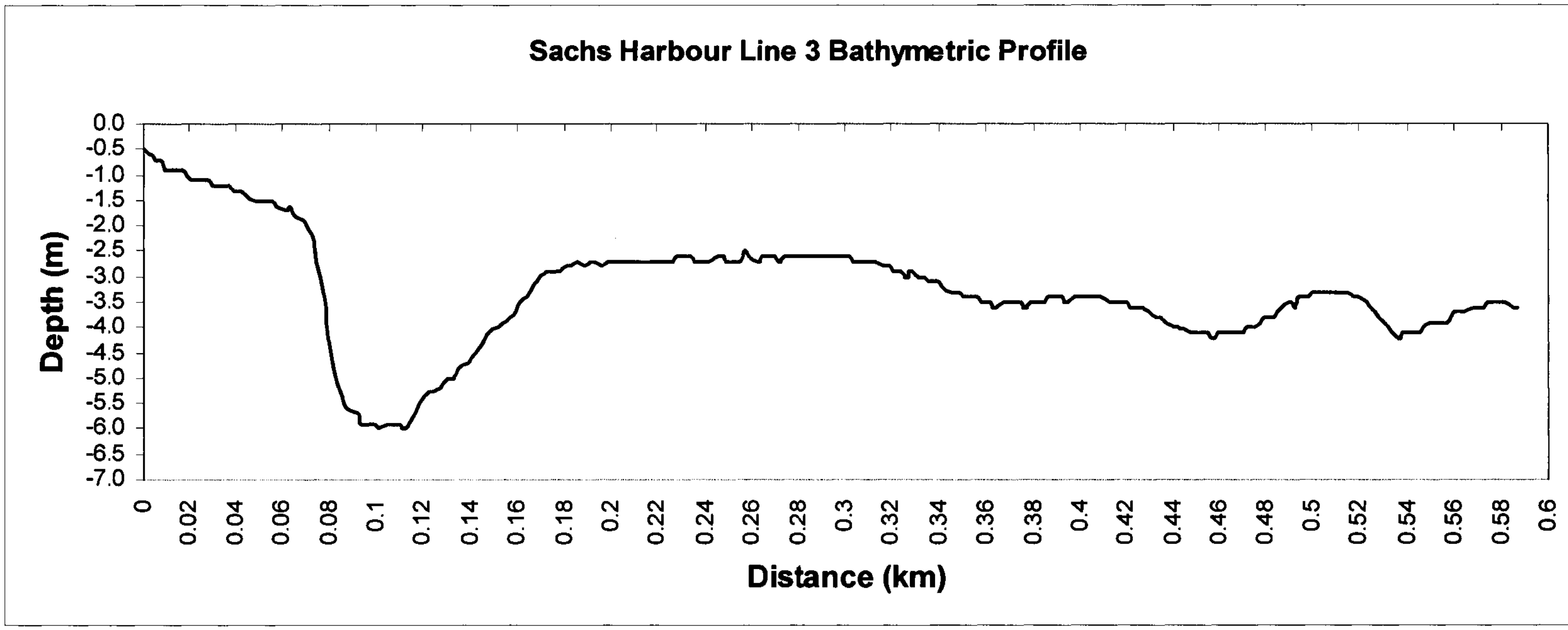


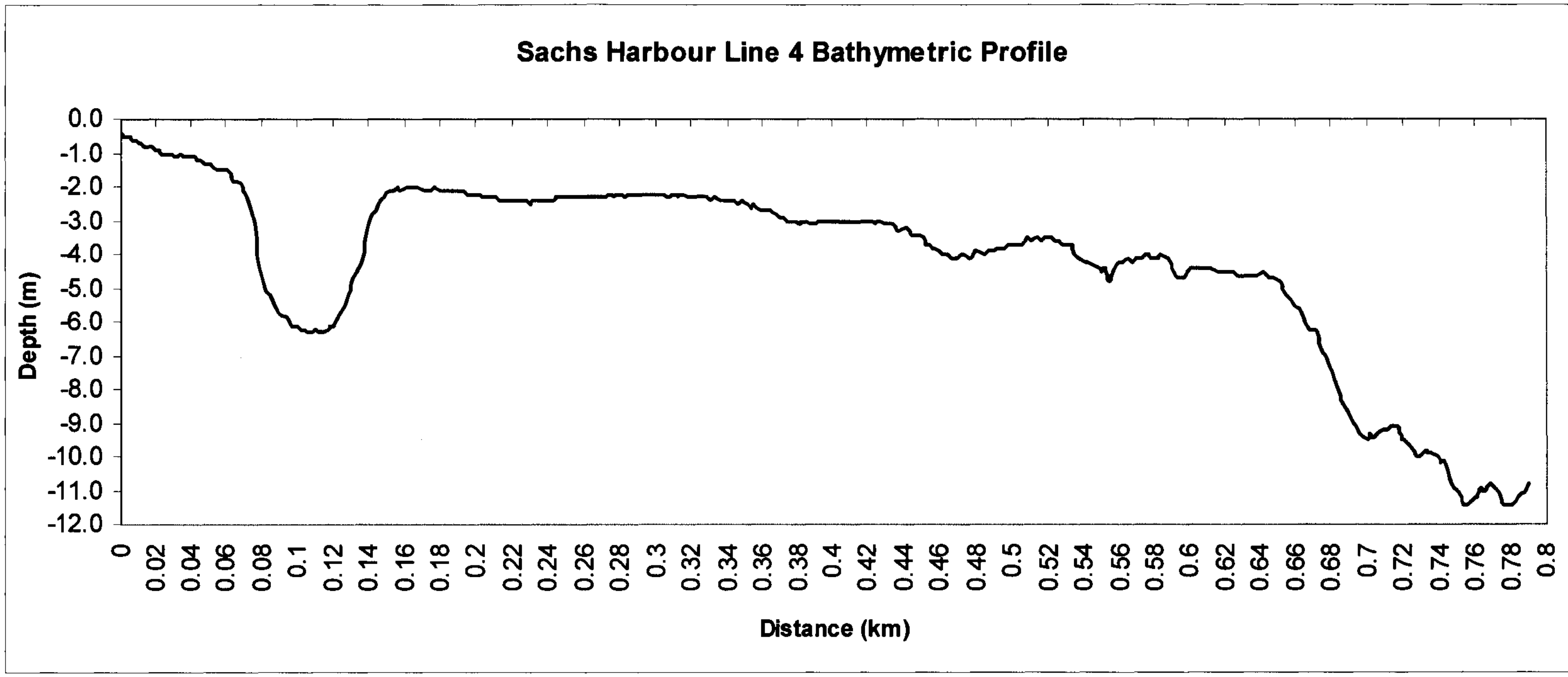
Sachs Spit Line 2 Bathymetric Profile
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
-6.5
-7
-7.5
-8
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22 0.24 0.26 0.28 0.3 0.32 0.34 0.36 0.38 0.4 0.42 0.44 0.46 0.48 0.5 0.52 0.54 0.56 0.58 0.6 0.62 0.64 0.66 0.68 0.7 0.72 0.74 0.76 0.78 0.8 0.82
Distance (km)

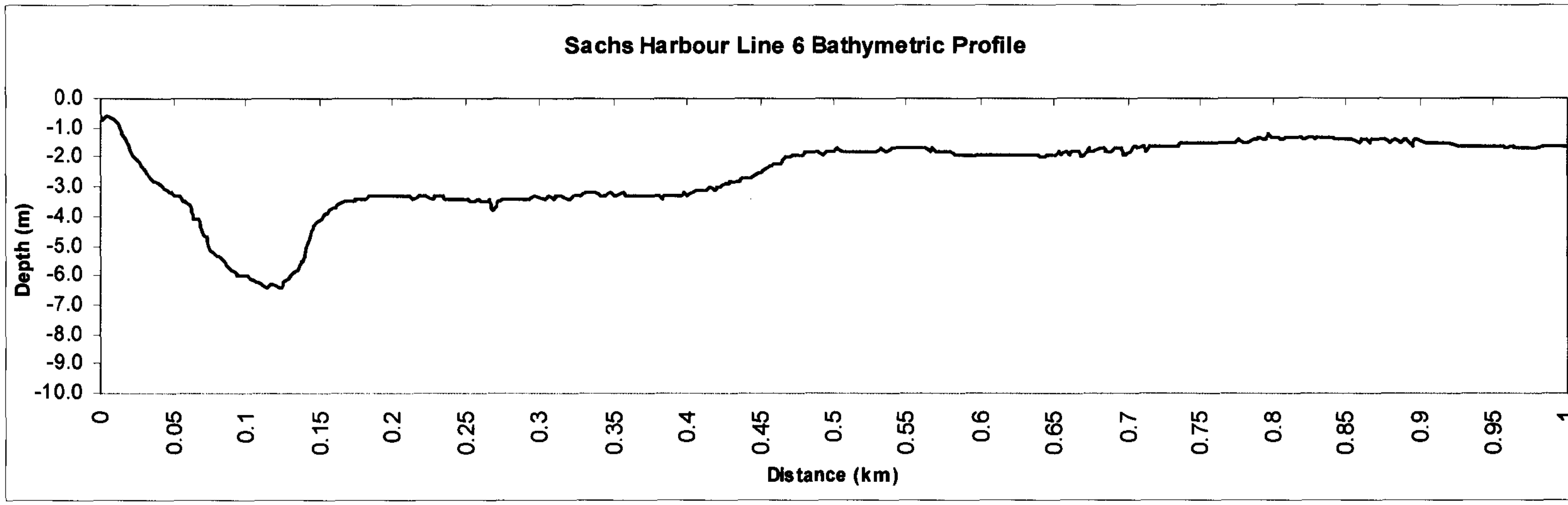

Sachs Spit Line 3 Bathymetric Profile (Eastward)
Depth (m)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Distance (km)

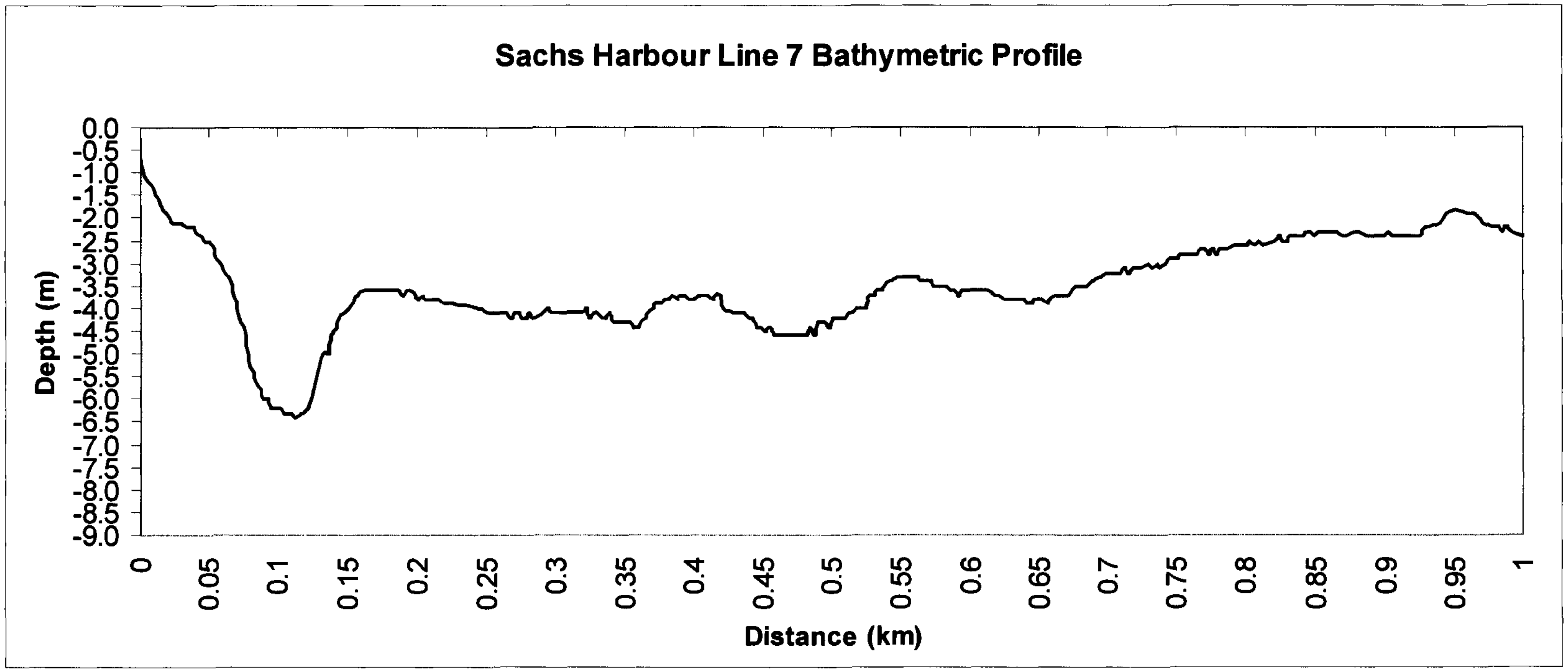

Sachs Spit Line 3 Bathymetric Profile (Westward)
Depth (m)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
-6.5
-7.0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.40
0.42
0.44
0.46
0.48
0.50
0.52
0.54
0.56
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
Distance (m)

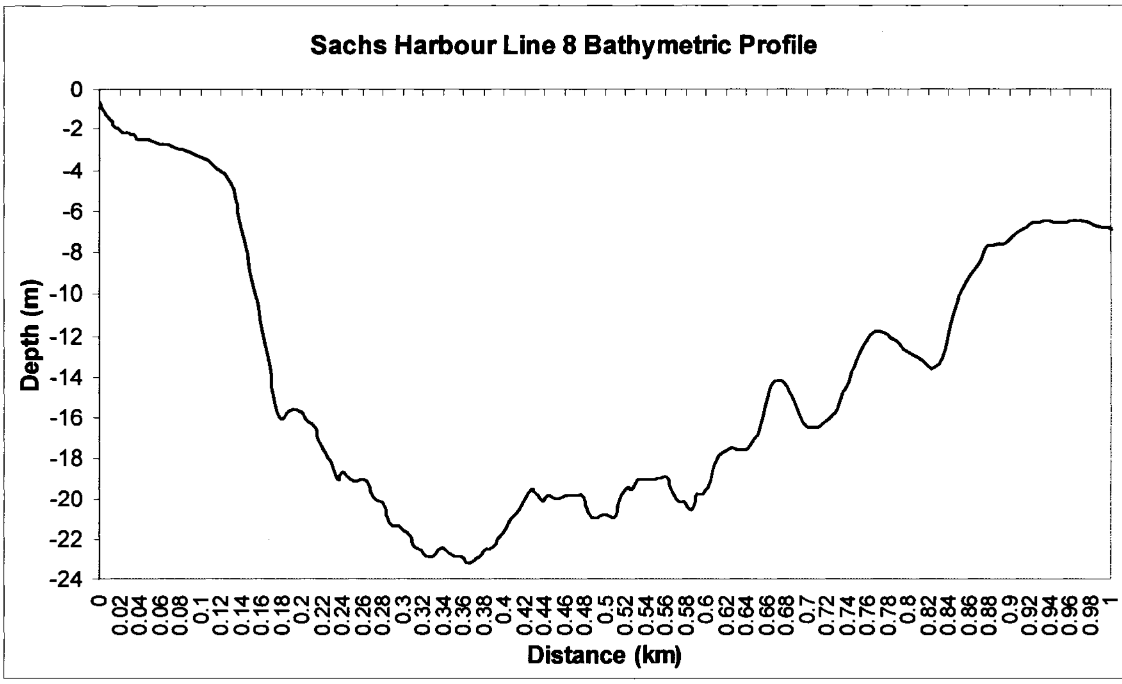

Sachs Harbour Line 0 Bathymetric profile
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
-6.5
-7
-7.5
-8
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
Distance (km)

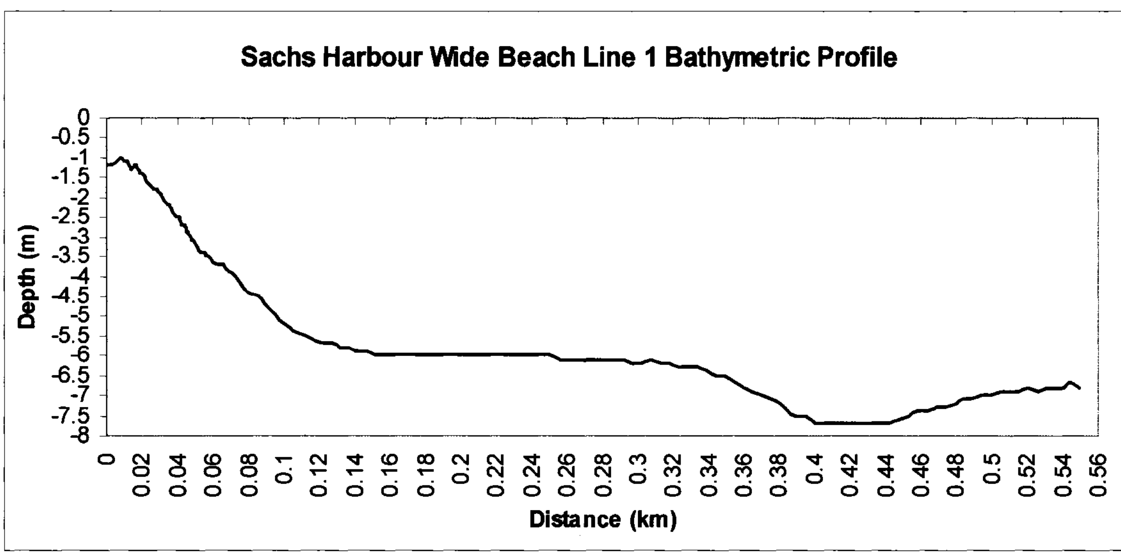

Sachs Harbour Line 3 Bathymetric Profile
Depth (m)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
-6.5
-7.0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
Distance (km)

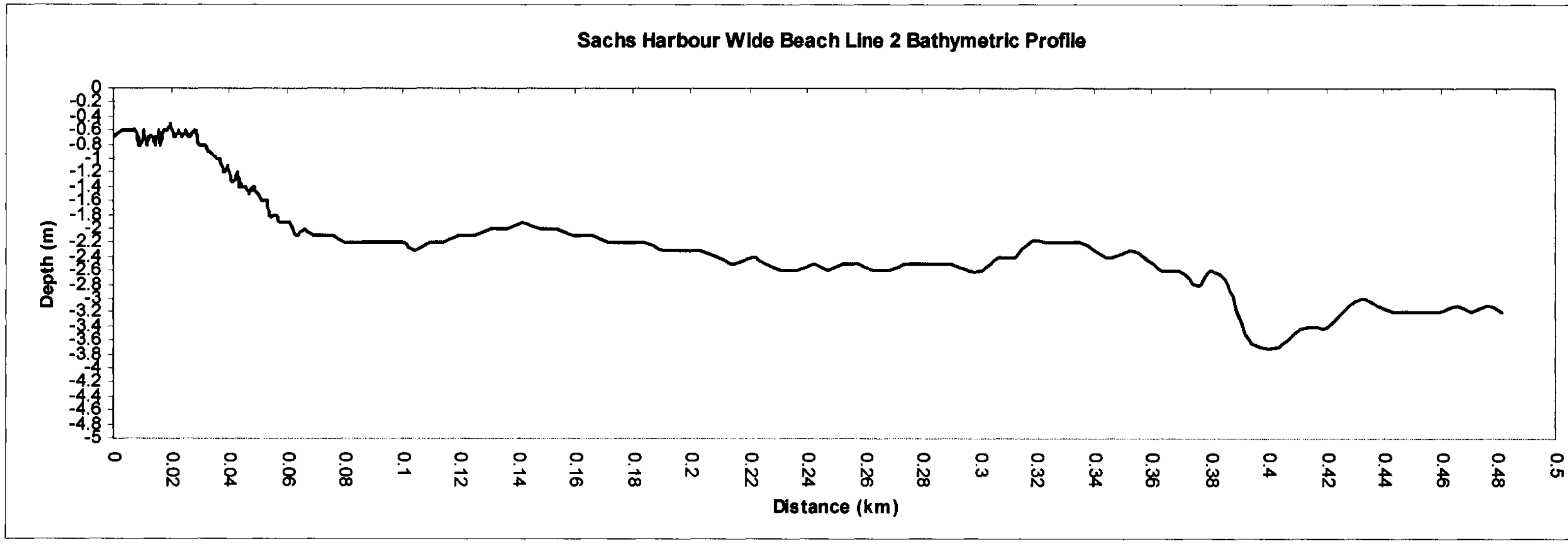

Sachs Harbour Line 4 Bathymetric Profile
Depth (m)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
-10.0
-11.0
-12.0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
0.62
0.64
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
Distance (km)

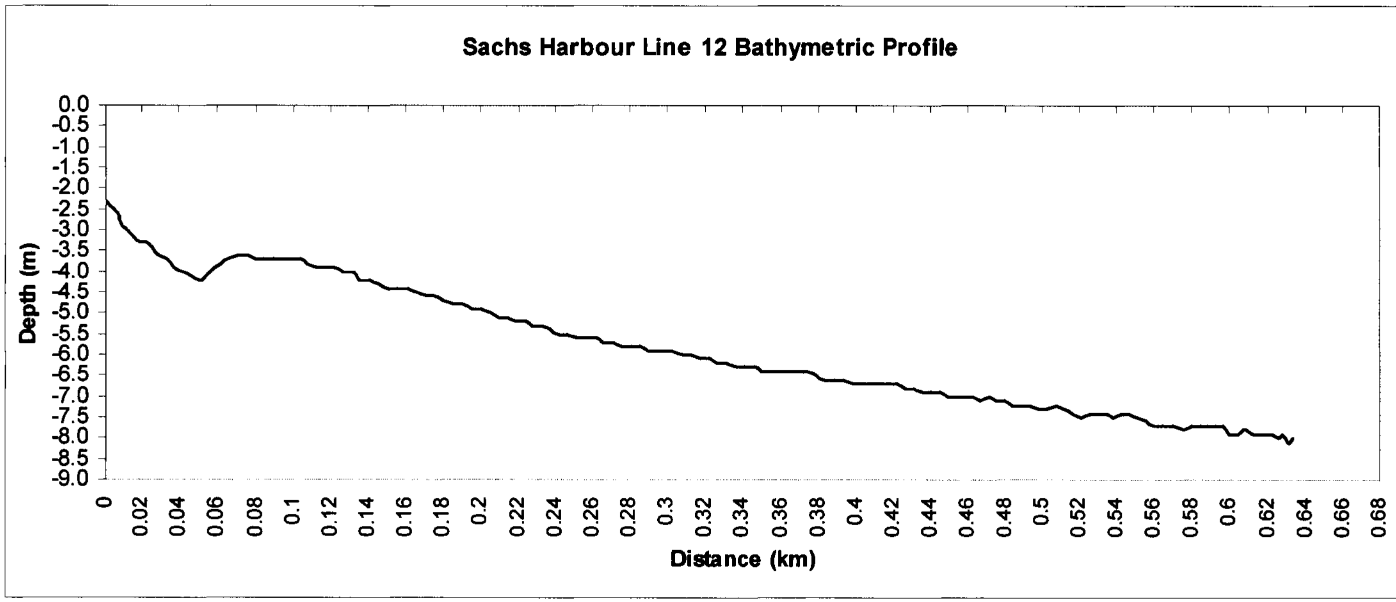

Sachs Harbour Line 6 Bathymetric Profile
Depth (m)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
-9.0
-10.0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Distance (km)

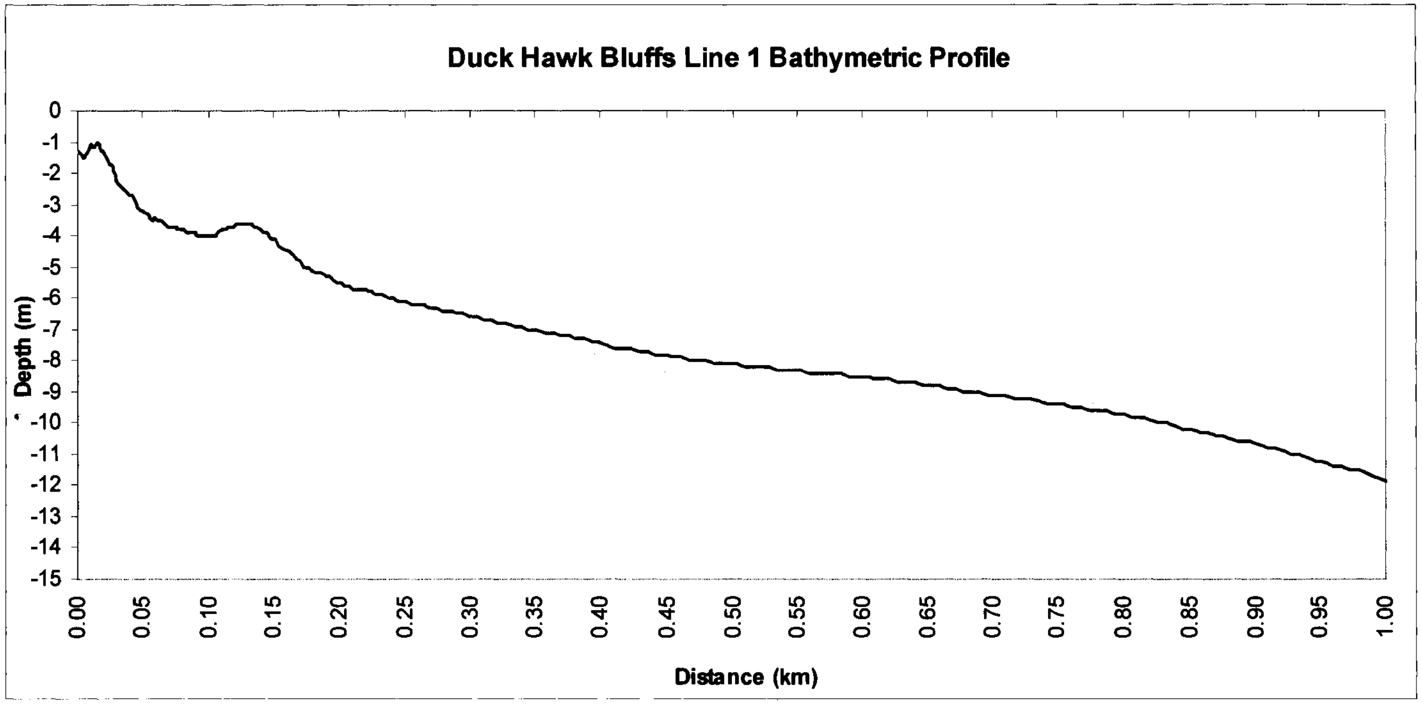

Sachs Harbour Line 7 Bathymetric Profile
Depth (m)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
-6.5
-7.0
-7.5
-8.0
-8.5
-9.0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Distance (km)

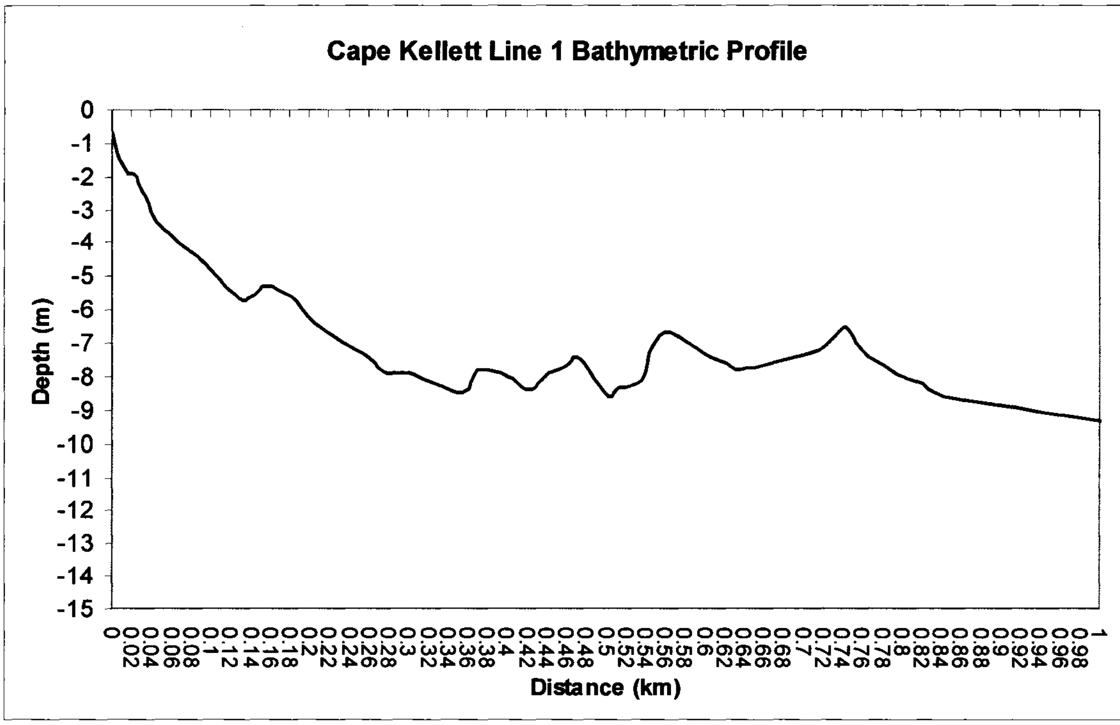

Sachs Harbour Line 8 Bathymetric Profile
Depth (m)
Distance (km)

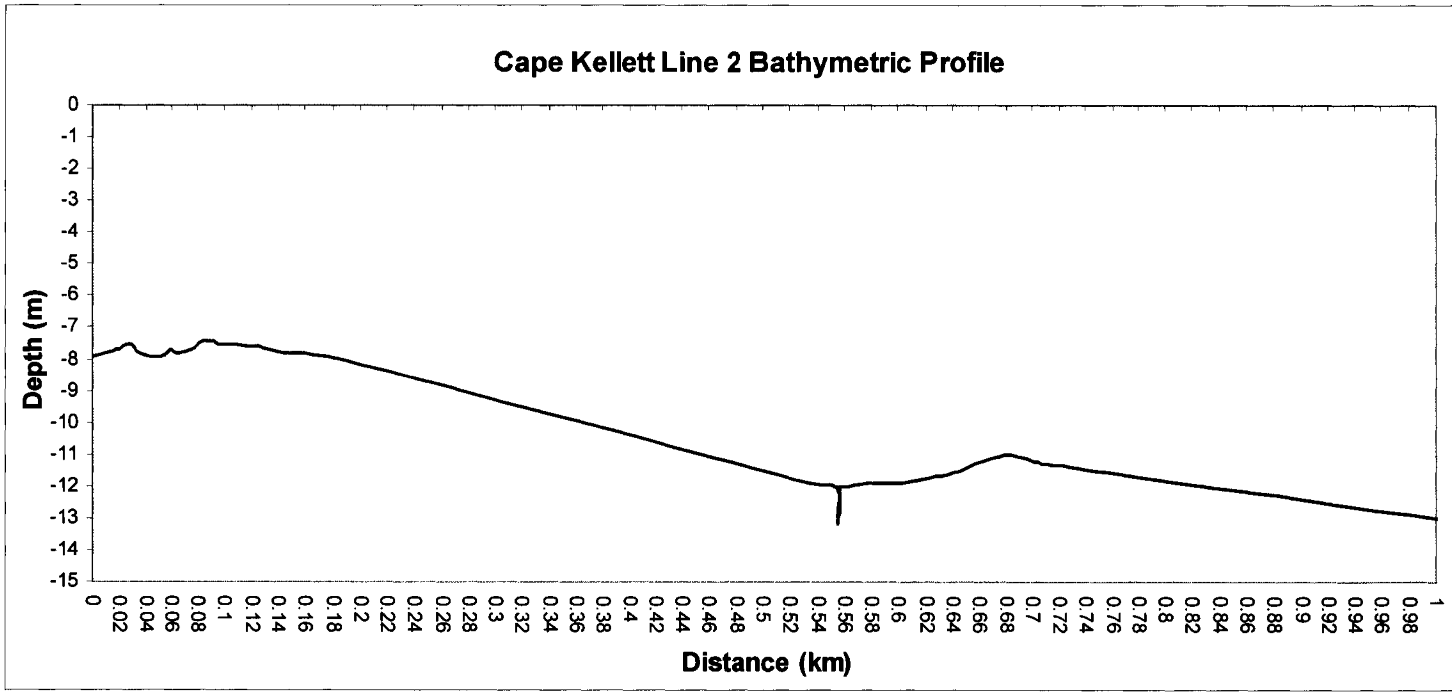

Sachs Harbour Wide Beach Line 1 Bathymetric Profile
Depth (m)
Distance (km)


Sachs Harbour Wide Beach Line 2 Bathymetric Profile
Depth (m)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
-2.8
-3
-3.2
-3.4
-3.6
-3.8
-4
-4.2
-4.4
-4.6
-4.8
-5
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
Distance (km)


Sachs Harbour Line 12 Bathymetric Profile
Depth (m)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
-6.5
-7.0
-7.5
-8.0
-8.5
-9.0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
0.62
0.64
0.66
0.68
Distance (km)


Duck Hawk Bluffs Line 1 Bathymetric Profile
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
Distance (km)


Cape Kellett Line 1 Bathymetric Profile
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
0.62
0.64
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
0.82
0.84
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1
Distance (km)


Cape Kellett Line 2 Bathymetric Profile
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
0.62
0.64
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
0.82
0.84
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1
Distance (km)

Appendix D – Sediment Sample Grain Size and Sorting

Sample	East (WGS 84)	North (WGS 84)	Grain Size	Sorting
Ln0_clf	423987	7988481	fine sand	moderately well sorted
Ln0_bh	423983	7988469	gravel	poorly sorted
Ln0_10	423982	7988457	Fine sand	very well sorted
Ln0_100	423982	7988363	medium sand	moderately sorted
Ln2_100	423028	7988500	very coarse sand	moderately well sorted
Bcn_bh	421073	7988788	coarse sand	poorly sorted
Bcn_20	421086	7988744	fine sand	moderately sorted
Bcn_100	421072	7988683	very fine sand	moderately sorted
WB1_bh	420713	7988789	medium sand	moderately well sorted
WB1_100	420764	7988656	fine sand	moderately well sorted
WB2_bh	420039	7988770	fine sand	well sorted
WB2_20	420048	7988741	medium sand	moderately well sorted
WB2_100	420046	7988650	very fine sand	moderately sorted
TH9_bh	417651	7988548	gravel	poorly sorted
TH9_20	417650	7988477	fine sand	well sorted
GI_20	417005	7988471	fine sand	moderataly well sorted
GI_100	417008	7988391	fine sand	moderately well sorted
TH10_clf	416710	7988490	silt	moderately well sorted
TH10_bh	416709	7988479	very coarse sand	poorly sorted
TH10_20	416707	7988456	fine sand	moderately well sorted
Th10_90	416675	7988385	fine sand	well sorted
TH11_bh	414985	7988291	very coarse sand	poorly sorted
Ln11_100	414977	7988164	fine sand	well sorted
TH12_clf	414434	7988218	coarse sand	very poorly sorted
Th12_bh	414436	7988203	very coarse sand	poorly sorted
Th12_100	414403	7988154	gravel	well sorted
DHB1_bh	404471	7986392	very coarse sand	moderately sorted
DHB1_20	411485	7987521	gravel	moderately sorted
DHB1_100	404474	7986296	gravel	moderately well sorted
DHB2_bh	411490	7987553	gravel	poorly sorted

DHB2_100	411488	7987450	Gravel	poorly sorted
CK1_S	401612	7986846	gravel	moderately sorted
CK_1S_100	401609	7986742	very coarse sand	very poorly sorted
CK2_S	399286	7987397	gravel	well sorted
CK_2S_100	399283	7987295	very coarse sand	poorly sorted
CK3_N	396626	7988501	gravel	poorly sorted
CK3_S	396142	7988429	gravel	well sorted
CK4_E	396791	7989544	very coarse sand	moderately well sorted
CK4_W	396742	7989566	gravel	well sorted
CK5_S	397860	7990214	gravel	poorly sorted
CK5S_100	396140	7988325	Silt	moderately sorted
SS1_bh	422527	7985346	medium sand	well sorted
SS1_20	422490	7985341	fine sand	very well sorted
SS1_100	422493	7985239	fine sand	very well sorted
SS1_780	422496	7984561	fine sand	moderately well sorted
SS2_E	422353	7985685	fine sand	well sorted
SS2_W	422297	7985655	fine sand	well sorted
SS2W_100	422291	7985528	medium sand	moderately well sorted
SS3_W	421807	7986314	medium sand	well sorted
SS3_20	421795	7986266	fine sand	well sorted
SS3_100	421795	7986196	fine sand	well sorted

Appendix E – Wind Frequency 1978 – 2005

Wind Frequency by direction, Sachs Harbour, July – September 1978 – 2005 (Data modified from Environment Canada).

Sector	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	N	Calm
July	8.31	4.34	4.14	1.35	4.38	7.30	13.07	3.87	6.51	4.92	5.77	1.54	7.14	6.68	13.72	5.63	1.37
Aug	6.72	3.54	4.20	1.23	6.93	9.04	13.49	3.13	5.53	3.98	6.66	2.69	7.60	7.51	11.90		
Sept	9.61	5.07	8.90	3.44	14.72	9.73	8.44	1.96	3.50	1.93	3.80	1.92	4.81	5.41	10.08	4.13	2.53
July-Sept	8.22	4.32	5.75	2.01	8.68	8.69	11.67	2.99	5.18	3.61	5.41	2.05	6.52	6.53	11.90	4.56	1.94

Wind Frequency by direction, Sachs Harbour, July – October 1978 – 2005 (Data modified from Environment Canada).

Sector	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	N	Calm
July	8.31	4.34	4.14	1.35	4.38	7.30	13.07	3.87	6.51	4.92	5.77	1.54	7.14	6.68	13.72	5.63	1.37
Aug	6.72	3.54	4.20	1.23	6.93	9.04	13.49	3.13	5.53	3.98	6.66	2.69	7.60	7.51	11.90		
Sept	9.61	5.07	8.90	3.44	14.72	9.73	8.44	1.96	3.50	1.93	3.80	1.92	4.81	5.41	10.08	4.13	2.53
Oct	8.89	8.75	12.93	4.78	20.19	9.32	5.27	1.15	2.20	1.53	2.48	1.67	4.70	3.85	6.93	3.32	2.05
July-Oct	8.39	5.42	7.54	2.70	11.56	8.85	10.07	2.53	4.43	3.09	4.68	1.95	6.06	5.86	10.66	4.25	1.97