Shorelines beneath the sea:
Geomorphology and characterization of the postglacial sea-level lowstand, Cumberland Peninsula, Baffin Island, Nunavut

by

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ABSTRACT

This thesis presents the discovery of eight submerged deltas (-19 to -45 m), the first documented submerged boulder barricade, a submerged sill platform and spits off the coast of Cumberland Peninsula, eastern Baffin Island, NU. The geomorphic characteristics of these features in relation to contemporaneous sea-level are presented and compared with the modern shore-zone. The submerged boulder barricade at Qikiqtarjuaq in the west indicates a -16 m sea level that isolated Broughton Channel from Baffin Bay to the north, changing the coastal dynamics from those observed at present. A shoreline deeper than -50 m planed off the fiord-mouth sill in Akpait Fiord and formed spits at -50 m and -30 m present depth. These features define a submerged shoreline gradient of 0.35 m/km to the east across northeastern Cumberland Peninsula. The linear gradient sediment supply requirements for delta formation suggest a synchronous lowstand, bracketed by ice margins and sourced from glacial outwash between 11.7-8.5 ka. This confirms the submergence trend hypothesized for eastern Cumberland Peninsula (Dyke, 1979).

ACKNOWLEDGEMENTS

This thesis would not have been possible without the help and support of many individuals, organizations and funding groups who require acknowledgement. I would first like to thank both of my supervisors, Dr. Donald Forbes and Dr. Trevor Bell for introducing me to the people and landscape of the Canadian Arctic and the research taking place; it was the experience of a lifetime. I have learned so much from their knowledge, stories and the experiences they have given me. I was motivated to always strive for more from their unimaginable knowledge and curiosity for the natural landscape.

I would like to thank the Hamlet of Qikiqtarjuaq, the Government of Nunavut, and the crewmembers of the *MV Nuliajuk*, led by Captain Cecil Bannister, for their enthusiasm and support with this project. In particular, our boatman, guide, ATV driver, carpenter, and bear monitor, Jonah Keyookta, who was the keystone to our fieldwork in Broughton Channel. I greatly appreciate the welcoming environment of Silasie and Ragelee Angnakok and the Angnakok family, who shared their home and introduced me to Qikiqtarjuaq. It was a pleasure to meet many members of the community who shared their language, stories about the land and the way of life in the Arctic. Qujannamiik.

Fieldwork in the Canadian Arctic is a great expense, and provides many challenges. ArcticNet, the Natural Sciences and Engineering Research Council (NSERC), the

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I would also like to thank some people who added greatly to this project in all aspects over the years, particularly James Muggah (OMG), Christine Legere (MUN), Alec Aitken (U of S), Annina Margreth (Dalhousie), Art Dyke (GSC) and many of the staff at the Geological Survey of Canada-Atlantic for their technical support, availability and advice during my fieldwork, data analysis and interpretation. The multibeam surveys and maps would not have been possible without the work of the Ocean Mapping Group at UNB.

Finally, I could not have made it this far, or into this field, without my parents' open minds and positive encouragement for whatever path I choose. I would like to thank my family and friends for their support, friendship, and curiosity in my field of study; they enhanced my interest and motivation for this project.

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LIST OF ABBREVIATIONS

asl	above sea level
bsl	below sea level
CIS	Coastal Information System
GIA	glacial isostatic adjustment
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
GSC	Geological Survey of Canada
IPCC	Intergovernmental Panel on Climate Change
LGM	Last Glacial Maximum
LIA	Little Ice Age
LIS	Laurentide Ice Sheet
MBES	multibeam bathymetry echosounder systems
MSL	mean sea level
NAPL	National Air Photo Library
OMG	Ocean Mapping Group
PIC	Penny Ice Cap
RSL	relative sea level
RTK	real-time kinematic

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CO-AUTHORSHIP STATEMENT

I was lead author on all chapters within this thesis, throughout which my academic supervisors, Dr. Trevor Bell and Dr. Donald Forbes, provided guidance and input on the research and writing.

My role in the preparation and production of this thesis included synthesizing the literature to outline the knowledge gaps and sea level hypothesis set out for eastern Cumberland Peninsula. From this dataset I outlined the objectives and scope of my research, after which I proceeded to collect, analyze and interpret the data, draft the thesis chapters and manuscripts, and complete revisions. My supervisors were involved with the fieldwork and acquisition of data as well as the development of the concepts and ideas explored, and provided edits of the prepared thesis. They delivered guidance and support in all aspects of the research and were responsible for securing funding for fieldwork and sample analysis, on which this thesis is based.

CHAPTER 1: INTRODUCTION

1.1 Research Context

Submerged shoreline features have been documented around the former ice margins of the Laurentide Ice Sheet (LIS) at depths indicative of differential glacial-isostatic adjustment (GIA; e.g. Belknap et al., 1987; Liverman, 1994; Forbes et al., 1993; Shaw and Forbes, 1995; Shaw, 2005). Models of GIA (the differential vertical motion of the crust due to glacial loading and unloading processes) have predicted the occurrence of submerged early Holocene shorelines on Cumberland Peninsula, Baffin Island (Fig. 1.1) at the easternmost margins of the LIS (Quinlan and Beaumont, 1981; Tarasov and Peltier, 2004). Miller and Dyke (1974) and Miller (1975) reported submerged delta terraces supporting the postglacial submergence model for northeastern Cumberland Peninsula. This thesis provides the first systematic documentation and characterization of submerged shoreline features in Cumberland Peninsula, including the first reported submerged boulder barricade in the literature.

Formerly glaciated regions of North America have experienced complex processes of GIA since the retreat of the LIS. At the easternmost limit of the LIS in the Canadian Arctic, Baffin Island (Nunavut) has recorded a postglacial history of isostatic adjustment and relative sea level (RSL) change. Cumberland Peninsula

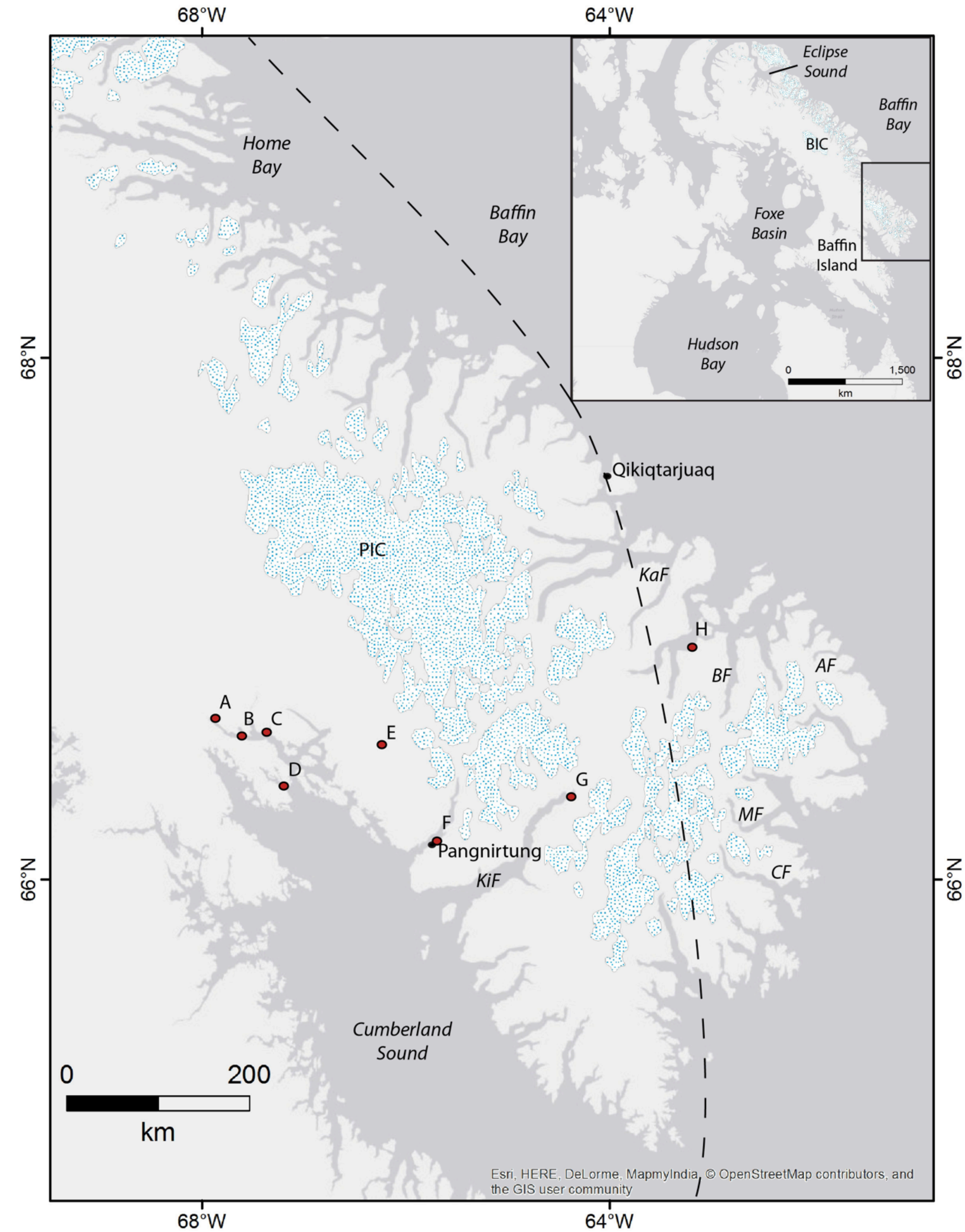

Figure 1.1: Cumberland Peninsula with inset of the eastern Canadian Arctic Archipelago. Dashed line represents the highly disputed present zero isobase, interpreted by Kaplan and Miller (2003). A-H mark the locations of Dyke's (1979) RSL curves (Fig. 1.6). PIC: Penny Ice Cap. BIC: Barnes Ice Cap. AF: Akpait Fiord. BF: Boas Fiord. CF: Clephane Fiord. KaF: Kangert Fiord. KiF: Kingnait Fiord. MF: Mermaid Fiord.

has experienced a postglacial RSL history that includes both emergence and submergence of its coastline (Dyke, 1979). These RSL trends have been extrapolated from marine limit shorelines dated 8.5 ka along the southwestern coast (Dyke, 1979). Together, these synchronous early Holocene raised deltas indicate an eastward dipping shoreline, which when extrapolated, intersects the present sea level east of Kingnait Fiord (southern Cumberland Peninsula, Fig. 1.1). Dyke (1979) hypothesized that this synchronous marine limit shoreline continued below sea level on the eastern Cumberland Peninsula (Pheasant and Andrews, 1973; England and Andrews, 1973; Dyke, 1979; Andrews, 1980; Clark, 1980; Andrews and Miller, 1985; Andrews, 1989).

The absence of documented raised early Holocene marine features on the eastern Cumberland Peninsula supports the hypothesis of postglacial submergence. Depth soundings in the northeastern fiords of Cumberland Peninsula presented the earliest evidence to support the submergence model (Miller and Dyke, 1974; Miller, 1975). These soundings recorded the first profiles of submerged terraces interpreted as deltas off eastern Baffin Island. The depositional age of these delta terraces was not established, but they were interpreted to correlate with late Foxe moraines (10,500-9400 ^{14}C yr BP; Miller, 1975). Without further information on the spatial distribution of submerged shorelines, the postglacial crustal tilt and sea-level trends of eastern Cumberland Peninsula remain poorly constrained.

Until this study, the submerged coastal setting in Cumberland Peninsula had not been explored because neither technological resources nor logistical access were readily available. Multibeam echosounder technology has developed to provide full-coverage, high-resolution, shaded relief imagery and maps of the seafloor topography. In 2011, the Government of Nunavut (GN) commissioned the research vessel, *MV Nuliajuk*, equipped with multibeam and subbottom echosounders to conduct research and training for Nunavut fisheries, as well as to map the uncharted waters of eastern Baffin Island. Seabed mapping surveys conducted by the *MV Nuliajuk* also aimed to document submerged shoreline features for evidence of submergence on eastern Cumberland Peninsula.

This research project was undertaken to extend the record of isostatic tilting and sea-level trends inferred from raised shorelines on Cumberland Peninsula. The main objectives of this research were:

(1) to locate and map submerged shoreline features within targeted fiords and inlets on Cumberland Peninsula;

(2) to map the water depths and geomorphology of these submerged shoreline features;

(3) to evaluate the utility of these features as submerged sea-level indicators;

(4) to interpret the spatial pattern of submergence on Cumberland Peninsula.

To achieve these objectives, fiords and coastal inlets on Cumberland Peninsula were surveyed from Qikiqtarjuaq in the north to Pangnirtung in the south. Using multibeam imagery and subbottom profiles, this thesis characterizes the geomorphology of submerged shorelines on Cumberland Peninsula, with particular emphasis on their spatial distribution and utility as sea-level index points.

1.2 Sea-level history in the Canadian Arctic

The Canadian Arctic has experienced a complex history of crustal adjustment from the legacy of Quaternary glaciation. Glacial isostatic adjustment played a significant role in the RSL history of glaciated landscapes. The loading and unloading of ice masses during and following the Last Glacial Maximum (LGM) resulted in the redistribution of mass in the lithosphere and vertical crustal adjustments, known as glacial-isostasy. The accumulation of ice mass on top of the crust formed a subglacial depression in the elastic lithosphere that extended beyond the margin of the ice sheet due to flexural rigidity (i.e. proglacial depression; Liverman, 1994; Gray, 1996). The asthenosphere was displaced away from the centre of loading and formed a forebulge around the peripheral margin of the LIS, beyond the zone of proglacial depression (Fig. 1.2). The thickness of the LIS varied spatially and resulted in differential loading of the crust, which was greatest where the ice was thickest and decreased towards the margin (Walcott, 1970).

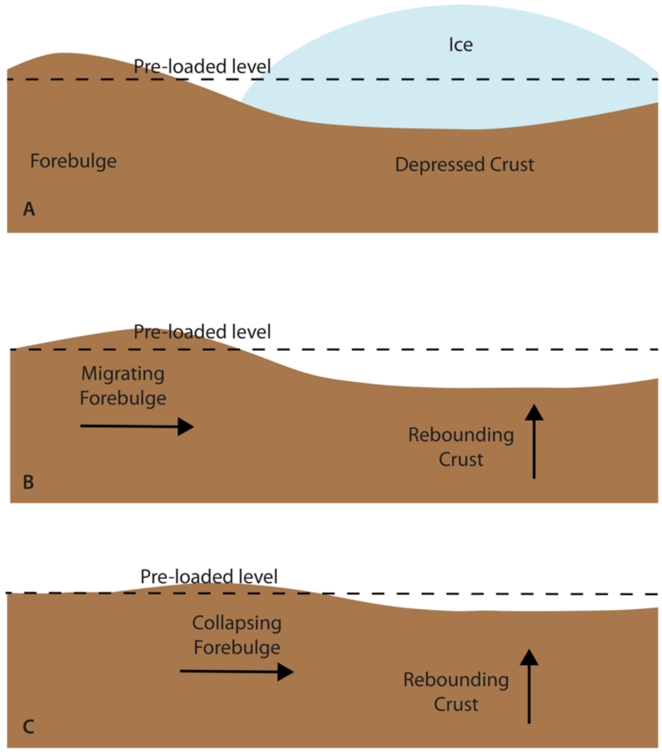

Figure 1.2**:** Schematic diagram (not to scale) of the loading and unloading processes on a glaciated landscape. A) LGM results in a loaded and depressed crust, with a proglacial depression at the ice margin and proximal forebulge. B) The recession of the ice mass results in a crustal rebound, while the forebulge migrates inwards towards the centre of the ice mass. C) Over the course of forebulge migration, it also collapses. All the while, the landscape is moving back to pre-loaded equilibrium. Based on Quinlan and Beaumont, 1981.

Unloading of the ice mass during deglaciation resulted in a rapid elastic crustal response and a slow ongoing viscous equilibration of the asthenosphere on the order of 10,000 years (Gray, 1996). Equilibration of the crust to its pre-loaded configuration is achieved through the inward migration and eventual collapse of the forebulge (Walcott, 1970; Quinlan and Beaumont, 1981; Gray, 1996; Woodroffe, 2002). Figure 1.3 is a schematic diagram of four locations on the forebulge and their modeled sea level curves as a result of postglacial forebulge migration.

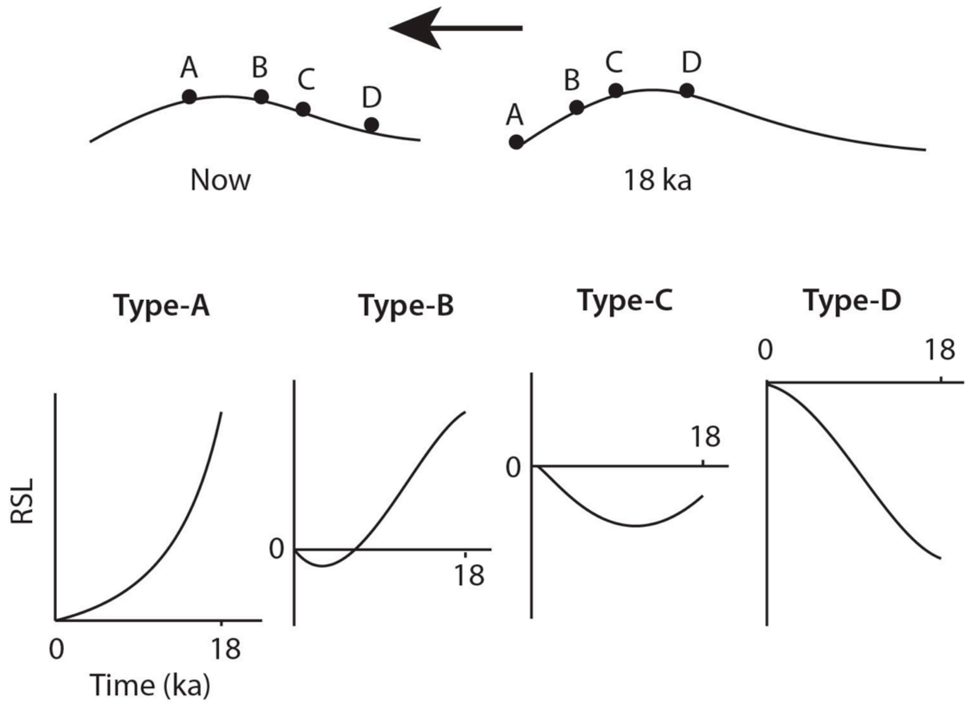

Figure 1.3: Schematic diagram for the postglacial forebulge migration (to the left), and the related RSL curve for sites A, B, C, and D. Modified from Quinlan and Beaumont (1981).

Subglacial landscapes experienced postglacial uplift and emergence (Type-A), whereas locations on the crest and outer slope of the forebulge experienced submergence (Type-D). Type-B and type-C curves present the typical J-shape predicted for regions influenced by the migration of the forebulge crest. These curves model the postglacial RSL fall to an inflection point when the crest of the forebulge reaches site B or C. The inflection point occurs when the RSL trend switches from emergence to submergence and is known as the local sea-level lowstand. Type-B and -C curves are characterized by the extent of the regressive limb down to the lowstand and the transgressive limb up to present sea level. Type-B curves delimit initial emergence as site B is uplifted by the crest of the forebulge, followed by recent submergence after the forebulge crest migrates through the location of site B. Type-B curves can result in a succession of raised shorelines down to modern sea level. Except at sites of substantial sediment supply, lowstand and post-lowstand transgressive shorelines have since been submerged (St.-Hilaire et al., 2015). In contrast, site C is located on the inner crest of the forebulge and experiences a relatively short emergence trend up the forebulge crest, and therefore Type-C curves are predominantly characterized by submergence related to the passing of the distal slope of the forebulge crest. Shoreline features formed along Type-C curves have all been submerged and the modern sea level marks the postglacial marine limit (Liverman, 1994).

Glacial isostasy, together with glacial eustasy (global mean sea level), caused the major sea level changes throughout the Late Quaternary. Glacial eustasy is affected by variability in the volume of water held in land-based ice. Oxygen-isotope analyses of foraminifera within deep-sea sediment cores have been used as proxies for trends in ice sheet and ocean volume during the Quaternary (Fairbridge, 1983; Gray, 1996). Regions influenced by glacial-isostasy have complex sea-level trends in comparison to non-glaciated regions, and therefore have been divided into zones (Clarke et al., 1978): Zone I is a region of continuous postglacial emergence, and Zone II is a region of continuous postglacial submergence. In between the zones of emergence and submergence is a transition zone (Zone I/II) influenced by the migration of the forebulge. The transition zone is dependent on the distance from the ice sheet and location on the forebulge, but is characterized by Type-B and –C curves (Fig.1.3) with a postglacial RSL trend of initial emergence, followed by submergence (Clarke et al., 1978; Quinlan and Beaumont, 1981).

The central Arctic, which was a major loading centre of the LIS, is currently experiencing crustal emergence, whereas shorelines in the eastern and western Arctic that are distal to former LIS limits are presently submerging. The boundary between Zones I and II is known as the zero isobase, which at present is poorly defined across the Canadian Arctic (Fig. 1.4; Andrews and Peltier, 1989; Forbes et al., 2004).

The Intergovernmental Panel on Climate Change (IPCC, 2013) reported that sea level has continued to rise over the recent decades as a result of ocean warming (thermal expansion) and melting of land-based glaciers and ice sheets. Reconstructed sea-level histories based on geological data have constrained the regional crustal responses since deglaciation and extended the record of RSL beyond the instrumental range. Current rates of vertical crustal motion and sea-level change are not well defined in the Canadian Arctic, due to the sparse array of long-term GPS and tide gauge recording stations (Fig. 1.4).

Sea-level fingerprinting refers to the sea-level response to the gravitational pull of ice sheets on the adjacent ocean water, and the major sources of ice mass loss

Figure 1.4: Overview map of the Canadian Arctic, highlighting the present zero isobase after Andrews (1989) and the episodic and continuous GPS (CGPS) monitoring sites and CGPS co-located with tide gauge equipment (WL; Water Level). The central Arctic, in between the bounding zero isobase, is experiencing uplift and land emergence. Whereas outside this zone, to the east and west, are regions of postglacial subsidence contributing to coastal submergence. Modified from Forbes et al. (2004).

around the world (James et al., 2014). Receding alpine glaciers and ice caps provide important sources of meltwater in Canada, but the Greenland Ice Sheet delivers a significant volume of meltwater to the oceans as a site of ice mass loss (James et al., 2014). As the ice sheet melts, the gravitational pull is reduced and the adjacent ocean surface falls (James et al., 2014). The eastern Canadian Arctic is particularly affected by sea-level fingerprinting from multiple ice sources, which is an important factor to incorporate into sea level projections.

The average positive sea-level trend on Arctic coastlines was 2.57 ± 0.45 mm/yr (for 1954-2009) after correction for GIA. This rate is considerably larger than that of the global mean sea level rise, which has an observed trend of 1.94 ± 0.47 mm/yr over the same time period (Forbes, 2011). The RSL rise observed across the Arctic Archipelago is attributed to ocean warming and expansion, freshening and wind-driven effects, and glacio-isostasy (Forbes, 2011; James et al., 2014). The positive sea-level trend is enhanced for regions experiencing subsidence along the eastern and western Arctic.

The IPCC (2013) projects global mean sea level to rise by the end of the century. Rising sea level will enhance the predicted changes in the sea ice extent and duration, storm intensity and wave action (Forbes, 2011). Future coastal stability is a complex issue with many variables; a more robust prediction of future sea-level change can help to understand this changing environment. Dated shoreline indicators are used to reconstruct the regional palaeo-sea-level trends, which help to validate and modify models of crustal geodynamics throughout the Quaternary (Simon et al., 2015). Added to the current observations, palaeo-sea level data provide a more robust baseline for future sea-level projections.

1.2.1 Eastern Baffin Island

Eastern Baffin Island uplifted tectonically when Greenland rifted from North America during the Late Cretaceous to Paleogene Period. Cumberland Peninsula, the easternmost limit of the Canadian Arctic, was formed as a horst to the Cumberland Sound graben at this time (Dyke et al., 1982; Kaplan and Miller, 2003). Its physiography is made up of mountainous terrain and fiords, carved by glacial and fluvial erosion of the uplifted landscape (Miller et al., 2005).

Baffin Island presents a multitude of coasts controlled by both the bedrock and general physiography as well as fluvial, glacial and oceanic processes (Miller et al., 1980). These coastal settings are mainly steep to moderately sloping bedrock cliffs, especially in the fiords of eastern Baffin Island. Localized coastal landforms common to the Canadian Arctic are also prominent along the east coast of Baffin Island. These include gravel to sand beaches, barriers and beach-ridge plains, tombolos and spits, deltas and sandurs, fiord sills, and tidal flats including boulder flats and boulder barricades (Church, 1972; Taylor, 1980; Miller et al., 1980; McCann et al., 1981; Sempels, 1982; Aitken et al, 1988; Andrews, 1989; Forbes and Syvitski, 1994; St-Hilaire-Gravel, 2011; St-Hilaire-Gravel et al., 2015).

Two communities are located on Cumberland Peninsula: the Hamlet of Qikiqtarjuaq in the northeast, and the Hamlet of Pangnirtung in the southwest (Fig. 1.1). Climate data taken from Foxe-5 DEW line site at the southeast corner of Broughton Island documents a mean annual temperature of -11.8 °C and a mean annual precipitation of 262 mm, the majority of which is in the form of snow, from November through to July (Environment Canada, 1971-2000).

Cumberland Peninsula is bordered by Cumberland Sound to the south, Davis Strait to the east and Baffin Bay to the northwest. The Baffin Current is a cold, low-salinity surface current that runs along the eastern coast of Baffin Island, and flows from the Arctic Ocean to the North Atlantic Ocean (Tang, et al., 2004). The physiography and scale of Cumberland Peninsula presents a tidally complex region, ranging from microtidal along the northern coast to macrotidal in Cumberland Sound (Brucker et al., 2013).

1.2.1.1 Glaciation

The physiography of Cumberland Peninsula was formed by the growth and recession of ice sheets and local alpine glaciers throughout the Quaternary. At present, the Penny Ice Cap (PIC) and hundreds of local cirque and valley glaciers are located on Cumberland Peninsula. The Barnes Ice Cap (BIC; a remnant of the LIS) is situated in central Baffin Island, to the north of Cumberland Peninsula. During the LGM, locally known as the Foxe Glaciation, the LIS, PIC and alpine glaciers reached their outermost limit along the eastern coast of Baffin Island and onto the adjacent continental shelf (Fig. 1.5; Kaplan and Miller, 2003; Miller et al., 2005; Briner et al., 2009, Margreth, 2015). The land-based LIS reached as far as western Pangnirtung Fiord, whereas a marine-based LIS ice stream occupied Cumberland Sound.

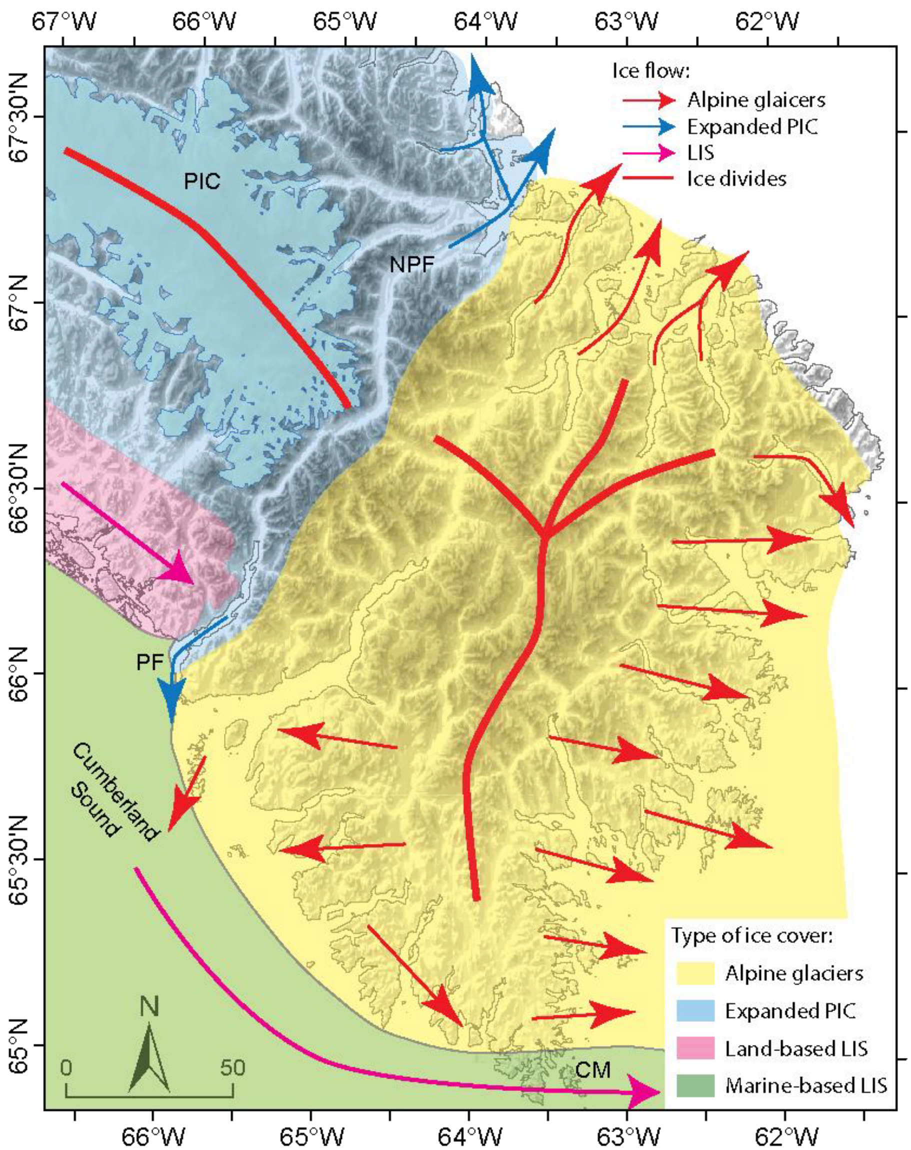

Figure 1 5: Map of generalized ice flow and extent during the LGM on Cumberland Peninsula. PIC: Penny Ice Cap, PF: Pangnirtung Fiord, CM: Cape Mercy, NPF: North Pangnirtung Fiord. From Margreth (2015).

Cumberland Peninsula was covered by alpine glacier systems in the east, deflected by the limit of the LIS in the south, and bounded by the PIC in the west (Margreth, 2015). At the LGM, low-gradient warm-based alpine outlet glaciers occupied most of the fiords and valleys of eastern Cumberland Peninsula, while much of the inter-fiord uplands remained ice-free or were covered by cold-based alpine glaciers (Kaplan and Miller, 2003; Miller et al., 2005; Margreth, 2015).

Canadian deglacial ice limits have been mapped by Dyke et al. (2003), however, at the scale of Cumberland Peninsula these limits are too low in resolution for substantial interpretation. More recently, Margreth (2015) produced the first high-resolution maps of glacial deposits combined with new cosmogenic nuclide and radiocarbon chronological data for three prominent late-glacial cooling events in Cumberland Peninsula. These provide more accurate ice limits for the late- to postglacial re-advances. Initial retreat from the LGM began by 15 ka[1], leaving the coastal fringe of eastern Cumberland Peninsula partially ice-free by 14 ka (Miller et al., 2005; Briner et al., 2009). Many cold events occurred throughout the overall glacial recession, in which the LIS, PIC and alpine glaciers re-advanced. Heinrich Event 1 (H-1) was the first re-advance of alpine ice shortly after the initial retreat of marine-based ice in Cumberland Sound (ca. 14.6 ^{14}C ka; Margreth, 2015). Two other major re-advances occurred during the Younger Dryas (YD) cold interval (ca. 12.9-11.7 ka) and the Cockburn Substage (ca. 9.5-8.5 ka).

By the end of the YD, the southeastern coast experienced rapid deglaciation that left it ice-free. Deglaciation was asymmetrical on Cumberland Peninsula, where the

[1] All calibrated ages in this thesis are indicated by ka. Uncalibrated ages are indicated by ^{14}C ka.

south coast experienced extensive deglaciation before the north (Margreth, 2015). At the YD, glaciers filled the northern fiords (Merchants Bay and Touak Fiord), were at the heads of fiords in the southeast of Cumberland Peninsula and inland of the fiord heads in the southwest (Margreth, 2015). Northern fiords experienced rapid deglaciation after the YD cold event (Dyke et al., 2003; Miller et al., 2005; Margreth, 2015).

The Cockburn Substage was a major re-advance of alpine glaciers to the fiord heads and coast (9.5-8.5 ka) during the overall deglaciation. The re-advance of Cockburn ice is attributed to increased rates of precipitation and snow accumulation instead of cooling, because peak summer temperatures occurred at 9.5 ka (Miller et al., 2005). Ice-marginal glaciomarine deposits date the Cockburn moraines to range from 9.5 to 8.5 ka (Miller and Dyke, 1974; Andrews and Ives, 1978; Briner et al., 2009). These moraines are traceable northward from Home Bay to Eclipse Sound, and are associated with ice-contact marine features (Miller, 1975; Andrews and Ives, 1978). On Cumberland Peninsula, the innermost pre-neoglacial moraines are interpreted as Cockburn-equivalent moraines, correlated to the dated Cockburn moraines along the northeast and northern margins of the LIS (Miller and Dyke, 1974; Andrews and Ives, 1978; Margreth, 2015).

After a partial recession from the Cockburn ice-limits, a re-advance of glaciers to the heads of several fiords (>8 ka) corresponds to the 8200-year cold climate event

(Miller et al., 2005; Briner et al., 2009), first recorded in the Greenland Ice Sheet (Alley et al., 1997). By 7.5 ka, a residual dome (Foxe Dome) of the LIS occupied Baffin Island. The Foxe Dome continued to recede throughout the Holocene with minor re-advances, culminating in its present limit at the Barnes Ice Cap (6000 km^2), the last remnant of the LIS (Miller et al., 2005; Briner et al., 2009). Neoglaciation began shortly after 5 ka with increased sea ice cover, which intensified between 1.9 and 1.1 ka and was followed by a recession during the Medieval warm interval (Margreth et al., 2014). The Little Ice Age (LIA) was a series of individual pulses of ice cap expansion (AD 1100-1850, 750-100 yr BP[2]) attributed to decreases in solar irradiance and the impact of large volcanic eruptions, amplified by positive sea-ice climate feedbacks (Anderson et al., 2008; Miller et al., 2012; Margreth et al., 2014).

1.2.1.2 Relative Sea Level

The ice recessional history of Cumberland Peninsula resulted in spatially variable glacial isostasy and complex regional sea-level trends. Throughout the Holocene, RSL change across most of Baffin Island was controlled by glacio-isostatic uplift and forced regression. Documented raised shorelines provide evidence of the postglacial emergence for the western Cumberland Peninsula. Dyke (1979) used these raised sea level indicators to extrapolate a series of postglacial sea-level curves along the southwestern coast of Cumberland Peninsula (Fig. 1.6). These curves are based on twenty-two radiocarbon dates on organic matter related to constructive marine features, including deltas and terraces, related to the Holocene marine limit. The

[2] yr BP refers to years before AD 1950 (Miller et al., 2012; Margreth, 2015).

marine limits form a relatively synchronous strandline at 8.5 ka with an eastward dipping gradient (0.59-0.62 m/km) that intersects present sea level east of Kingnait Fiord (Dyke, 1979). Postglacial marine shorelines were hypothesized to be below present sea level because of the eastward tilt of the shoreline gradient and the lack of raised shorelines along the eastern peninsula (Dyke, 1979; Dyke & Margreth, pers. com. 2014).

Dyke's (1979) southwestern Cumberland Peninsula sea-level curves are mainly Type-B curves of varying degrees, but range from Type-A in the west to Type-C in the east. These sea-level curves are presented as a conceptual model for the postglacial sea-level history of the region (Fig. 1.6). More explicitly, Dyke (1979) inferred that the easternmost coast has sustained continuous submergence since the LGM (Zone II), in contrast to the continuous emergence experienced on the west coast of Cumberland Peninsula and the mainland of Baffin Island (Zone I). The zero isobase is situated between the two, where the GIA and RSL trends are affected by the migration of the forebulge; however, the exact location is not well constrained. Dyke and other researchers have determined that modern sea level marks the postglacial marine limit on the outermost coast of Cumberland Peninsula, as RSL has risen from a lowstand over at least the past ca. 6 ka (Pheasant and Andrews, 1973; England and Andrews, 1973; Dyke, 1979; Andrews and Miller, 1985; Andrews, 1989).

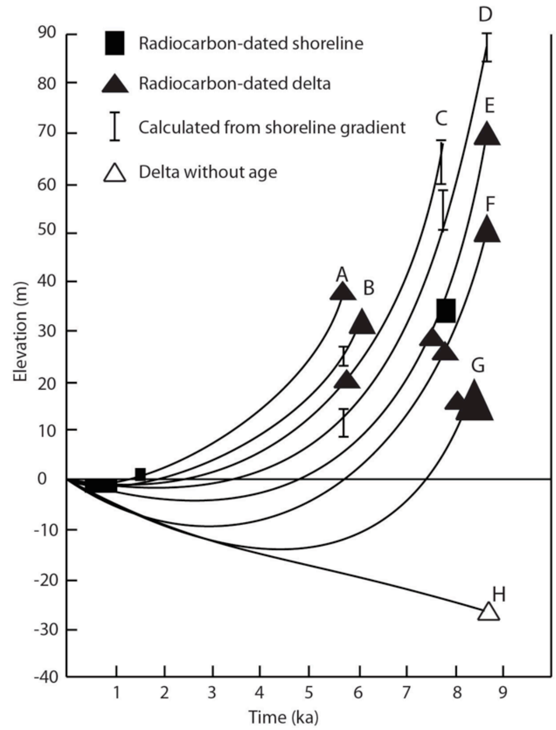

Figure 1.6: Hypothetical RSL curves for southwestern Cumberland Peninsula. Curves move progressively eastwards from the head of Cumberland Sound (A) to outer Cumberland peninsula (H). Modified from Dyke (1979).

The location of the zero isobase throughout the postglacial period has been debated in the literature. The marine limit elevation gradient between Pangnirtung and Kingnait fiords led Dyke (1979) to infer that the Late Foxe zero isobase (10,500-9400 ^{14}C yr BP) was located to the east of Kingnait Fiord. Kaplan and Miller (2003) inferred the zero isobase to lie at the eastern extent of the peninsula during this time, encompassing the peninsula in the zone of emergence. The present zero isobase is not well constrained because of the lack of long-term GPS and tide-gauge measurements, and the knowledge gap in the submerged sea-level history for the region. Kaplan and Miller (2003) constrain the present zero isobase from the RSL dataset to run north-south through central Cumberland Peninsula (Fig. 1.1).

Dyke's (1979) postglacial sea-level curves infer the submergence of eastern Cumberland Peninsula based on submerged deltas documented (28-38 m below present sea level) along the northeast coast (Miller and Dyke, 1974; Miller, 1975). Miller (1975) determined these deltas to be of Late Foxe age, however the age of deposition has not been constrained. No further investigation of the submerged postglacial setting has been conducted prior to this study, leaving a large gap in our understanding of the crustal adjustment and RSL trends of easternmost Baffin Island.

1.3 Coastal Communities

Climate change has had a significant effect in the Arctic. The major impacts of climate change on coastal stability are related to changes in: precipitation, ground air and sea surface temperatures, RSL, permafrost and ground ice, storm intensity, wave action and the extent, thickness and duration of sea ice (Forbes, 2011). Among Arctic settlements, 80% of the population lives along the coast (Forbes, 2011). Coastal residents depend on marine resources and are greatly influenced by marine conditions for hunting, fishing and transportation.

With the changing climate, coastal erosion is threatening buildings, landfills, sewage lagoons and water resources, with implications for environmental damage and health risks (Forbes, 2011). The impacts of coastal flooding, increased storm surges, and coastal erosion create further demand for strategies regarding coastal infrastructure and sustainable development in Arctic communities (Forbes, 2011). Comprehensive studies are necessary to formulate well-constrained estimates of the anticipated increase in coastal flooding, wave action, and erosion and their impact on coastal communities. Studies such as this one will help to develop more adaptation and coastal management strategies to limit the degradation of coastal landscapes and infrastructure in Arctic coastal communities.

Palaeo-sea level research provides fundamental baseline datasets to support more robust projections of future sea levels under various climate change scenarios (Woodroffe and Murray-Wallace, 2012). Continuous GIA models require long-term crustal rebound and RSL trends to model future RSL change on a local scale. Sea-level projections provide important guidance for the management of coastal hazards, erosion and sustainable community development. The Hamlet of Qikiqtarjuaq in the north, and the Hamlet of Pangnirtung in the south are two communities likely to be influenced by coastal change on Cumberland Peninsula (Fig. 1.1).

1.4 Methods and Materials

Over the past decades, the lack of high-resolution seafloor mapping technology and the low accessibility for exploratory surveys in the fiords of Baffin Island have resulted in limited knowledge of the submerged sea-level limits. Recently, the following resources for seabed mapping in eastern Baffin Island became available: (a) multibeam echosounders as a method of providing high-resolution topographic maps of the seafloor; (b) the commissioning of the *MV Nuliajuk* with hull-mounted multibeam and sounding equipment; and (c) the Government of Nunavut's (GN) objective for charting the coastal waters of eastern Baffin Island with added ArcticNet funds for this project. Multibeam and subbottom echosounders provide important datasets in the exploration and documentation of submerged landforms that represent lower sea levels than present. With these resources at hand, multibeam surveys were conducted in the coastal waters of Cumberland Peninsula to address the knowledge gap.

Multibeam surveys took place over three consecutive field seasons, 2012-2014, aboard the *MV Nuliajuk*. Each survey used the findings from the previous year to revise the survey strategy based on patterns in the geographic settings. This resulted in the discovery and documentation of eight submerged deltas and three additional submerged coastal landforms: a boulder barricade, a sill platform and two spits. Though these other features were not targeted, they provide important information about the submerged coastline and coastal dynamics at a lower RSL.

1.4.1 Multibeam Echosounder

Multibeam bathymetry echosounder systems (MBES) have advanced through the 1990s to revolutionize the field of marine geology, providing the marine equivalent of aerial photography (Courtney and Shaw, 2000; Todd and Shaw, 2009). This mapping technology allows for complete coverage of large areas of seabed, to a metre-scale horizontally and to a centimetre-scale vertically (Courtney and Shaw, 2000; Dartnell and Gardner, 2004). Multibeam transducers project sound in cone-shaped beams towards the seabed. These beams fan out, such that the width on the seafloor (beam footprint) is dependent on the water depth, the receiver beam width and the angle of incidence (Fig. 1.7; Courtney and Shaw, 2000; Dartnell and Gardner, 2004). The depth from the transducer to the target seabed is determined as the product of the two-way travel time and the speed of sound in water. The two-way travel time is measured from the time gap between the starting pulse of the transducer array, and the recorded echo from the seabed. By running survey lines so that adjacent swaths overlap within a systematic grid, a complete high-resolution digital terrain model can be made, with full coverage of the seabed below (Courtney and Shaw, 2000).

In the present study, MBES was used to explore the coastal inlets and fiords of northeastern Cumberland Peninsula to map uncharted coastal waters and explore for submerged shorelines. A Kongsberg EM3002 multibeam transducer and transceiver were hull-mounted and operated by the Ocean Mapping Group (OMG)

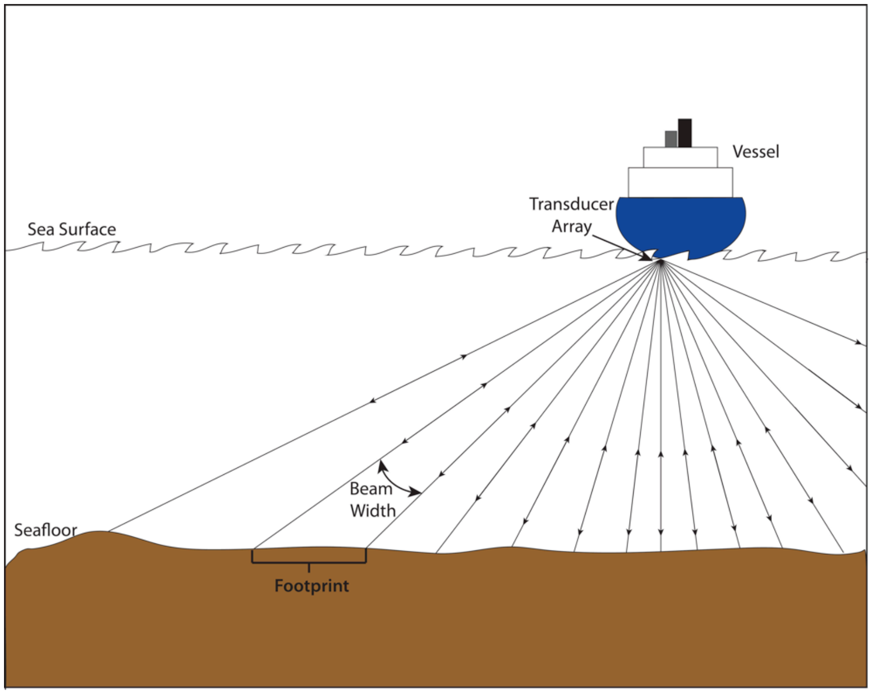

Figure 1.7: Schematic diagram of a hull-mounted multibeam system. Modified from Courtney and Shaw (2000).

from the University of New Brunswick (UNB). This system is designed for shallow water mapping of seabed corridors, with a swath width of approximately 4 times the water depth. The processing equipment and multibeam system used over the course of these surveys is detailed in Brucker et al. (2013). The multibeam bathymetry in this thesis is displayed as depth pixels in a red – blue spectrum, where red represents the shallowest and blue the deepest seafloor. Shaded relief and illumination creates an image of a third dimension to the multibeam imagery of the seafloor. Multibeam bathymetric shaded relief maps were generated for visualization and characterization of the mapped submerged shorelines.

Along with the bathymetry, corresponding backscatter maps were produced from the intensity of acoustic return off the seafloor. The degree of scattering and the portion of signal reflected and recorded by the receiver control the backscatter intensity (Lurton & Lamarche, 2015). The intensity of backscatter depends on the substrate characteristics and the irregularity of the seabed topography. Backscatter predicts the physical attributes of the seabed alongside the interpreted geomorphology from the multibeam bathymetry. Backscatter imagery is presented in greyscale under the convention set by the Ocean Mapping Group, in which the lighter pixels correspond to high-intensity backscatter (strong acoustic return) as opposed to darker pixels of low-intensity backscatter (weak acoustic return; Brucker et al., 2013). The greyscale imagery provides the basis for interpretation of the seafloor substrate, which is validated by grab samples and underwater video transects.

1.4.2 Subbottom Echosounder

Subbottom echosounders generate profiles of the subsurface sedimentary sequences based on the reflection and detection of acoustic energy. Acoustic energy is reflected from boundaries of differing acoustic impedance, where the impedance contrast between layers determines the reflection strength (Stoker et al., 1997). The type of acoustic generator, or source, is dependent on the resolution and penetration requirements of the survey. The resolution is dependent on the frequency of the acoustic energy, such that the higher the frequency the better (higher) the resolution. The attenuation of acoustic energy in sediment or rock is also dependent on the frequency, since higher frequencies are attenuated more rapidly than lower frequencies, resulting in less penetration (Stoker et al., 1997).

Subbottom profiles are used to identify sedimentary sequences within submerged shoreline features. Common seismic reflector patterns are outlined in Figure 1.8. For example, Forbes et al. (1993) documented lowstand marine deltas at -25 m in Port au Port Bay, NL, formed by fluvial incision of cross-valley glacial deposits. A submerged delta overlain by transgressive shoreline deposits was interpreted from the surface-towed sparker profile. Submerged deltas are identified by packages of oblique clinform reflectors increasing in amplitude down-dip into the prodelta facies. Characteristically prodelta facies are reflection-free, indicating dominantly uniform sediments (Cameron et al., 1993). Most of the seismic sequence boundaries

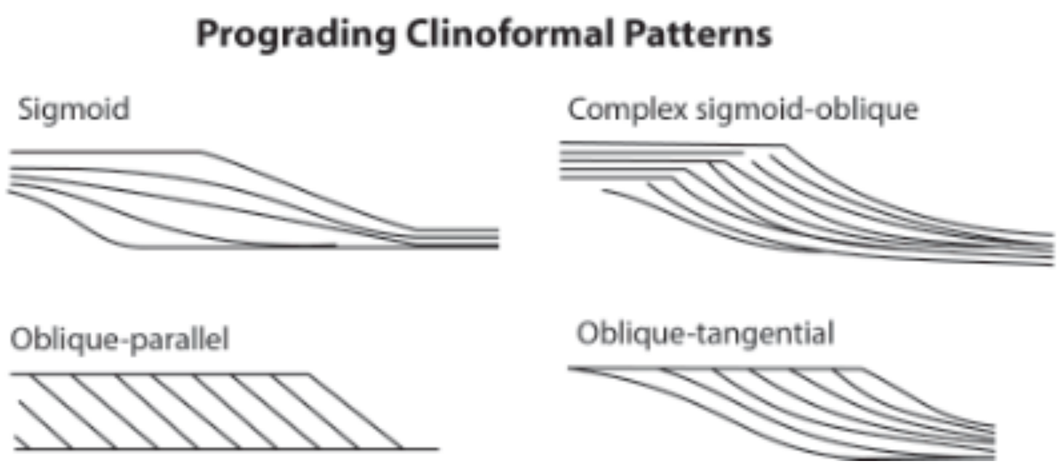

Figure 1.8: Clinoformal reflector patterns from seismic profiles. Modified from Stoker et al. (1997).

are defined by coastal onlap of flat-lying delta top reflectors (topsets) on the underlying sequence of the delta front (clinoformal foresets; Cameron et al., 1993).

This sequence boundary, or the transgressive surface, indicates the depth of the lowstand during the delta deposition. The transgressive surface is the erosional base of the delta terrace, achieved through the migration of braided channels that downcut the foreset beds to the lowest water level during progradation (Church, 1972). Forbes et al. (1993) show the topset-foreset boundary to be at approximately -27 m below sea level (Fig. 1.9), which added new evidence for the postglacial lowstand in the region of Port au Port Bay, NL.

During the 2012-2014 field seasons, the *MV Nuliajuk* was equipped with a standard shallow-water hull-mounted Knudsen 3.5 kHz chirped subbottom profiler, with a beam width of ~80°. This system ran concurrently with the MBES and recorded subbottom profiles of features on the seafloor. The system broke shortly after the start of the 2013 survey; therefore no subbottom profiles were generated for the majority of the surveyed seabed.

1.4.3 Shore-zone Classification

Classification of the modern shore-zone, adjacent to that of the submerged setting, is important for the characterization of regional coastal dynamics and resulting geomorphology. The objective of this classification is to catalogue the various shore

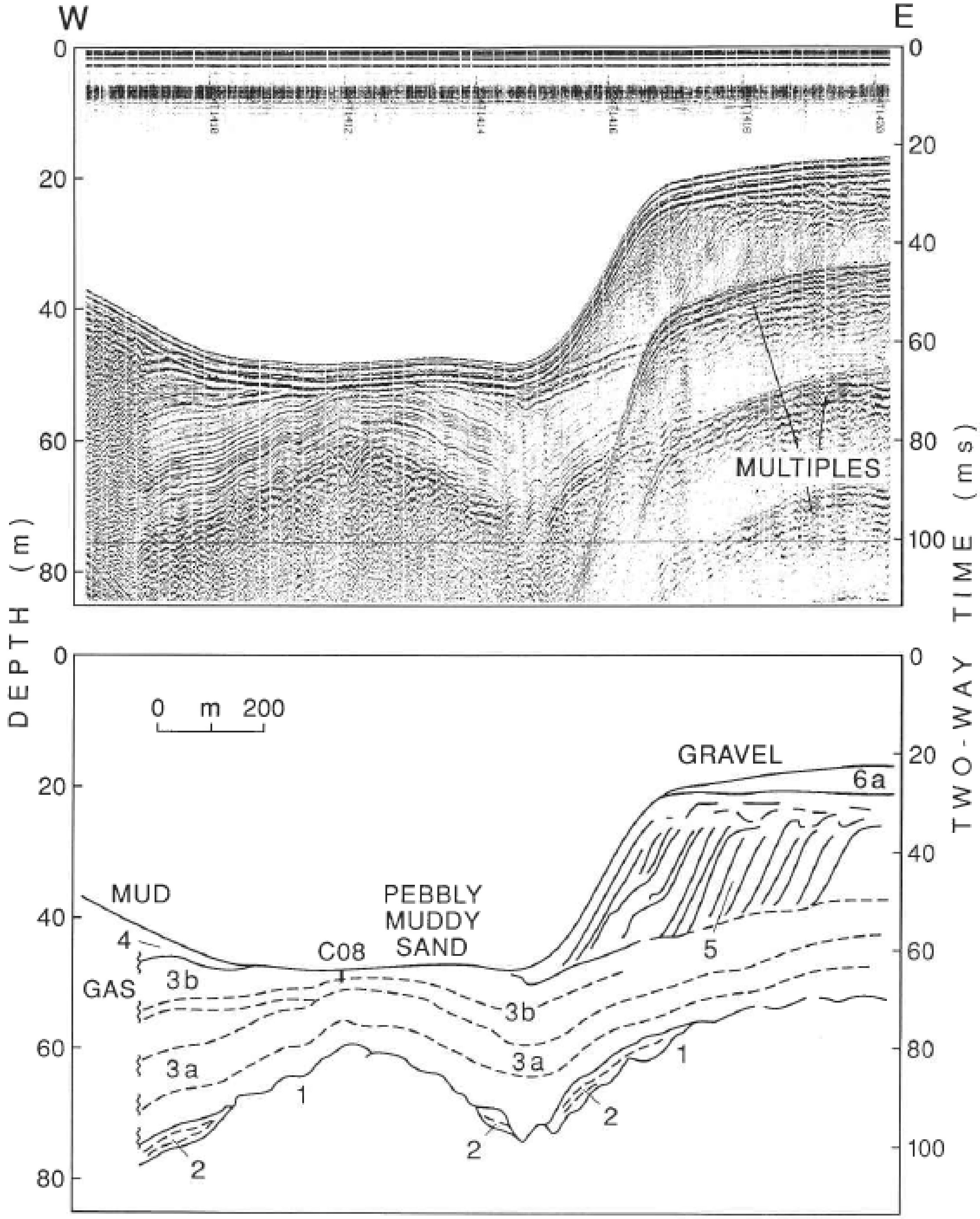

Figure 1.9: Sparker seismic profile and interpretation of a subbottom transect across a submerged delta off Fox Island River, Port au Port Bay, NL. Acoustic units are (1) acoustically unstratified ice-contact deposits, including till; (2) ice-contact sand and gravel; (3) glaciomarine sandy silt and clay; (4) postglacial mud; (5) postglacial deltaic sand and gravel; and (6) transgressive shoreface deposits. From Forbes et al. (1993).

types along the northeastern coast of Cumberland Peninsula adjacent to the mapped submerged features. The submerged coasts are then characterized and compared with the catalogue of modern coastal features.

The Geological Survey of Canada (GSC) developed a Coastal Information System (CIS) for classifying the coastline based on the geomorphic form and material of the backshore, foreshore, and nearshore zones. The CIS used coastal aerial video surveys to augment aerial photography for the entire coast of Nova Scotia, New Brunswick, Prince Edward Island, the island and parts of the province of Newfoundland and Labrador, Lake Winnipeg, and several large sites across the Canadian Arctic (Couture et al., 2015). This thesis will classify three shorelines along northeastern Cumberland Peninsula using the tools developed by the CIS. The data interpreted from video and photographs are stored as lines and points spatially referenced with dynamic segmentation of a referenced shoreline in ArcGIS (v. 9.0). The CIS system consists of standard coastal features classified into two themes (form and material) and four levels of hierarchy (super-type, type, sub-type, and feature; Couture, et al., 2015).

Aerial photographs from the National Air Photo Library (NAPL), along with topographic maps and surficial geology maps (Dyke, 2011 and 2013a, b, c), were analyzed to classify the geomorphic form and material of the modern shoreline at three study sites in northeastern Cumberland Peninsula: Broughton Channel adjacent to Qikiqtarjuaq, Boas Fiord, and the coast surrounding Akpait Fiord (Fig. 1.1). Each region is host to an adjacent submerged shoreline: boulder barricade, delta, sill platform or spit. In the case of Broughton Channel, Real Time Kinematic (RTK) surveys and grain-size analysis were used to ground-truth the aerial photographs. From the coastal classification, shoreline maps were generated for each of the three modern coasts and were used to compare with those mapped below sea level.

1.5 Thesis Outline

The results of this research project are divided between two stand-alone manuscripts that are structured for submission to an academic journal for review. The two manuscripts are presented as thesis chapters but contain all the elements of a standard journal paper. Each paper was written to be independent of the other so there is some repetition in the project background and study area.

Chapter 2, the first manuscript, focuses on the submerged deltas around outer Cumberland Peninsula. Documentation and characterization of eight submerged deltas (-19 to -45 m), defines the spatial distribution of the postglacial lowstand. The age of their deposition is inferred from ice margins and is correlated with the deglacial history of the peninsula. The lowstand elevation and spatial distribution are compared to the eastward-descending gradient of raised shorelines documented in the southwest (Dyke, 1979). These results provide evidence of the submerged RSL history and refine the RSL models for Cumberland Peninsula.

Chapter 3, the second manuscript, highlights the geomorphology of four submerged shoreline features and compares these with the present coastal setting. In addition to submerged deltas, this chapter describes a submerged boulder barricade, a sill platform and two spits offshore from Cumberland Peninsula. These four features are characterized in the context of shoreline geomorphology and as indicators of past sea-level. The submerged shoreline features are then compared to their modern analogues in terms of geomorphology and coastal dynamics. Finally, this chapter discusses the potential for utilizing palaeo-shoreline configurations and settings to predict the occurrence of submerged shorelines.

Chapter 4 summarizes the findings of the previous chapters with respect to the overall objectives of this project. The individual findings are combined to present the overall geomorphic history of submergence across Cumberland Peninsula. Knowledge gaps are addressed with suggestions for future work. Finally, this research is put into the perspective of the postglacial sea level history and the contributions made to the scientific literature.

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CHAPTER 2: SPATIAL DISTRIBUTION AND CHARACTERISTICS OF THE POSTGLACIAL SEA LEVEL LOWSTAND ON EASTERN BAFFIN ISLAND, NU

Abstract

This study investigates the submerged sea-level history of eastern Cumberland Peninsula, a region of Baffin Island where submerged shorelines have been predicted. Baffin Island is located near the former eastern margin of the Laurentide Ice Sheet (LIS) in the Canadian Arctic, and has a complex history of postglacial isostatic adjustment and relative sea-level change. Previous research into eastward-dipping, Holocene-aged deltas and fiord-head moraine gradients resulted in a conceptual model for continuous postglacial submergence of eastern Cumberland Peninsula (Dyke, 1979). Only recently were the coastal waters of Cumberland Peninsula mapped in high-resolution, including eight submerged deltas surveyed at 19-45 m below sea level over the course of three multibeam survey expeditions (2012-2014). The submerged deltas increase in depth towards the east, with a slope (0.35 m/km) similar to that of raised shoreline features previously documented in the west. A comparison between the distribution of the submerged ice contact and ice proximal deltas with deglacial ice limits suggests that they were deposited between ca. 11.7 to 8.5 ka, bounded by the recession of Younger Dryas glaciers (maximum age) and Cockburn-equivalent (minimum age) glaciers. These results confirm Dyke's (1979) conceptual model of postglacial submergence of outer Cumberland Peninsula that reveal substantial evidence of the early Holocene lowstand in northeastern Canada.

2.1 Introduction

The existence of submerged postglacial coastal landforms is predicted by glacial-isostatic adjustment models (Quinlan and Beaumont, 1981; Tarasov and Peltier, 2004) and documented around the margins of late Quaternary ice sheets (e.g. Belknap et al., 1987; Liverman, 1994; Forbes et al., 1993; Shaw and Forbes, 1995; Shaw, 2005). Andrews (1980) identified easternmost Baffin Island, near the ice limit of the Foxe sector of the Laurentide Ice Sheet (LIS) during the last glaciation, as a region that potentially preserved a submerged sea-level record. Andrews' hypothesis was supported in part by the observations of Miller and Dyke (1974) and Miller (1975), who reported submerged deltas at 28-38 m below sea level (bsl) from depth soundings in the fiords of northern Cumberland Peninsula (Fig. 2.1). This study reports the results of the first systematic, targeted survey to map and characterize submerged deltas in fiords around Cumberland Peninsula.

Multibeam sonar technology generates high-resolution bathymetric maps of the seafloor and has been used to efficiently map continental shelves and provide full-coverage of uncharted regions (Courtney and Shaw, 2000; Dartnell and Gardner, 2004; Shaw, et al., 2009). In 2012 the Government of Nunavut (GN) and ArcticNet collaborated to equip a fisheries research and training vessel with multibeam sonar for the purpose of charting coastal waters in eastern Nunavut in support of safe navigation, new fisheries development and coastal infrastructure assessment

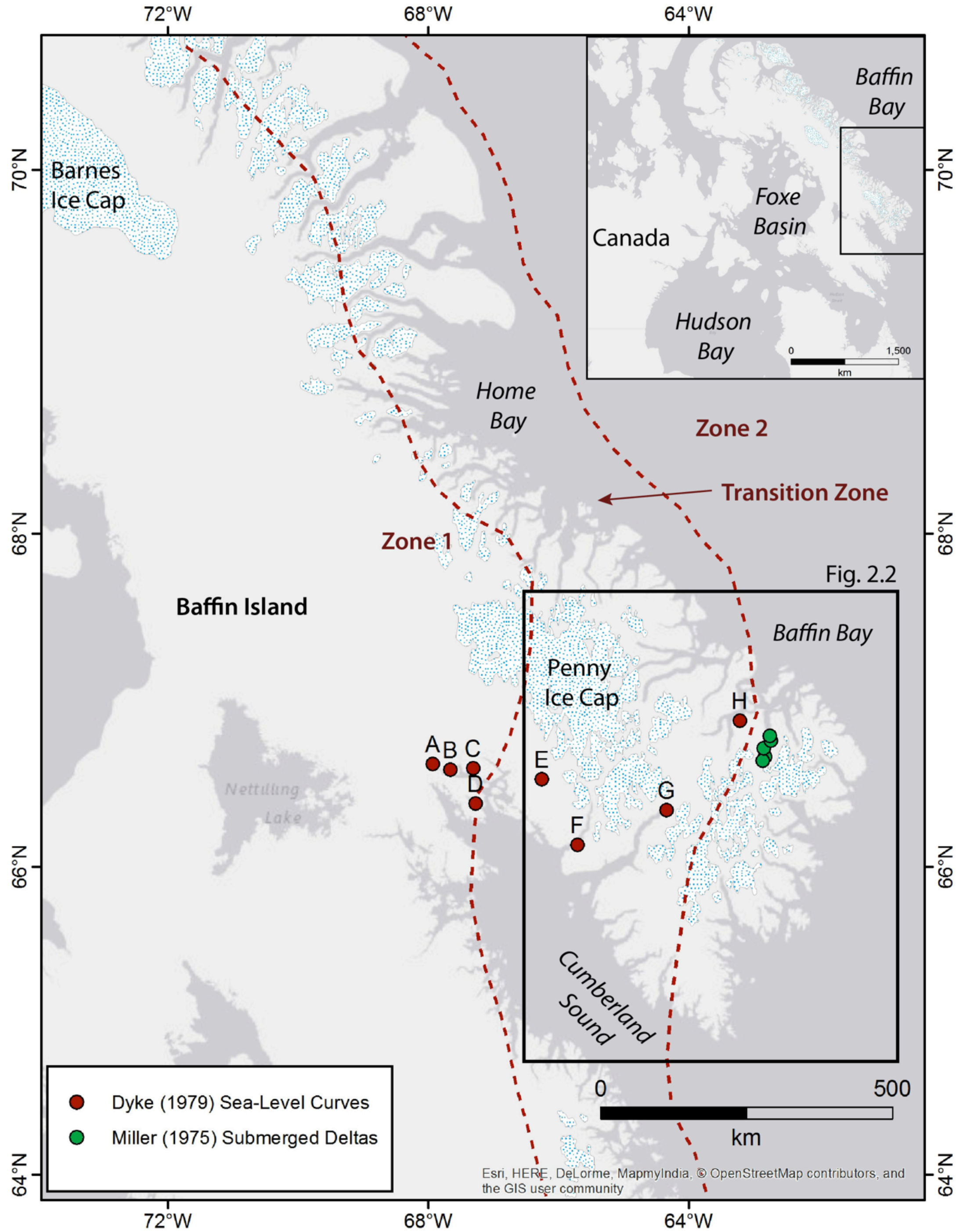

Figure 2.1**:** Map of eastern Baffin Island with locations of submerged deltas located by Miller (1975) and dated terrestrial marine limits A-G from Dyke (1979; Fig. 2.3). Red dashed boundaries outline zones of sea level response from Andrews (1989). Inset map shows location of Baffin Island in northeastern Canada.

(Brucker, et al., 2013; Hughes Clarke, et al., 2015). Working within the mandate of this collaborative project, fiords and marine embayments of Cumberland Peninsula between Pangnirtung and Qikiqtarjuaq were also targeted to search for submerged sea-level features.

The targeted multibeam surveys were based on current knowledge of where and at what depth submerged deltas most likely formed during deglaciation. Fiord heads and sheltered side-entry valleys for example were targeted as environmental settings that promote the formation (meltwater and sediment supply) and preservation (sheltered from currents) of submerged deltas. Reported submerged sea level features and the depth limitations of the research vessel both constrained the survey targets to a depth range between 55 and 10 m bsl, respectively, in the study area (England and Andrews, 1973; Pheasant and Andrews, 1973; Miller and Dyke, 1974; Miller, 1975; Locke, 1980; 1987).

This study reports eight submerged deltas at depths of 19 to 45 m bsl in northern and eastern Cumberland Peninsula that display a pattern of increasing depth eastward. Reconstruction of the magnitude and pattern of the sea level lowstand offers insights into glacial isostatic responses to ice unloading during the late Foxe and early Holocene deglaciation, and provides a framework for interpreting the submerged sea level history in other similar ice marginal regions.

2.1.1 Submerged Sea-level Records in the Canadian Arctic

Relative sea level (RSL) records in formerly glaciated regions reflect the complex history and interaction of glacial isostastatic adjustment (GIA) and eustasy in the postglacial period. The unloading of the LIS and associated glacial isostatic uplift continues to shape RSL change in the Canadian Arctic Archipelago, while glacial eustatic rise ended around 5000 years ago with the final Laurentide and Fennoscandian ice sheet melting. Relict shoreline features along with continuous GPS monitoring stations co-located with tide gauges are important for constraining regional GIA and RSL models and provide the data required to construct RSL curves for the Canadian Arctic (Forbes, et al., 2004).

The unloading of the LIS during deglaciation resulted in differential isostatic adjustment across ice-covered and ice-marginal regions. Crustal depression beneath the LIS extended beyond the ice margin, forming the proglacial depression. The displaced mantel material from the crustal depression formed the forebulge beyond the peripheral margin of the ice sheet (Walcott, 1970; Liverman, 1994; Gray, 1996). Regions under the influence of the migrating forebulge have a complex history of postglacial RSL change. For instance, those on the leading edge (ice-proximal side) of the forebulge would have experienced initial crustal uplift and emergence (RSL fall), followed by subsidence and submergence (RSL rise) once the forebulge crest had passed through the region (Quinlan and Beaumont, 1981). In contrast, regions initially located beyond the forebulge crest (ice-distal side) would only experience crustal subsidence and net submergence. Areas that were isostatically depressed, well within the former margins of the LIS, would experience continuous uplift and net emergence. Clarke et al. (1978) classified these regions as three zones, each having distinctive postglacial RSL histories (displayed in Fig. 2.1 for eastern Baffin Island). Relative sea-level curves that exhibit continuous emergence to the present day occur in Zone 1. Regions that experienced continuous submergence are in Zone II and have RSL curves defined by continuous transgression. The transitional Zone I/II is influenced by the migration and eventual collapse of the peripheral forebulge, and has a J-shaped RSL curve (i.e. forced regression to a lowstand followed by, usually, a transgression). The regressive limb of the J-shaped curve decreases in elevation from the deglacial marine limit to an inflection point in the curve that marks the postglacial lowstand. The inflection point indicates a temporary, stable RSL, after which the transgressive limb rises to modern sea-level, thereby submerging lowstand shoreline features to their present depth.

Some evidence of lower postglacial RSLs have been observed along the eastern and western fringes of the former LIS, within Zone I/II and Zone II. These include submerged wave-cut terraces, deltas, beach ridges, incised bedrock, barrier platforms and flooded isolated basins (e.g. Miller and Dyke, 1974; Miller, 1975; Locke, 1980; 1987; England and Andrews, 1973; Shaw and Forbes, 1995; Bell et al., 2003; Shaw, 2005; Nixon et al., 2014). Although these features have been reported in many locations the lowstand has not been dated and the submerged RSL history remains poorly constrained. The sparse array of long-term GPS and tide gauge measurements across the Canadian Arctic, together with a relatively small number of submerged sea-level data, has resulted in poorly constrained crustal geodynamics and regional RSL trends. Given that global mean sea level will continue to rise over the coming decades (IPCC, 2013), already submergent regions in Zone II along the eastern and western Arctic will experience enhanced sea level rise (James et al., 2010). Reconstruction of past submergence trends for these regions will help to validate crustal geodynamic models and projections of future sea-level change (James et al., 2014).

2.2 Quaternary Glacial and Relative Sea Level History of Cumberland Peninsula

2.2.1 Glaciation

Cumberland Peninsula extends southeastward from central Baffin Island and is the easternmost landmass in the Canadian Arctic Archipelago (Fig. 2.1). It is bounded by Baffin Bay to the north, Davis Strait to the east, and Cumberland Sound to the south. During the Last Glacial Maximum (LGM), locally identified as the Foxe Glaciation, the Foxe sector of the LIS covered Baffin Island, terminating at fiord mouths and on the adjacent continental shelf, landward of the shelf edge (Marsella et al., 2000; Dyke et al., 2002; Miller et al., 2005; Briner et al., 2009). The grounded component of the LIS reached as far as Pangnirtung Fiord on southern Cumberland Peninsula, while the tidewater component reached the mouth of Cumberland Sound at the LGM (Margreth, 2015). The Penny Ice Cap (PIC) expanded from its upland centre onto the continental shelf around Qikiqtarjuaq in the north, and east of Pangnirtung Fiord to the south. East of the Pangnirtung Pass (running from Pangnirtung Fiord to North Pangnirtung Fiord; Fig. 2.2), the Cumberland Peninsula was covered by expanded alpine glaciers that reached the continental shelf in the southeast, and to the outer coast in the north (Merchants Bay; Margreth, 2015). Low-gradient warm-based outlet glaciers filled the main fiords of Cumberland Peninsula, while the inter-fiord uplands remained ice-free or covered by cold-based glaciers (Kaplan and Miller, 2003; Miller et al., 2005).

Recession from LGM ice margins was underway by 15 ka, and by 14 ka most of the southeastern coast of Cumberland Peninsula was ice-free (Miller et al., 2005; Briner et al., 2009). Three prominent ice marginal moraines were formed in Cumberland Peninsula during deglaciation. Interpreted to represent distinct glacial re-advances, these include the Heinrich-1 event (H-1) at 14.6 ka, the Younger Dryas (YD) at 11.7 ka, and the Cockburn Substage at 9.5 ka (Margreth, 2015). By 14.6 ka the tidewater component of the LIS in Cumberland Sound had retreated west of the mouth of Pangnirtung Fiord, and local ice had retreated to the mouths of fiords, valleys and embayments along the outer coast of Cumberland Peninsula (Jennings, 1993; Kaplan et al., 2001; Margreth, 2015).

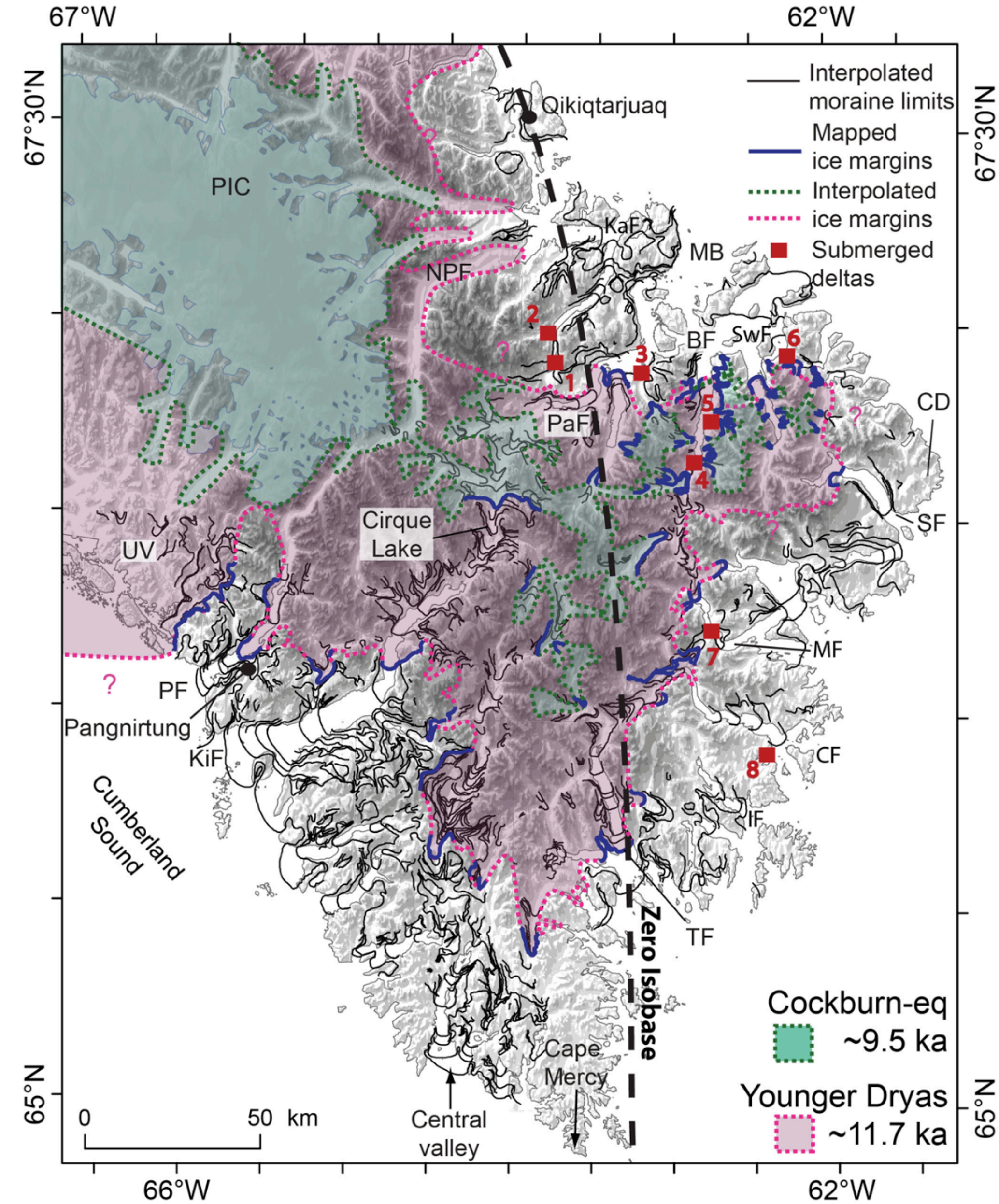

Figure 2.2**:** Locations of submerged deltas that were mapped for this thesis in eastern Cumberland Peninsula, Margreth's (2015) early Holocene ice margins for YD (11.7 ka), and Cockburn-equivalent (9.5 ka), with the present zero isobase from Kaplan and Miller (2003). 1) Delta at the head of Kangert Fiord. 2) Kangert side-entry delta. 3) Outer Padle Fiord delta. 4) Delta at the head of Boas Fiord. 5) Boas side-entry delta. 6) Inner Durban Harbour delta. 7) Mermaid Fiord side-entry delta. 8) Outer Clephane Fiord delta. NPF: North Pangnirtung Fiord, PaF: Padle Fiord, MB: Merchants Bay, BF: Boas Fiord, SwF: Southwind Fiord, CD: Cape Dyer, SF: Sunneshine Fiord, MF: Mermaid Fiord, CF: Clephane Fiord, TF: Touak Fiord, KaF: Kangert Fiord, KiF: Kingnait Fiord, PF: Pangnirtung Fiord, UV: Usualuk Valley, PIC: Penny Ice Cap. Modified from Margreth (2015).

Rapid retreat from the H-1 (14.6 ka) ice margins on the southern coast of Cumberland Peninsula ensued until the re-advance of the YD (11.7 ka). Deglaciation was asymmetrical across the peninsula: the fastest ice recession occurred along the southwestern coast, while the slowest ice recession occurred along the northeastern coast. By the YD, ice was limited to the fiords of Merchants Bay and Touak Fiord in the northeast, at fiord-heads in the southeast, and inland in the southwest (Fig. 2.2; Margreth, 2015).

The Holocene Thermal Maximum (10.2-8.5 ka) resulted in rapid deglaciation of fiord heads as alpine glaciers retreated upland into the valleys of Cumberland Peninsula (Miller et al., 2005). The Cockburn Substage was a re-advance at 9.5 ka resulting from increased precipitation and snow accumulation despite peak summer temperatures (Miller et al., 2005). Pre-neoglacial moraine ridges on Cumberland Peninsula have been correlated to the type Cockburn moraines of Home Bay to Eclipse Sound along the northeast margin of the LIS (Miller 1975; Andrews and Ives, 1978; Margreth, 2015). East of the Penny Ice Cap, Cockburn-equivalent ice margins extended to fiord-heads and were restricted to the re-advance of interior alpine ice masses. These moraines are considered Cockburn-equivalent as they have not been dated but are correlated to the 9.5-8.5 ka dated Cockburn ice margins (Fig. 2.2; Margreth, 2015).

After the recession from the Cockburn-equivalent ice margins, a cold event resulted in the re-advance of ice to the heads of several fiords (Miller et al., 2005; Briner et al., 2009). This cold event occurred before 8 ka and corresponds to the 8200-year cold climate event recorded in the Greenland Ice Sheet (Alley et al., 1997). By 7.5 ka the Foxe Dome over Baffin Island had separated from the mainland LIS, as deglaciation continued across northern Canada.

Neoglaciation began shortly after 5 ka, when sea ice cover increased. This intensified between 1.9 and 1.1 ka, but was followed by the Medieval warm interval (Margreth et al., 2014). The Little Ice Age cooling event occurred after 0.8 ka from a combination of large volcanic eruptions and low solar activity, which resulted in renewed pulses of ice expansion on Cumberland Peninsula (Margreth et al., 2014). At present, Cumberland Peninsula is the site of hundreds of cirque and valley glaciers as well as the Penny Ice Cap (6000 km^2; Dyke, 1979; Marsella et al., 2000; Miller et al., 2005).

2.2.2 Sea-Level History

Dyke (1979) constructed a series of postglacial RSL curves for Cumberland Peninsula based on marine limit shorelines mapped across southwestern Cumberland Peninsula (Fig. 2.3; located in Fig. 2.1). The curves were extrapolated from twenty-two radiocarbon dated marine features related to Holocene RSL. The RSL curves in the west (A-D) exhibit almost continuous emergence, as in Zone I, however pass below modern sea-level between ca. 3.5 and 1 ka before rising to its

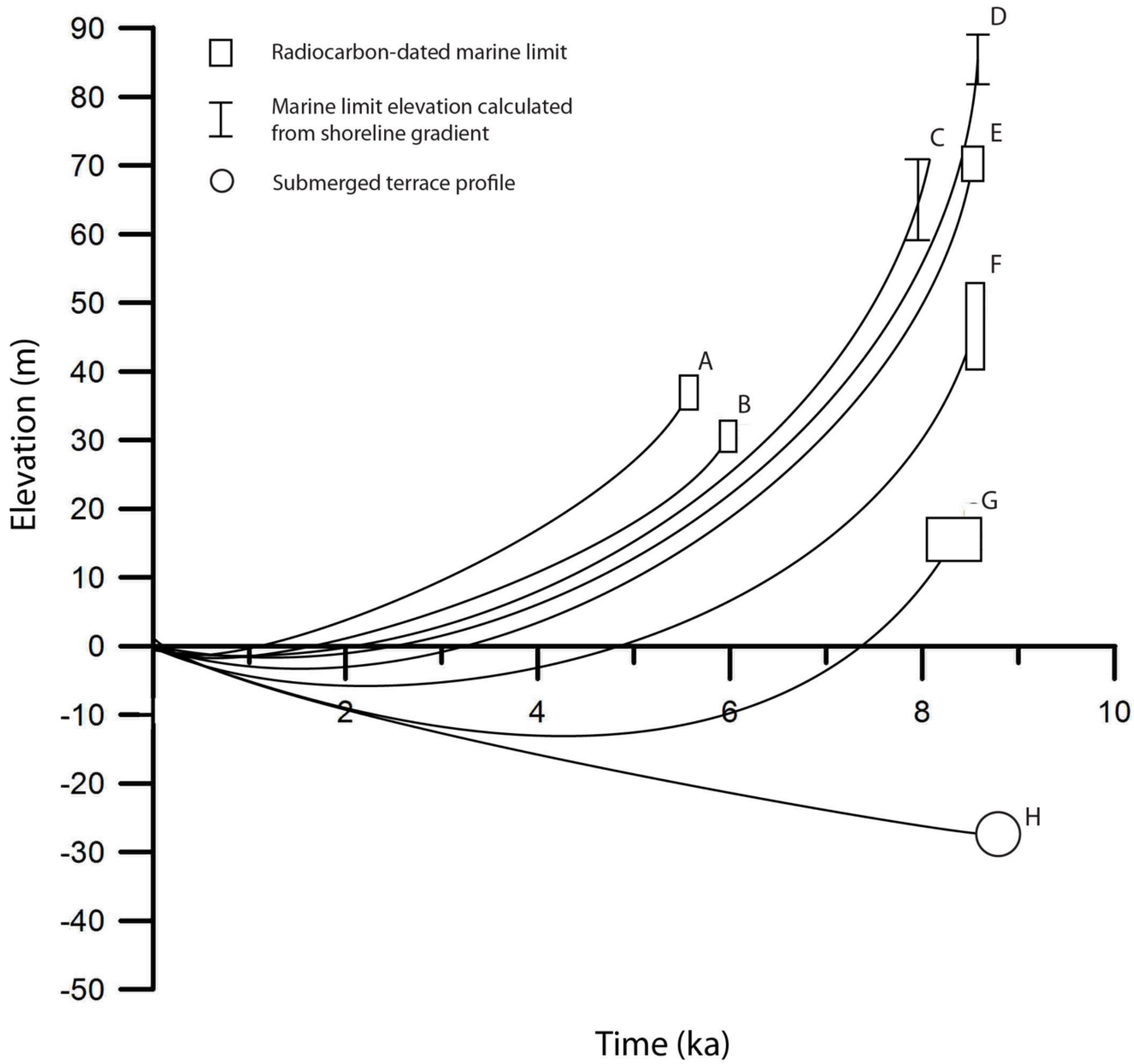

Figure 2.3: Marine limit elevations plotted against known or extrapolated ages and presumed RSL curves for southwestern Cumberland Peninsula. Locations of RSL curves are shown in Figure 2.1. A) Clearwater Fiord, B) Middle Clearwater Fiord, C) Shilmilik Bay, D) Kangerk Fiord, E) Usualuk Fiord, F) Pangnirtung Fiord, G) Kingnait Fiord, H) Padle Fiord. Modified from Dyke (1979).

modern limit. Curves E-G all display the J-shaped curve, to different degrees, characteristic of the transitional Zone I/II. These curves were constructed on the assumption that postglacial sea-level passed below present, although evidence of submerged coastal features had yet to be discovered. Curve H, characteristic of continuous submergence in Zone II, was extrapolated from a depth sounding of a submerged terrace on northeastern Cumberland Peninsula (Miller and Dyke, 1974). Since the initial depth sounding, submerged terraces were documented, but not dated between 28 and 38 m bsl in Boas Fiord, northeastern Cumberland Peninsula (H; Fig. 2.1; Miller, 1975).

The extrapolated RSL curves provide a conceptual model for sea-level change on eastern Cumberland Peninsula that suggests a postglacial RSL record continuously below present sea level (e.g. curve H, Fig. 2.3). The marine limits at sites E-G form a reasonably synchronous early Holocene strandline (ca. 8.5 ka) with an eastward gradient of 0.59-0.62 m/km. Extrapolation of this gradient suggests that marine limits intersect present sea level east of a line roughly running north-south from Qikiqtarjuaq to Cape Mercy (zero isobase, Fig. 2.2). The absence of raised shorelines reported in the literature for the eastern half of Cumberland Peninsula support the conceptual model (Pheasant and Andrews, 1973; Dyke, 1977; 1979; Andrews, 1980; Clark, 1980). More recently raised shorelines were observed on the eastern coast of the peninsula, but are presumed to pre-date the LGM (Locke, 1987; Dyke and Margreth, pers. com., 2014).

In further support of this conceptual RSL model is the interpretation of submerged deltas on the northeastern coast of Cumberland Peninsula. For his PhD research, Miler (1975) used a single-beam depth profiler to document flat-topped submerged terraces 28-38 m bsl at the mouths of valleys containing local moraine deposits in outer Padle Fiord (site H on Fig. 2.1) and Boas Fiord (Fig. 2.1). Miller (1975) and Miller and Dyke (1974) interpreted these features as ice-contact glacial-marine deltas formed from the outwash of local valley glaciers that had down-cut early Holocene moraine deposits.

Although not dated, the submerged deltas in northeastern Cumberland Peninsula were correlated to major early Holocene emerged deltas to the northwest (ca. 8.5-7 ka BP), due to the lack of raised deltas of this age in the region (Miller and Dyke, 1974; Miller, 1975). Earlier studies to the north of Cumberland Peninsula, including Home Bay, suggested that postglacial raised shorelines dip N50°E (Andrews et al., 1970; Pheasant and Andrews, 1973), whereas England and Andrews (1973) argued that the postglacial shorelines on Cumberland Peninsula should dip progressively more to the east (N60°E) based on the geometry and relationships to local ice centres.

More recently the moraines associated with the submerged deltas in Padle and Boas fiords were determined to be Cockburn-equivalent moraines, which are 9.5-8.5 ka (Dyke and Margreth, pers. com., 2014). The depth at which these submerged deltas were located could not be attributed solely to eustatic sea-level rise since their formation, and accordingly, Miller (1975) proposed that they were additionally influenced by the collapse of the peripheral forebulge. Miller and Dyke (1974) further argued that the evidence of submerged deltas and the absence of a raised marine record implied that eastern Cumberland Peninsula had a limited ice load during the late Foxe glaciation, which was beyond the zero isobase for postglacial emergence and had experienced differential submergence. These interpretations also fit with modeled postglacial RSL trends for Cumberland Peninsula (Pheasant and Andrews, 1973; Andrews, 1980; Clark, 1980).

In general, submerged deltas in formerly glaciated regions would most likely have been deposited at either deglacial marine limit or postglacial lowstand RSL positions. In the former case, these deltas would have been deposited immediately upon deglaciation and marine inundation in an ice-contact or ice-proximal environment. Following initial coastal emergence and associated fluvial incision and down cutting, the delta would have undergone submergence by subsequent RSL rise, potentially reworked during marine transgression and draped by post-submergence sediments. Lowstand deltas on the other hand, would typically be deposited in an ice-proximal to ice-distal environment, depending on the rate of ice retreat, during a relatively stable RSL position within continuous submergence or as the coastal system switched between net emergence and submergence (Shaw and Forbes, 1995). A key element in the construction of lowstand deltas is a sediment supply that may be derived from a glacial re-advance or from paraglacial erosion of deglacial sediments (Forbes and Syvitski, 1994).

Gilbert-type deltas are commonly formed at deglacial marine limit and postglacial lowstand positions (Church, 1972; Forbes and Syvitski, 1994; Shaw and Forbes, 1995; Shaw, 2005). They are characterized by a tripartite system of horizontal bottomset beds in the prodelta setting overlain by steeply dipping foreset beds that are onlapped by aggradational horizontal topset beds (Suter, 1994). The truncation of the foresets by the topset beds (the transgressive surface) records the lowest erosional depth at the lowstand, and is interpreted as the corresponding sea level (van der Straaten, 1990; Bell et al., 2003; Gutsell et al., 2004). The truncation of the foresets is achieved through the downcutting of migrating braided channels in the coarse-grained sediments of the delta plain (Church, 1972; van der Straaten, 1990). Alternatively, Shaw and Forbes (1995) interpret the lip (break in slope) depth of the delta terrace to indicate the lower water level, in which case the local tidal range determines the depth of former mean sea level above this limit. Therefore accessing the delta stratigraphy or subbottom profiles can provide the limit of local sea level at the time of delta progradation.

Recent trends in RSL for the study area include geomorphic evidence of a late Holocene transgression, known as the Canso Channel Transgression, that was documented along the northeastern coast of Cumberland Peninsula, supporting coastal submergence for at least the past 1200 years (Pheasant and Andrews, 1973; Dyke, 1979; Andrews and Miller, 1985). In contrast, recent tide gauge data

(Fisheries and Oceans Canada, 2015) along with Global Navigation Satellite System (GNSS) vertical motion data suggest an emerging coast over the last decade at Qikiqtarjuaq (James et al., 2011; 2014). This apparent contradiction is likely due to the short-term nature of the instrumental records, which require decades of further measurements to separate the trend from the noise.

2.3 Methodology and Materials

The research and design of this project was primarily based on seabed mapping surveys in the fiords of eastern Cumberland Peninsula. The surveys were conducted aboard the *MV Nuliajuk* with a mapping strategy that involved single-line transits to target sites, exploratory wide-spaced lines to test for the presence of submerged deltas, and if detected, full coverage surveys of the delta terrace and upper slope. The target locations were determined based on high probability for formation and preservation of deglacial deltas. The survey strategy was refined over the course of three field seasons (2012-2014; Hughes Clarke et al., 2015).

2.3.1 Survey Strategy

Fiords were targeted as the ideal setting for formation and preservation of deltas because they are characterized by discrete sediment inputs and sheltered coastal environments. Deglacial deltas are typically preserved at fiord heads and side-entry valley locations (Gutsell et al., 2004). Side-entry deltas are deposited at the mouths of tributary valleys that incise steep fiord sidewalls and drain upland glacierized terrain. Because of the steep relief and shore drainage distances, it is anticipated that associated deltas would be coarse grained, unless lake basins impede direct sediment transportation to the fiord. Side-entry deltas are commonly deposited into deep middle or outer fiord basins, resulting in landforms of relatively small areal extent because delta progradation is limited in deep water. In summary, side entry drainage systems tend to produce small, triangular-shaped, coarse-grained deltas (Syvitski et al., 1987; Prior et al., 1990). All of the submerged deltas reported by Miller (1975) in Boas Fiord were at the mouths of side-entry valleys (Fig. 2.1).

Fiord-heads are typically characterized by steep sidewalls that confine glaciofluvial drainage to low-gradient sandur on valley bottoms (Church, 1972; Syvitski et al. 1987; Hein and Syvitski, 1992). Although fiord-head systems tend to generate high sediment fluxes from large glacierized catchments up-valley, the presence of lake basins and outwash plains may capture much of the coarsest sediment. On the other hand, shallow water depths at the fiord head can promote rapid seaward progradation of delta fronts, infilling fiord-head basins and producing elongated deltas with relatively straight progradational fronts (Prior et al., 1990).

The water depth anticipated for submerged deltas ranged between modern sea level and 55 m bsl. The former, although not practical for ship-based survey, was based on the projected slope of marine limit deltas in southwestern Cumberland Peninsula (see section 1.2.1). The latter depth was established by the deepest reported submerged feature on Cumberland Peninsula, a submerged wave-cut platform and beach terraces of unknown age reported by Locke (1980; 1987).

Practical limitations on the surveys were the acoustic attenuation of the multibeam system and the minimum water depth accessible by the *MV Nuliajuk*. The EM3002 echosounder is designed for shallow water mapping of seabed corridors at typical depth ranges of 5 to 200 m. The minimum safe operation water depth for the *MV Nuliajuk* is very much dependent on local weather and sea conditions, but is generally around 10 m depth. Survey targets therefore were generally limited to fiord settings within a depth range of 10 to 200 m.

In summary, the survey strategy targeted sites with high potential for submerged delta deposition and preservation. These targets were typically at fiord heads and the mouths of side-entry valleys that contained evidence of late-lying ice (potentially Cockburn-equivalent moraines) to act as a sediment supply. Valleys with evidence of Neoglacial tidewater glacier activity at the coast were avoided as any early to mid Holocene landforms would likely have been eroded. Valleys with large lake systems were also given lower priority. The survey strategy was revised each year based on the outcomes of previous surveys.

2.3.2 Sonar Echosounders

The GN provided the research vessel *MV Nuliajuk* equipped with geoscience and hydrographic survey equipment, including a Kongsberg EM3002 multibeam echosounder and a 3.5 kHz Knudsen chirp 3200 echosounder. Brucker et al. (2013) detail the multibeam system and processing equipment used during this project. Over the course of the three surveys, fourteen fiords and many bays, channels and inlets were surveyed.

Bathymetric and backscatter data were processed by the Ocean Mapping Group (OMG) with Seafloor Information System and Swath Editor software (Muggah, pers. comm., 2012). The multibeam depths were adjusted to Mean Sea Level and corrected for tidal variations with the WebTide Arctic v.9 model for Baffin Island (Department of Fisheries and Oceans). The sonar survey data were provided by OMG as a series of raster datasets, with xyz values gridded to 1 m spatial resolution in ESRI format, in the WGS84 Mercator projection. The backscatter data were also provided as a series of raster datasets complementing those of the bathymetry, with x, y, and intensity values observed in greyscale and gridded to 1 m spatial resolution in ESRI format. Backscatter data is presented following the conventions set by OMG, where black indicates low backscatter and white indicates high backscatter values. Using ArcGIS Spatial Analyst (v.10), the bathymetric raster grids were used to create a shaded-relief raster (hillshade), which include the effects of both local illumination angle and shadow, allowing for relief portrayal of the seafloor. Profiles of the submerged features were created with ArcGIS 3D Analyst (v.10). Upper delta-front slope angle was measured as the average slope over 20 m of water depth starting at the terrace lip. Multibeam and backscatter maps were displayed over 1:50,000 digital National Topographic System (NTS) basemaps (GeoGratis portal, Natural Resources Canada).

The 3.5 kHz chirp echosounder provides subbottom profiles of the sedimentary sequences below the seafloor. They were acquired at the same time as the multibeam surveys, except in 2013 when there was a critical equipment failure that terminated the subbottom survey program for the season. The acoustic energy from the sounder (80° beam width) penetrates the seafloor sediments and reflects off boundaries between sedimentary units of differing acoustic impedance, generating sedimentary profiles along the ship transect (Stoker et al., 1997). SounderSuite: EchoControlClient-2.64 software was used for controlling and recording data acquisition (Muggah, pers. comm., 2012). The files were recorded in binary "echogram" format (.keb), converted to SEGY and then JPEG2000 files by the SegyJP2 program, and viewed using SegyJp2Viewer (Courtney, 2012).

2.3.3 Seabed Imagery and Sampling

To ground-truth the bathymetry and backscatter data, underwater video footage and sediment samples were acquired at selected sites dependent on accessibility, weather and the time constraints of the *MV Nuliajuk*. A Deep Blue Sea-Pro Underwater Video system (Oceans System Inc.) was used to record footage of the seabed, while sediment samples were taken with a Wildco ponar grab (9"x9"; 8.2L). Sediment texture was analyzed using a Horiba L-950 laser grain-size analyzer.

2.4 Submerged Deltas

High-resolution bathymetry revealed eight submerged deltas in eastern Cumberland Peninsula. Two deltas were identified in a fiord-head setting (#1, 4), four at fiord side-entry valleys (#2, 3, 5, 7) and two in small sheltered embayments (#6, 8; Fig. 2.2). Of these sites, Kangert and Boas fiords, along the northern coast, include both fiord-head and side-entry deltas. The following text describes each of these sites in sequence and Table 2.1 provides a summary of the dimensions and depths of each feature. They range in depth from 19 to 45 m bsl.

2.4.1 Kangert Fiord

Kangert Fiord extends northeast-southwest for 45 km, with an average width of 2 km (Figs. 2.2 and 2.4). The head of Kangert Fiord comprises a till veneer plain and short glaciofuvial outwash plain. Kangert Fiord is made up of a single basin (up to 270 m deep), with a deep sill at its mouth (100 m bsl). Two submerged deltas were mapped, one at the fiord head and the other at the mouth of the only side-entry valley in the fiord (Fig. 2.4).

Table 2.1: Location and dimensions of submerged deltas mapped during this study.

Site	Fiord	Latitude (N)	Longitude (W)	Delta Terrace Depth[1] (m)	Delta Terrace Slope (°)	Delta Front Slope[2] (°)	Interpreted Paleo Sea Level Depth[3] (m)	Width (m)	Length (m)	Delta Terrace Area[4] (km^2)	Valley Drainage Area (km^2)
1	Kangert	66°55'23.6"	63°46'49.1"	19 ± 0.09	0.8	12	20	575	4000	1.6	50
2	Kangert	66°59'47.4"	63°48'57.4"	19 ± 0.19	0.5	19	20	720	710	0.4	115
3	Padle	66°54'00.3"	63°13'13.4"	29 ± 0.21	1.6	16	30	1300	700	1.2	115
4	Boas	66°56'50.7"	62°16'27.1"	33 ± 0.25	0.3	7	34	2050	7500	9.5	631
5	Boas	66°46'36.1"	62°44'56"	37 ± 0.20	1.3	16	38	1800	1000	1.7	94
6	Durban Harbour	66°41'12.7"	62°50'42.8"	44 ± 0.13	0.5	12	45	900	>1600	1.4	75
7	Mermaid	66°13'36.3"	62°45'57.4"	36 ± 0.20	0.5	23	37	1000	>800	0.8	38
8	Clephane	65°54'40.4"	62°25'46.5"	45 ± 0.20	1.1	5	46	915	>1200	1.1	63

[1] Delta terrace depth is calculated as the average terrace lip depth (n=20), with the calculated standard error margin.
[2] Delta front slopes were calculated for the upper slope only, over a depth range of 20 m starting at the delta lip.
[3] Paleo sea levels are interpreted as 1 m below the average delta lip depth. See section 2.5.1 for discussion.
[4] Delta terrace area is measured from the river mouth to the terrace lip.

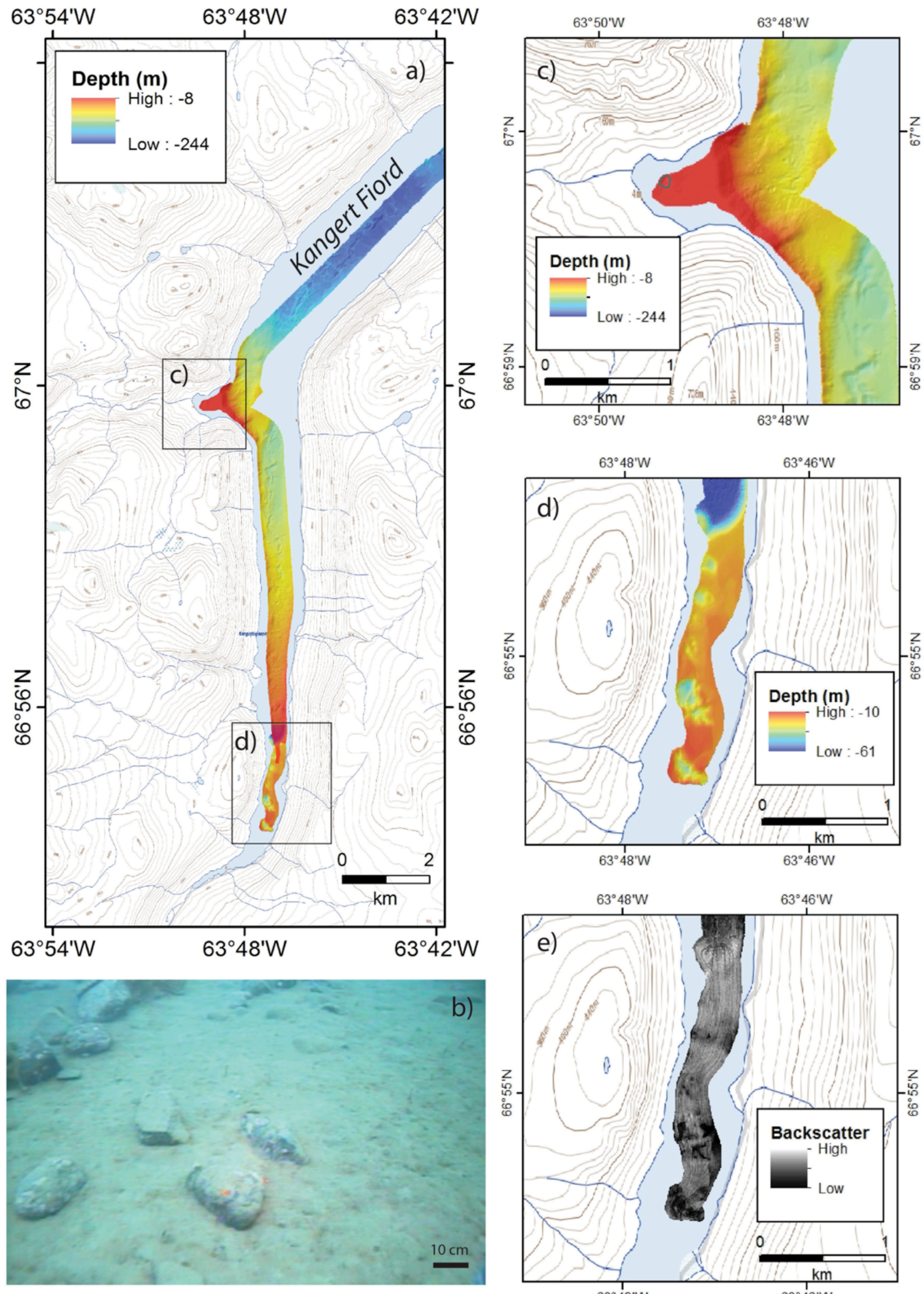

Figure 2.4: Multibeam bathymetry and backscatter of submerged deltas in Kangert Fiord. A) Overview map of Kangert Fiord deltas. B) Photograph of the substrate on the fiord-delta terrace, with red laser points spaced 10 cm apart. C) Multibeam bathymetry of the side-entry submerged delta in Kangert Fiord, 19 m bsl. Depression at the head of the delta is outlined in grey. D) Multibeam bathymetry of submerged delta at the head of Kangert Fiord, 19 m bsl. E) Backscatter of the submerged delta terrace at the head of Kangert Fiord.

At the head of Kangert Fiord (Fig. 2.4d) is a submerged delta terrace 19 ± 0.1 m bsl (Table 2.1; Fig. 2.2). The delta terrace extends down fiord 4 km from the modern river mouth, covering an area of ca. 1.6 km^2. On the relict terrace are several depressions, the deepest of which has a relief of 20 m and is 250 m wide. The smaller depressions (n=9) are bowl shaped, with gentle slopes, whereas the largest is steep-sided. All are apparently filled with fine-grained sediment, evident from the low backscatter return (Fig. 2.4e), and confirmed in the video imagery. Limited gravel is observed in the depressions relative to the delta terrace, which consists of a surface lag (sub-rounded cobbles to boulders) covered by a thin silt cap (Fig. 2.4b). The closer to the lip of the delta terrace, the more winnowed and coarser the sediments become, with a higher backscatter return. The silt cap on the delta terrace has experienced only minor reworking by icebergs, in contrast to the prodelta and delta front.

Along the western sidewall, near the fiord head, is a tributary valley draped with till veneer. Glacial deposits and moraines are scarce in comparison with the source drainage basins for other submerged deltas. Two large lakes near the terminus of the local glacier drain into the fiord. Off the mouth of the side-entry valley is a submerged triangular-shaped delta at 19 ± 0.2 m bsl (Fig. 2.2, # 2). A large, shallow depression, 6 m deep and 70 m wide, occurs near the delta apex (outlined in grey, Fig. 2.4c). The delta terrace comprises a smooth featureless surface, blanketed by mud, presumably of post-submergence age. The outer edge of the terrace and front are reworked by ice scouring. Remnant chutes draped in mud extend down the delta front and prodelta into the deep fiord basin.

2.4.2 Outer Padle Fiord

Padle Fiord is located in Merchant's Bay to the southeast of Kangert Fiord, protected by the Duck Islands. Padle Fiord extends 15 km northeast-southwest, with an average width of 3 km in the inner fiord, before it opens to 7 km width near its mouth (outer fiord). A side-entry valley enters the outer fiord from the southeast and is the site of a submerged triangular-shaped delta. The submerged delta is preserved at the mouth of a drainage basin (115 km^2) sourced from large meltwater lakes and rivers that downcut through till veneer and morainal deposits.

The outer lip of the submerged delta terrace was only partially mapped at an average depth of 29 ± 0.2 m bsl (Appendix C; Fig. C.10). Another terrace or low sloping fan at 20 m bsl is visible on the main delta terrace. A steep (16°) delta front slopes down to the outer fiord basin (290 m bsl) and displays evidence of chutes and mass transport deposits reflecting slope instability (Table 2.1; Fig. 2.2, #3).

2.4.3 Boas Fiord

Boas Fiord is located along the southern coast of Merchant's Bay, aligned north-south for 34 km, with an average width of 2.7 km. Surrounding the head of Boas Fiord to the south are remnant valley and cirque glaciers providing meltwater and sediment for an extensive braided sandur (Fig. 2.5a). Boas Fiord is made up of two basins; the outer basin at >300 m water depth is separated from an inner basin at 90 m depth by a bedrock sill ≤10 m deep. Glacial veneer and morainal deposits mantle the fiord sidewalls, and the trunk and tributary valleys (Dyke, 2013c).

The submerged delta at the fiord-head (Site #4) is situated between the mouth of the trunk valley and a tributary valley from the east. The tributary valley has moraines presumed Late Foxe age (Miller, 1975), lining the tributary valley walls, and encroaching on the modern shoreline. A small glaciofluvial outwash fan occupies the valley mouth. The main valley has an extensive braided outwash plain overlying a thin layer of till, which is crosscut by recessional moraines up to the terminus of the modern valley glacier (Dyke, 2013c). The submerged fiord-head delta has a straight progradational front that wraps along the eastern sidewall. It has a flat terrace (33 ± 0.3 m bsl) surface and a delta front that slopes gently (7°) to the inner basin (90 m bsl; Fig. 2.2, #4). The delta terrace extends 7.5 km down valley from the modern delta front and occupies ca. 9.5 km^2 of the inner fiord. The front and edge of the delta terrace display pits and wallows, evidence for reworking by icebergs (Fig. 2.5c). The terrace surface consists of medium-coarse silt with scattered gravel (sub-angular).

Down fiord is a side-entry valley blanketed by till veneer with a moraine loop across its mouth (Site #5). This moraine and its associated submerged terrace was

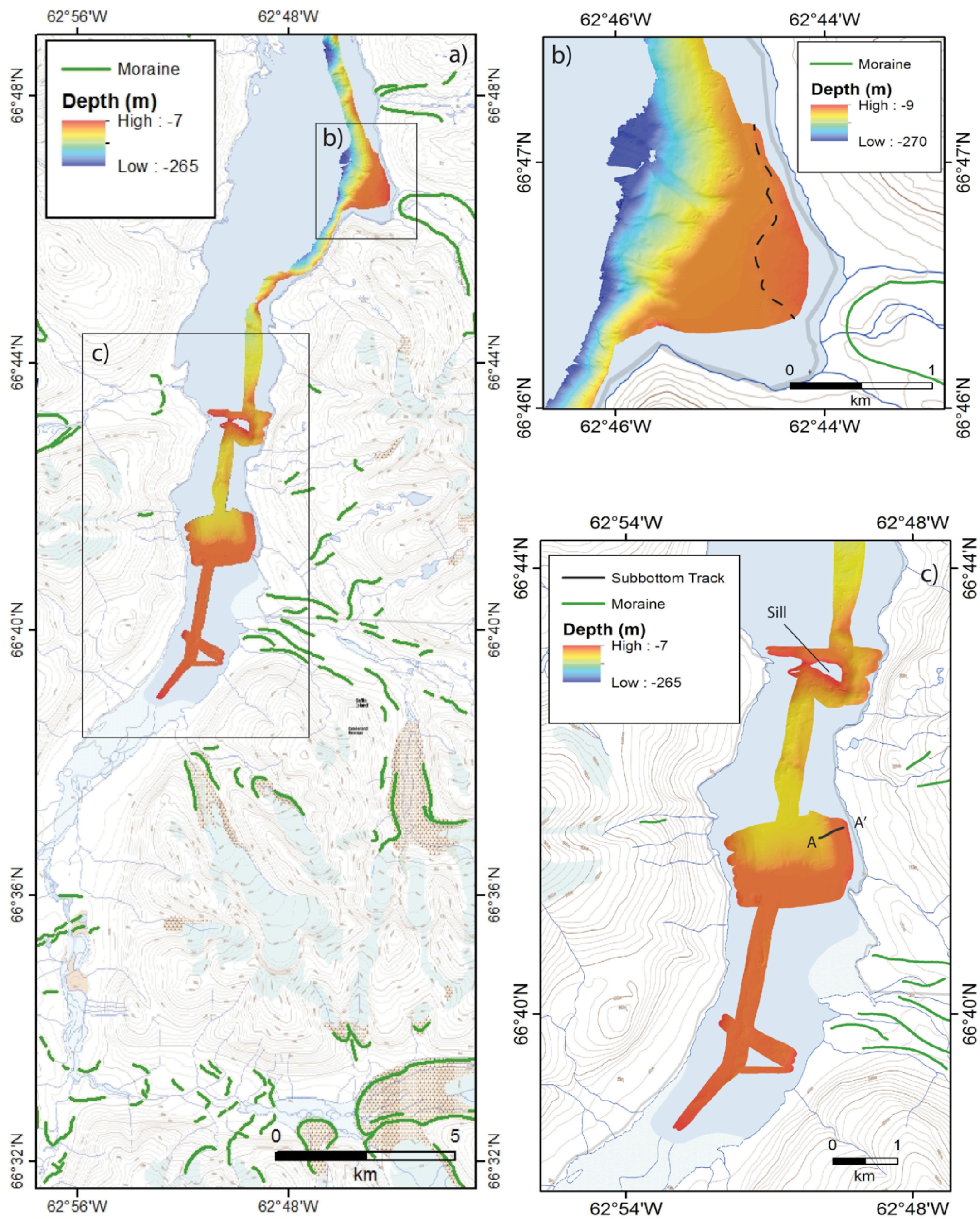

Figure 2.5: Multibeam bathymetry of Boas Fiord submerged deltas. A) Overview map of Boas Fiord bathymetry and geographic setting, with moraine systems from Dyke et al. (2013c). B) Multibeam bathymetry of the submerged side-entry delta in Boas Fiord. Note the small fan deposit located on the delta top, outlined by a dashed line. C) Multibeam bathymetry of the submerged delta at the head of Boas Fiord. Note subbottom track A-A' location (Fig. 2.6).

correlated to the Late Foxe moraines by Miller (1975), which have since been re-evaluated as early Holocene, Cockburn-equivalent moraines (Dyke, pers. comm., 2014). The present fluvial system is made up of a small braid plain that leads to the apex of the submerged delta, with meltwater sourced from a local glacier upvalley. The triangular-shaped delta is made up of a main terrace at 37± 0.2 m bsl (Fig. 2.5b) and a secondary terrace or low-sloping fan at 27 m bsl (Fig. 2.2, # 5). The upper terrace/fan has a slightly coarser silt cover than the main terrace, though both include shell hash and rare sub-angular to sub-rounded boulders (20-50 cm diameter). The delta front displays submarine chutes of various widths and evidence of reworking by iceberg grounding.

The fiord-head delta in Boas Fiord is the only site where substantial penetration of delta sediment was achieved for interpretation of the internal structure of submerged deltas (Fig. 2.6). The strongest acoustic reflector in the record, other than the seabed, bounds the bedrock basement (Unit A on Fig. 2.6b). The basal acoustic unit that overlies the bedrock basement unit is by far the thickest (10-20 m) and structurally most complex of the delta (Unit B on Fig. 2.6b). It is acoustically stratified upslope, composed of steeply dipping, oblique tangential, prograded clinoformal reflectors. Downslope the internal reflectors are less continuous and lose their definition. Although poorly documented, there is a suggestion that these reflectors flatten out beyond the steep delta slope and below the basin floor.

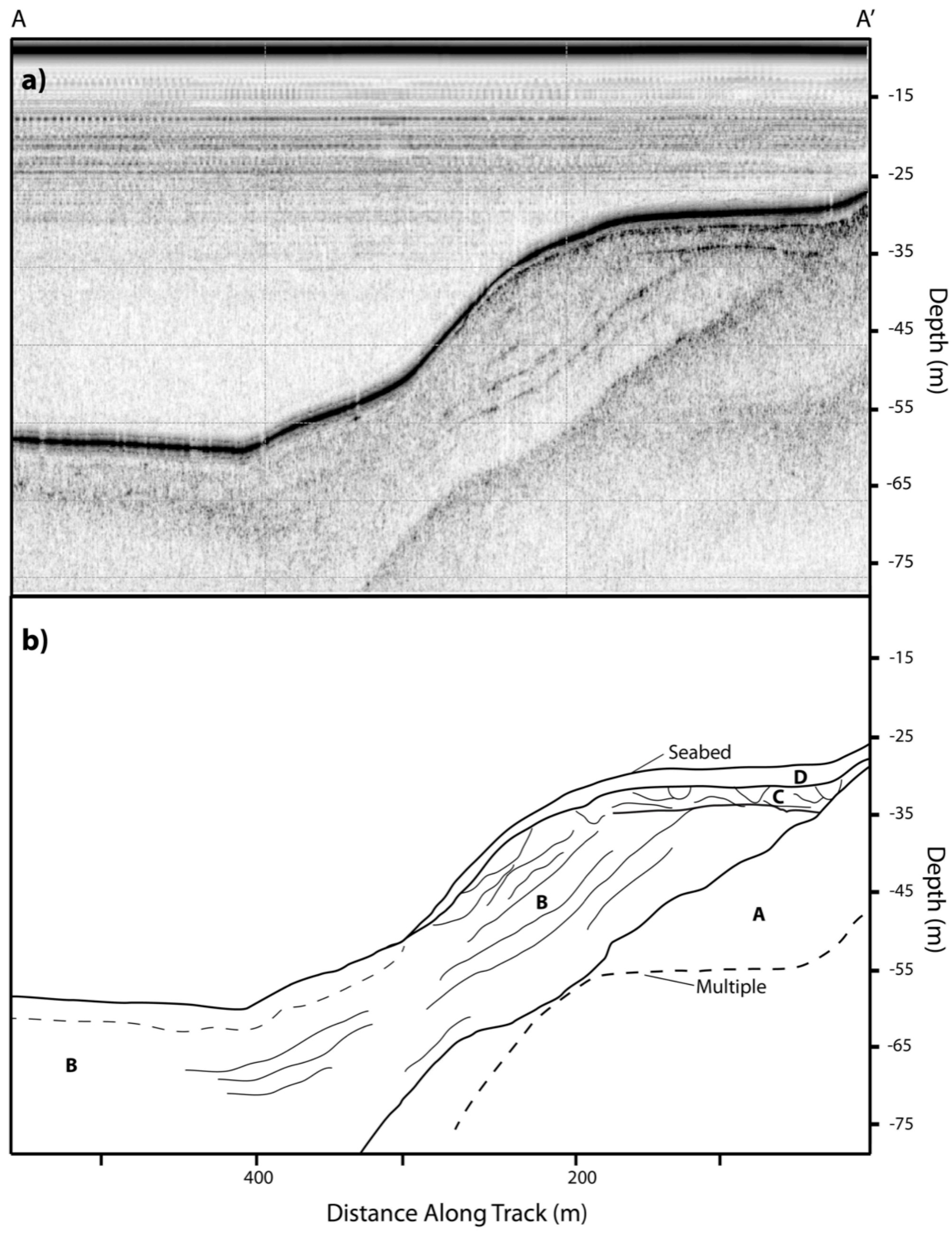

Figure 2.6: Subbottom profile A-A′ of the head of Boas Fiord (Fig. 2.5). A) 3.5 kHz acoustic record of the delta front (depths assume an acoustic velocity of 1500 m/s in water). B) Interpretation of subbottom stratigraphy based on the 3.5 kHz acoustic record in A. Dashed line marks the seabed multiple from the delta top and delta front. Acoustic units: A) Bedrock basement; B) delta front foresets; C) horizontal delta topsets; D) post-submergence mud drape.

Overlying this unit below the delta terrace is a 2-4 m thick horizontal unit made up of sub-parallel and concave-up reflector patters (Unit C on Fig. 2.6b). This unit truncated the inclined reflectors of Unit B along an erosional unconformity, which is marked by a strong basal reflector that becomes discontinuous towards the delta lip. The thin uppermost unit (at most up to 2 m thick) appears acoustically transparent and reflector-free and drapes the delta terrace and upper slope (Unit D on Fig. 2.6b). Unit D thins out along the mid slope and is poorly defined if it occurs at all as a separate unit on the lower slope and main fiord basin.

The subbottom stratigraphy expresses the characteristic tripartite structure of a Gilbert-type delta, with horizontally stratified topsets truncating steeply dipping, stratified foresets that grade downslope into more massive prodelta bottomsets (Cameron et al., 1993; Lønne, 1995; Masselink et al., 2003). The topsets exhibit remnant cut-and-fill channels, and the delta front shows evidence of buried mass movement deposits. The erosional unconformity between the foresets and topsets, or the transgressive surface, is situated approximately 2 m below the depth of the delta terrace lip.

2.4.4 Inner Durban Harbour

Inner Durban Harbour is the informal name for the embayment where a submerged delta was located to the east of the entrance to Southwind Fiord, south of Durban

Harbour (Fig. 2.2, #6). The apex of the delta is located at the confluence of several drainage systems sourced from high-elevation lakes and small remnant cirque and valley glaciers. The submerged delta is contained within a narrow embayment (ca. 900 m wide) that opens into a wider outer basin. Moraine deposits line the inner slope at the head of the inlet, while till veneer covers the western valley walls (Dyke, 2013c). According to Miller (1975), the moraine at the head of the inlet is presumed to be Late Foxe in age.

The submerged delta terrace at 44 ± 0.1 m bsl (Appendix A: Fig. A.26) in the inner Durban Harbour exhibits a straight progradational delta front. The delta front drops off abruptly to >110 m bsl, giving the delta a relief of ca. 67 m above the seafloor (Table 2.1; Fig. 2.2, #6). The delta terrace surface is blanketed by mud that was likely deposited post-submergence. Iceberg scours are evident on the delta front.

2.4.5 Mermaid Fiord

Mermaid Fiord is 23.5 km long and on average 2.2 km wide, opening into the 230-m-deep Exeter Sound from the southwest. A deep sill (80 m bsl) at the entrance of the fiord partially isolates the fiord basin, which has a maximum depth of 140 m. Three trunk valleys and a hanging valley feed the head of the fiord. The main fluvial source follows a long drainage system that starts at the terminus of a valley glacier 30 km up-valley and opens into the fiord on an extensive sandur plain.

Down-fiord is a side-entry valley along the western fiord wall; it connects Mermaid Fiord to the head of Clephane Fiord. The side valley is blanketed with till veneer and nested recessional moraines continue into Clephane Fiord (Dyke, 2011; Margreth, 2015). The main drainage system flows into the head of Clephane Fiord, and therefore at present Mermaid Fiord has little sediment supply from this side-entry drainage basin (38 km^2).

A submerged delta was deposited and preserved at the mouth of the side-entry valley, most likely at a time when ice occupied the recessional moraines in the valley and produced meltwater and sediment to feed the delta. The delta has a flat, triangular-shaped terrace at 36 ± 0.2 m bsl (Appendix A: Fig. A.35) that steeply slopes into the main fiord basin (100 m bsl; Table 2.1, #7). The delta slope displays a prominent seabed mass-failure that created a well-defined scarp on the delta front and redeposited delta sediments onto the basin floor.

2.4.6 Outer Clephane Fiord

A submerged delta was mapped in a narrow coastal inlet southwest of the entrance to Clephane Fiord (Fig. 2.2, #8; Fig. 2.7). The geographic setting and geomorphology share similar characteristics with the submerged delta located in Inner Durban Harbour (Site # 6). The head of the inlet is at the mouth of a U-shaped valley that drains many upland lakes and remnant cirque glaciers. The valley is draped with till veneer and contains a glaciofluvial outwash plain (Dyke, 2011). Within the narrow

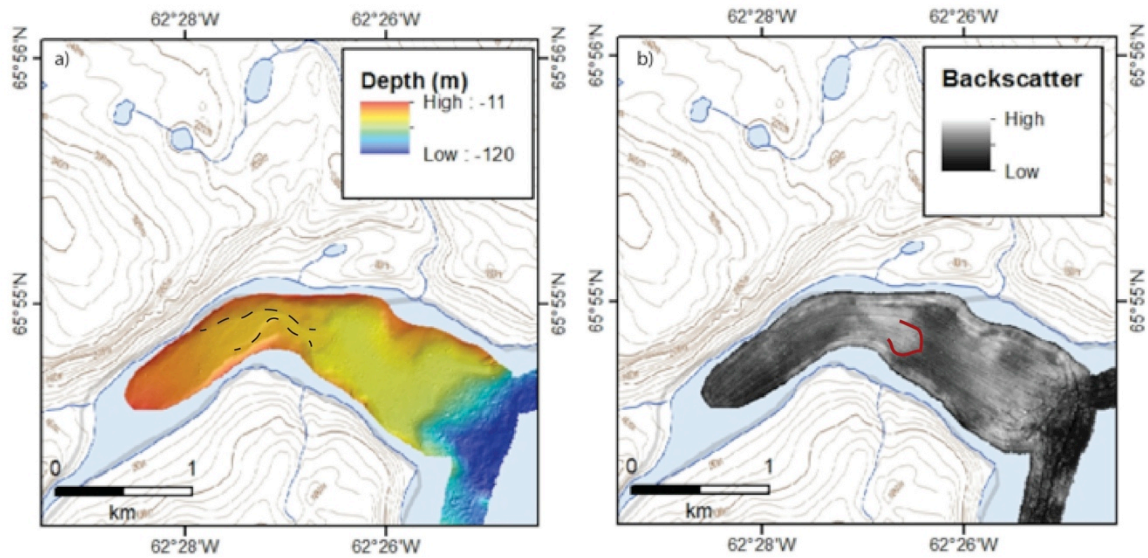

Figure 2.7: A) Multibeam bathymetry with post-sedimentation channel outlined by a dashed line, and B) backscatter imagery of the submerged delta at the mouth of Clephane Fiord (#7, Table 2.1, Fig. 2.2) with a fan deposit outlined by a red line.

inlet is a submerged delta at 45 ± 0.2 m bsl that drops off abruptly to 180 m bsl (Table 2.1; Fig. 2.2, #8). Icebergs enter and ground on the delta front, leaving pit and wallow marks (Fig. 2.7a). The delta terrace is remarkably flat and draped by post-submergence mud. The outline of a channel is visible through the mud veneer on the delta terrace (outlined in black, Fig.2.7a), which is also recorded in the backscatter map by a low return channel bounded laterally by high return levees (Fig. 2.7b). The channel runs along a gentle gradient and has deposited a small fan on the surface of the submerged delta terrace. This deposit may be from a triggered slope failure along the slope of the submarine channel, or it may be a fan deposit at the mouth of a subaerial channel during the transgression from the lowstand.

2.4.7 Summary and Interpretation of Results

Eight submerged deltas were mapped on eastern Cumberland Peninsula at depths of 19 to 45 m bsl within four fiords and two outer embayments. Most of the submerged deltas (6 of 8) are located at the terminus of glaciofluvial outwash systems that incise cross-valley moraines or till plains. These deposits were originally assigned Late Foxe age (Miller, 1975) due to the lack of raised shorelines of this age, but recently were reinterpreted to be of Cockburn-age (Dyke and Margreth, pers. com., 2014).

Kangert, outer Padle, Boas and Mermaid Fiords each have a triangular-shaped side-entry delta deposited down-fiord; they typically have a 1:1 ratio of length to width. The heads of Kangert and Boas fiords have characteristic fiord-head deltas with straight progradational fronts deposited at the end of long, narrow delta terraces within a narrow trunk valley. The variability in the shapes of these deltas is due to the accommodation space and sediment supply available. The side-entry deltas were deposited into open basins, in contrast to the confined valleys of the fiord-heads. Each of the side-entry deltas was preserved in a sheltered setting along embayed sidewalls. The fiord-heads typically have larger deltas than the side-entry valleys due to the higher sediment influx from larger drainage areas. The two submerged deltas deposited in the outer embayments (Site #6 & 8) have a similar characteristic shape to those found at fiord-heads, with straight delta fronts deposited within confined valleys. These embayments have medium drainage areas (Table 2.1) and similar depositional settings as fiord-head environments.

The depressions found on the surface of the submerged delta plains of Kangert Fiord (Site #1 & 2) are interpreted as kettle holes and provide evidence for delta deposition in contact with valley glaciers at a lower RSL. Kangert Fiord is the westernmost fiord where submerged deltas were documented. To the east, the submerged deltas lack kettle holes and therefore were deposited as ice-proximal to ice-distal deltas when valley glaciers had receded up-valley, out of contact with the delta.

All of the submerged delta terraces have slopes within a narrow range between 0.3 and 1.6°. The delta fronts show a larger slope range, between 5 and 23° (Table 2.1; Fig. 2.8). The slopes of characteristic side-entry delta fronts are steeper (>16°; dashed profiles in Fig. 2.8) than those found at fiord heads (<12°; solid profiles in Fig. 2.8) or outer embayments (#6 and 8; <11.8°). In the fiord-head settings there is also a characteristic prodelta slope (the break in slope from the delta front into the basin). Bathymetry for sites #3 and 5 shows a second terrace or fan below the apex of the main submerged delta terrace. These landforms are interpreted to represent renewed glaciofluvial deposition postdating the main delta formation but there is no clear RSL position associated with them. They may indicate renewed glacial activity in the drainage basin and as such may be of Neoglacial age.

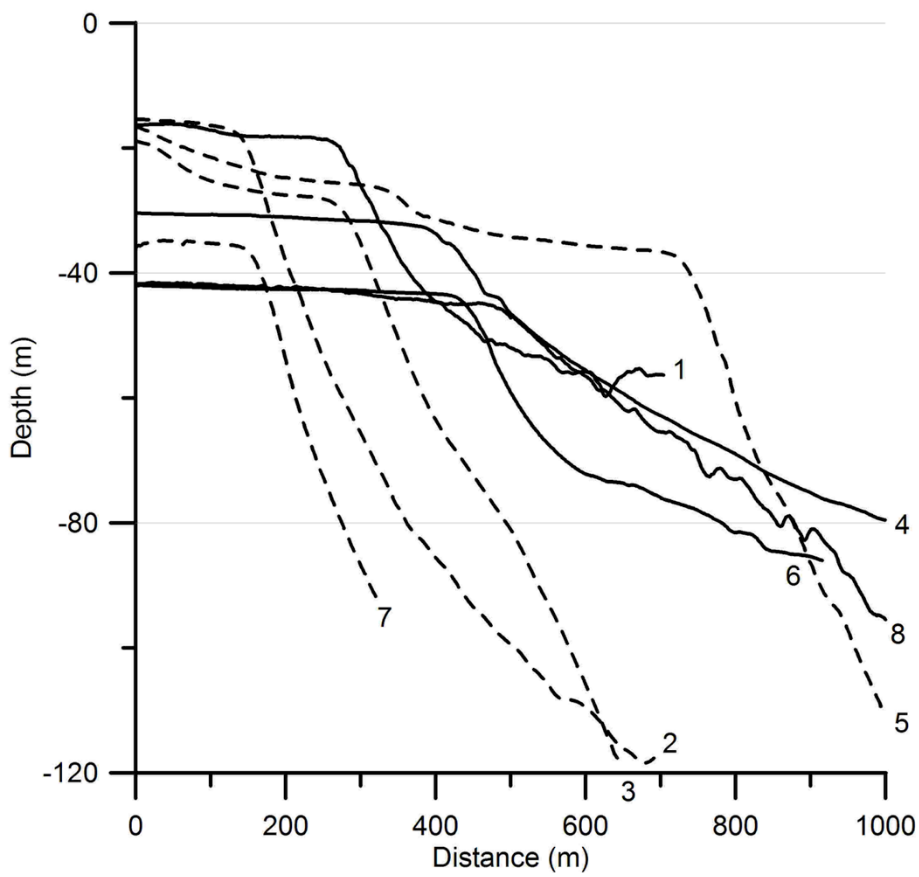

Figure 2 8: Submerged delta profiles reconstructed from the multibeam bathymetric data. Dashed lines show profiles of side-entry deltas. 1) head of Kangert Fiord, 2) side-entry valley in Kangert Fiord, 3) side-entry valley in outer Padle Fiord, 4) head of Boas Fiord, 5) side-entry valley in Boas Fiord, 6) Inner Durbhan Harbour, 7) side-entry valley in Mermaid Fiord, 8) outer Clephane Fiord. Locations are identified by number in Figure 2.2 and dimensions for deltas provided in Table 2.1. Vertical exaggeration: 8.33X.

2.5 Discussion

The discovery and bathymetric mapping of eight submerged deltas confirm the hypothesis for past submergence of eastern Cumberland Peninsula; however, these features cannot provide sea-level index points for the RSL history of the region without depositional ages. To better constrain the age of the deltas, we discuss the evidence for the lowstand deposition and interpret its occurrence within the overall deglacial chronology. The depth of submergence is discussed in terms of the lowest sea-level indicators, the spatial distribution and trends of submergence across the peninsula.

2.5.1 Submerged Deltas

Submerged deltas on Cumberland Peninsula were mapped at water depths between 19 and 45 m bsl. Contemporaneous sea levels during deposition of the Gilbert-type deltas can be estimated from the depth of the transgressive surface. The submerged delta at the head of Boas Fiord (Site #4; Fig. 2.2), the only site with well-imaged subbottom stratigraphy (Fig. 2.6), was used as an analogue for estimating the palaeo-sea level positions for deltas without subbottom profiles. The transgressive surface was identified ca. 2 m below the average delta terrace lip at the head of Boas Fiord. This depth marks the erosional base of former braided channels during deposition of the delta foresets, thereby delimiting the lowest possible water level at the time of deposition. Taking into account a microtidal range, averaging 1 m for northeast Cumberland Peninsula, the high-tide limit of palaeo-sea level would be about 1 m below the average terrace lip depth (Table 2.1).

The Boas Fiord site can be used as an analogue for other deltas if we assume that they had similar rates of post-depositional sedimentation and similar delta-front dynamics. This assumption has uncertainties for those delta sites with minimal paraglacial sedimentation compared to the head of Boas Fiord, such as the two in Kangert Fiord and one in inner Durban Harbour. The difference in post-depositional sediment levels affects the depth of the transgressive surface below the delta terrace lip, which cannot be determined without well-imaged subbottom stratigraphy from all the deltas.

The submerged deltas off eastern Cumberland Peninsula are indicative of either deglacial marine limits, postglacial lowstand or along the transgressive limb. Marine limit deltas are typically incised, with evidence of terraces that formed as sea level fell below the prograded delta depth to form a lower delta. Lowstand deltas are deposited at stable sea level during the postglacial RSL inflection point from regression to transgression, which typically results in extensive delta formations. As incision and downcut terraces were not observed on the submerged deltas it is unlikely that they were deposited on the regressive limb of their local sea-level curve. Instead, these deltas were more likely to have been deposited during the lowstand or on the transgressive limb of the local sea-level curve. If the latter is correct, the deltas may represent a pulse of sediment delivered from the recession of ice cover landward of the fiord-heads under a rising RSL (e.g. following the YD or Cockburn substage).

The termination of delta growth may result from two independent factors: (1) the flooding of the delta terrace during transgression, or (2) a rapid decline in paraglacial sediment supply as ice retreats inland (Forbes and Syvitski, 1994). Preservation of eight deltas 19-45 m bsl attests to a postglacial decrease in sediment supply on Cumberland Peninsula during the following transgression. However, only with absolute ages of the submerged deltas and their proximal moraines, can a full understanding of the postglacial sea level history be formulated.

2.5.2 Shoreline Gradient

Of the eight submerged deltas, the shallowest (19 m bsl) is found in the west and the deepest (45 m bsl) in the east, exhibiting an eastward-dipping linear gradient of 0.35 m/km (Fig. 2.9). This documentation of a lower RSL confirms the trend hypothesized by Dyke (1979) for eastern Cumberland Peninsula. He proposed that the 0.59-0.62 m/km eastward gradient of the raised early Holocene marine limits (Fig. 2.9; E-G) on the south coast of Cumberland Peninsula continues below sea level in the east. In this paper, we report eight submerged deltas consistent with this eastward dipping plane, but at a shallower gradient and offset at a greater depth than expected.

The shoreline gradient presented for the submerged deltas (Fig. 2.9) is aligned perpendicular to the 8.5 ka isobases presented in Kaplan and Miller (2003), which run north-south across the central peninsula with a maximum cross-isobase gradient of 0.61 m/km. Here the maximum gradient across the isobases is aligned east-west, whereas to the north of Qikiqtarjuaq it is directed more toward the NE. The results of this study reveal a shoreline gradient towards the east, plotted along an east-west transect in Figure 2.9. Thus the discovery of eight submerged shorelines along an eastward dipping relict shoreline confirms the alignment of the

8.5 ka isobase of Kaplan and Miller (2003) and revises their interpretation of the present zero isobase to fall west of Kangert Fiord.

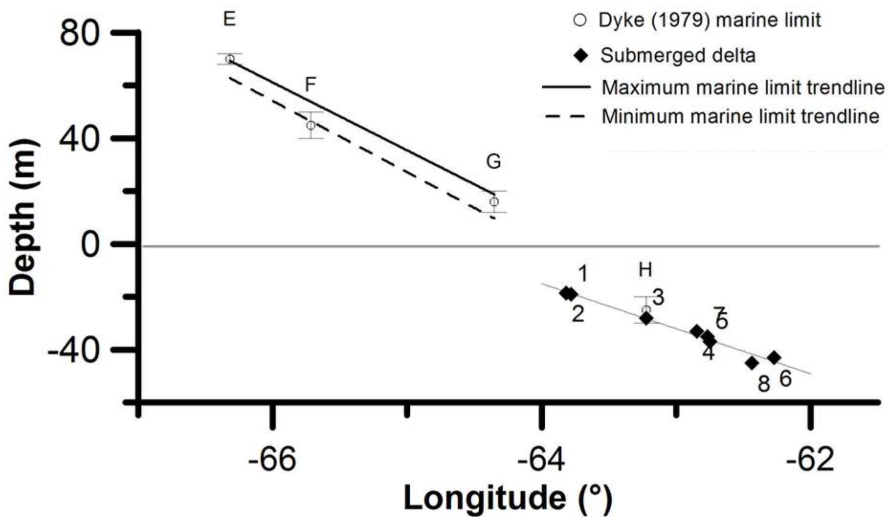

Figure 2.9: Longitudinal trend in the delta terrace depths from west to east across Cumberland Peninsula (Table 2.1), with the maximum and minimum trend of raised marine limits (ca. 8.5 ka; Dyke, 1979). Numbers denote submerged delta locations in Figure 2.2 and Table 2.1; letters correspond to sea-level curves in Figure 2.3 (Dyke, 1979).

The timing of the rapid deglaciation of the LIS and peripheral local glaciers was time-transgressive around the perimeter of Cumberland Peninsula, beginning earlier in the south (Miller, 1975; Margreth, 2015). In this context, the submerged shorelines delimited by deltas formed at initial deglaciation would be diachronous.

In contrast, Dyke (1979) showed that the marine limits (E-G), the highest postglacial preserved shorelines in the western part of Cumberland Peninsula, formed synchronously at ca. 8.5 ka. The tightly fitted linear gradient presented for the submerged deltas in Figure 2.9 also suggests a relatively synchronous deposition at a shoreline-building episode during the overall deglaciation. These deltas are interpreted to have formed from a pulse of sediment and meltwater coeval with a climatically controlled glacial recession. This results in a linear shoreline gradient that postdates the 8.5 ka marine limit trendline. The formation of submerged deltas at a younger age than Dyke's (1979) marine limits to the west would result in an offset of the submerged shoreline gradient at a greater depth from the marine limit gradient. Furthermore, the reduced glacial-isostatic rates since the lowstand deposition account for the lower slope of the submerged shoreline gradient. The submerged dataset presented here can be used to better constrain the postglacial isostatic adjustment and sea-level history of the region.

2.5.3 Temporal Constraints of the Lowstand

In this paper the depositional ages are inferred from recessional ice limits across Cumberland Peninsula and the deglacial chronology within the literature. Based on deglacial ice limits (Fig.2.2; Margreth, 2015), the maximum age of deposition is determined by the age of the closest ice limit up-valley from the submerged ice-contact and ice-proximal deltas. The locations of surveyed deltas were all ice-covered at the start of deglaciation, ca. 14 ka. Rapid recession from the fiord mouths proceeded until the re-advance of YD ice limits at 11.7 ka, when the two submerged deltas in the east (Sites #7 and 8) were ice-free (Fig. 2.2). This interpretation makes assumptions for site #8, as the glacial limits for the YD are interpolated and have not been mapped.

The recession of the easternmost coast was more extensive than in the north, where alpine glaciers remained in the fiords at the YD re-advance and the submerged delta sites in Boas Fiord were still covered by ice (Sites #4 and 5). Kangert Fiord in the west does not have mapped moraine deposits for the YD, but the glacial limits are interpreted to be further inland from the fiord heads. The ice had receded further up valley from the outer Padle Fiord submerged delta (Site #3), to be contained within the inter-fiord region. The YD ice limit at inner Durban Harbour wrapped around the coast (Site #6). These interpretations suggest that many of the submerged delta locations became ice-free before the re-advance of the YD. This paper proposes that the deposition of these submerged deltas required adjacent ice margins at a time when the fiord-heads were ice-free, which determines that the maximum age of deposition is from the YD recession, after ca. 11.7 ka.

By 9.5 ka, at the re-advance of the Cockburn Substage, all submerged delta locations were ice-free. Cockburn-equivalent moraines in Boas Fiord wrap around the coast at the fiord-head and side-entry valleys. In the west, around Kangert Fiord, Cockburn-equivalent moraines have not been identified, but lake sediments dated at 9.5± 0.1 ka constrain the glacier system to a position up-valley from the head of Padle Fiord (Frechette and de Vernal, 2009; Margreth, 2015). In outer Padle Fiord, the ice margin is presumed to have remained at the limit of the YD ice margin, within the inter-fiord region. Based on the limits of the Cockburn-equivalent glacier re-advance, the minimum age of delta formation is coincident with the recession of the

Cockburn Substage, which began ca. 8.5 ka (Briner et al., 2009). This minimum age constraint is consistent with our interpretation of a synchronous delta deposition that postdates the 8.5 ka marine limits recorded by Dyke (1979) and aligns with the 8.5 ka isobase gradient of Kaplan and Miller (2003).

The deglacial ice margins along northern Cumberland Peninsula are interpreted from observations and have not been dated (Margreth, 2015). In these cases, the submerged deltas may provide insight into the extent of the ice limits. The submerged ice-contact deltas in Kangert Fiord delimit the ice margin, as is evident from the kettle holes on their surface. Kettle holes could be present below post-depositional sediment on the surfaces of other submerged delta terraces, but have since been filled by sediment. Kangert Fiord has a limited drainage area (Table 2.1) and associated paraglacial sediment supply, and therefore a restricted postglacial sediment fill, which did not infill the kettle holes on the surface. Whether the submerged deltas in this fiord constrain YD or Cockburn-equivalent ice margins requires ages on the moraines mapped at the head of Kangert Fiord (Fig. 2.2).

The depths of the submerged deltas are plotted on the original sea-level curves from Dyke (1979) in Figure 2.10. The age range plotted in Figure 2.10 is interpreted from the recessional age extents of the YD and Cockburn Substage, and the submergence curves are extrapolated up to the present sea level. The continuous submergence of the Zone II RSL curve explains the lack of postglacial marine limits observed in the region, as the submerged deltas do not necessarily record a postglacial lowstand but were deposited at a lower-than-present shoreline-building episode.

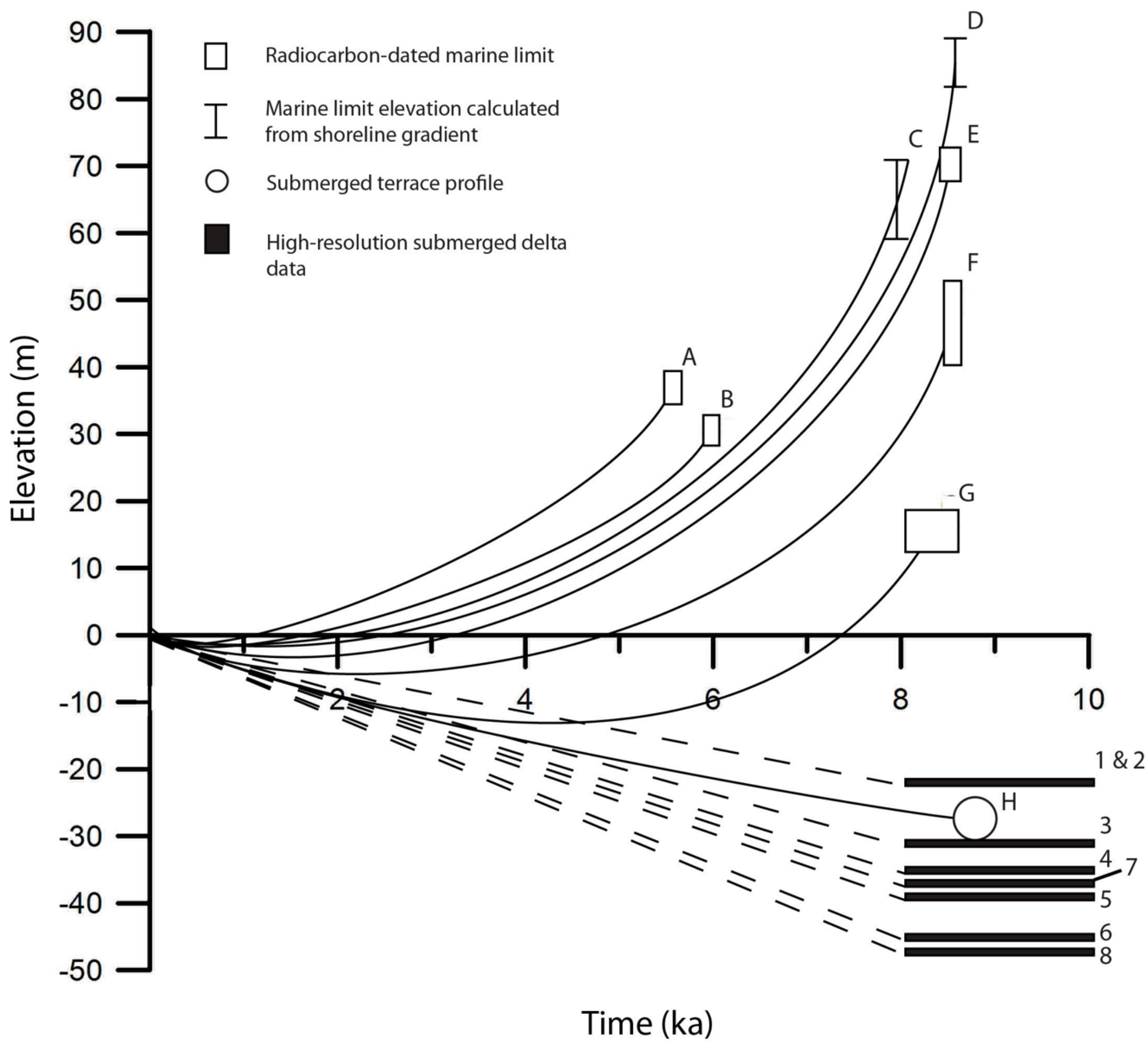

Figure 2.10: Sea-level curves extrapolated from radiocarbon-dated marine limits on southwestern Cumberland Peninsula and the depths and interpreted age constraints of the submerged deltas from eastern and northeastern Cumberland Peninsula. Modified from Dyke (1979).

Potentially conflicting with this sea-level model, raised terraces interpreted as possible marine features have been observed on the eastern coast of the peninsula south of Cape Dyer and at the head of Mermaid Fiord, although no ages have been recorded (Locke, 1980; Dyke, pers. com., 2014). These may be kame terraces, and glaciofluvial deposits correlated to the Sunneshine ice margin (37.2 ± 0.8 ka BP) on the outer peninsula (Locke, 1980; 1987). These deposits add to the previously outlined conceptual model if they are dated to the Sunneshine ice margin.

Alternatively, if the higher terraces are related to the Late Foxe marine limit, then the submerged deltas are younger than originally hypothesized. In this context, the submerged deltas mark the postglacial lowstand after the rapid rebound of the late Foxe marine limits on the outer coast. An uncertainty for this interpretation is that it does not account for the lack of sediment deposits correlated to the recession of the LGM.

In either interpretation, the eustatic rise in sea level since 8 ka (16 m; Miller, 1975) does not account for the depth of submerged deltas (19-45 m bsl). The collapse of the forebulge is an additional factor that adds to the depth of submergence. Either the submerged deltas mark a strandline on the transgressive limb or they delimit the lowstand at the inflection point after a rapid rebound from the late Foxe marine limits. Until the moraines, glaciofluvial and glaciomarine deposits are dated, many assumptions are made for the sea level history of northeastern Cumberland Peninsula since the LGM.

2.6 Conclusion

Over the past several years, the necessity for high-resolution mapping of submerged shorelines along the eastern coast of Cumberland Peninsula has been increasingly recognized. Three mapping surveys (2012-2014) set out to fill this knowledge gap by creating high-resolution maps of the seabed and documenting shoreline deposits. The multibeam surveys mapped eight submerged ice-proximal deltas (19-45 m bsl) along the northern and eastern coasts of Cumberland Peninsula. Submerged delta terraces were mapped at fiord-heads and side-entry valleys, along with sheltered outer embayment settings. A subbottom profile of the fiord-head delta in Boas Fiord revealed the transgressive surface of erosion and indicates that high-tide reached 1 m below the documented delta terrace lip. This sea-level marker was used to delimit the depositional sea-level for the other submerged delta features. After the pulse of sediment that initiated deltaic deposition, a paraglacial decrease in sediment supply combined with flooding of the delta terrace during the rapid transgression allowed for the preservation of the submerged deltas on the seabed.

These shoreline features were deposited synchronously with respect to the deglaciation, and are constrained to have formed from meltwater and sediment sourced from a glacial recession bracketed by the YD (maximum age of deposition after ca. 11.7 ka) and the Cockburn Substage (minimum age of deposition after ca. 8.5 ka) ice limits. The lowstand shorelines follow a 0.35 m/km gradient towards the east, confirming the eastward tilt of the postglacial shoreline gradient hypothesized from marine limits in the southwest (Dyke, 1979). The offset from the marine limit shoreline gradient is explained by decelerating rates of glacial-isostatic adjustment and reduced differential uplift over time.

Coordinating with the continued efforts to map submerged shorelines in the nearshore of Cumberland Peninsula, the priority is to constrain the lowstand chronology and therefore the sea level history and trends of postglacial crustal response. In particular, piston cores of the prodelta bottomsets and gravity cores of the delta topsets should be collected from the mapped deltas to provide facies interpretation of the sedimentation packages and potential mollusk shells for radiocarbon dating. To add to this research, cosmogenic radionuclide dating of the adjacent, up-valley, moraine deposits would constrain the associated deposition of submerged glaciomarine deltas as well as the chronology of the proximal glacial recession in the northern Cumberland Peninsula.

2.7 References

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CHAPTER 3: THE EARLY HOLOCENE SUBMERGED SHORELINES OF EASTERN BAFFIN ISLAND, NU: IS THE MODERN COAST A SUITABLE ANALOGUE?

Abstract

The recent discovery of eight submerged deltas in the fiords of Cumberland Peninsula provide fundamental evidence for postglacial submergence, hypothesized since the 1970s on eastern Baffin Island, NU. In addition to the submerged deltas, a boulder barricade, a wave-trimmed sill platform, and relict spits were recently mapped on the seabed in the same region. Though raised boulder barricades have been used to record sea level, this is the first documentation of a submerged boulder barricade. This paper compares the geomorphology of the modern coast and the early Holocene submerged shoreline (16-52 m below sea level) in three localities on Cumberland Peninsula. Bedrock cliffs with fringing, pocket and barrier beaches, spits, tombolos, and numerous deltas characterize the coastline of northeastern Cumberland Peninsula today. Spits and deltas are also documented below sea level in Akpait and Boas fiords, indicative of the early Holocene shoreline. The morainal sill at the mouth of Akpait Fiord may have been very shallow to emergent at the lowest postglacial sea level. In Broughton Channel there is no boulder barricade along the modern shore, but a submerged relict barricade is reported at 16 m below present sea level. This discrepancy may be attributed to the opening of Broughton Channel as the Holocene transgression overtopped the sill at its north end. As water over the sill deepened, it converted a semi-enclosed tidal embayment into a tidal passage swept by strong currents, promoting earlier sea-ice breakup and thereby

removing conditions required for the formation of boulder barricades. This demonstrates the sensitivity of the coastal environment to sea level, bathymetry and exposure.

3.1 Introduction

There is little information in the literature on the character of submerged relict shorelines in Arctic regions (e.g. Miller and Dyke, 1974; Miller, 1975; Dyke, 1998; Rasch, 2000; Sparrenbom et al., 2006). This is in part because many Arctic coasts are affected by glacial-isostatic uplift and are emergent, with relict shorelines raised above present sea level, and in part because the technology to map submerged coastal geomorphic features has not been widely deployed until recently (Hughes Clarke et al., 2015).

The eastern fringe of Baffin Island is one region in which coastal submergence has been documented (Chapter 2; Miller and Dyke, 1974; Miller, 1975), leading to the expectation that a geomorphic and sedimentary record of relict shorelines may be present on the sea floor. This study has explored the submerged coast of eastern Cumberland Peninsula, an area of rugged relief representing the easternmost coast in the Canadian Arctic Archipelago (Fig. 3.1A). The modern shoreline in this region is largely sediment-starved, with extensive rock cliffs and discontinuous,

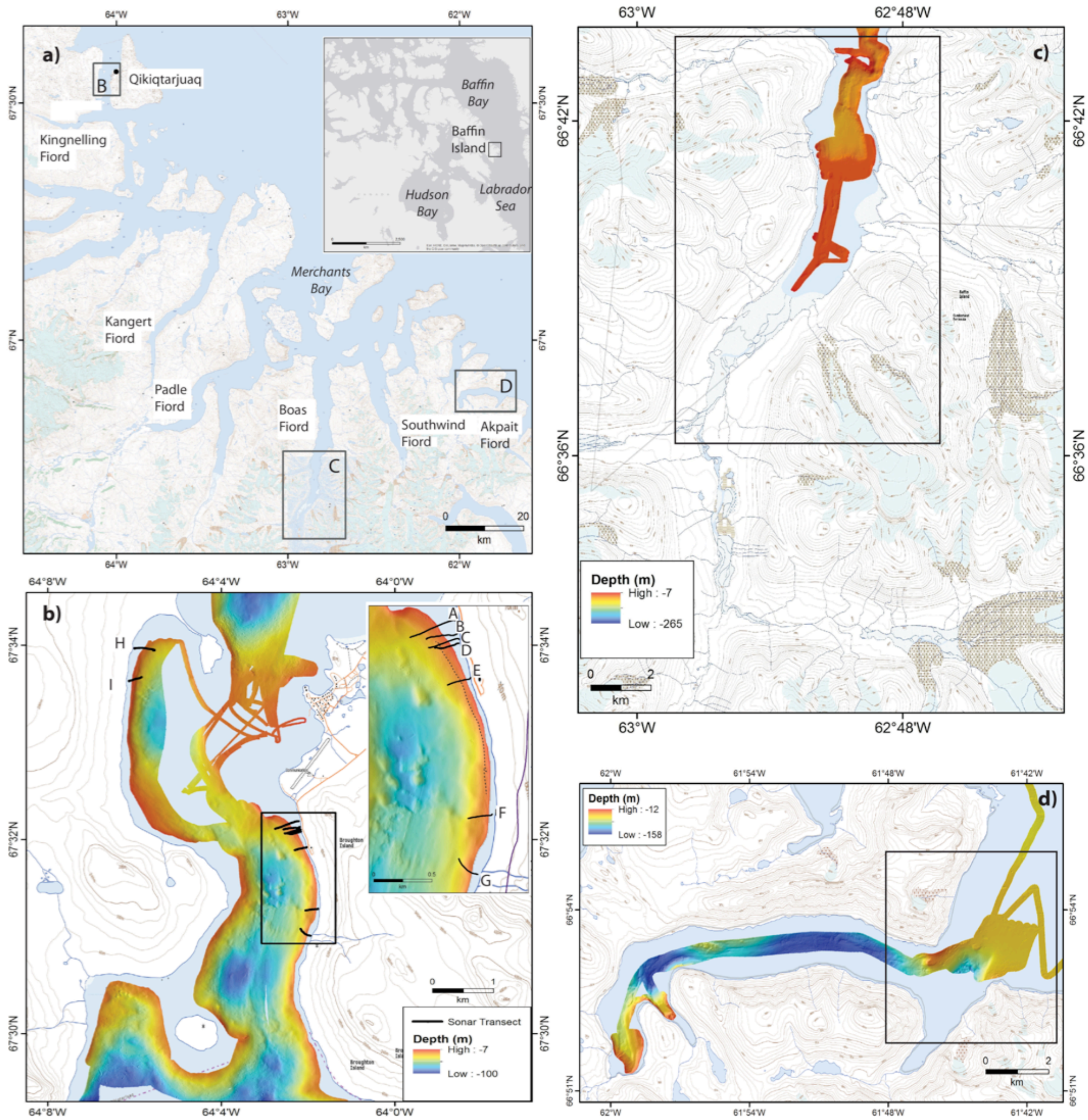

Figure 3.1: A) Map of Cumberland Peninsula, with Broughton Channel (B), Boas Fiord (C), and Akpait Fiord (D) study sites outlined. Inset map locate Baffin Island in the eastern Canadian Arctic. B) Multibeam imagery of Broughton Channel, including sonar transects displayed in Figure 3.5. Inset map highlights eastern Broughton Channel, the location of the submerged boulder barricade (grey dashed line). C) Multibeam imagery of inner Boas Fiord and the submerged fiord-head delta. D) Multibeam imagery of Akpait Fiord, with the site of the submerged sill platform highlighted.

predominantly small-scale development of coastal sedimentary deposits. Prior to this work, little was known of the character of the submerged shoreline (Miller and Dyke, 1974; Miller, 1975) or of the extent to which it is analogous to the modern coast. This paper examines the geomorphic similarities and differences of the modern and submerged shore-zones in three study areas along the coast of northeastern Cumberland Peninsula. It further considers the interpretation and utility of various submerged coastal landforms as indicators of former sea levels and coastal sedimentary processes, and the reasons for the absence of some submerged features in the present-day shore zone.

Submerged deltas are commonly used relict sea-level indicators with the potential to provide chronological control. Two other less common sea-level indicators observed in the study region are, (1) a boulder ridge interpreted to be a submerged boulder barricade (to our knowledge, the first reported in the literature), and (2) a truncated fiord-sill platform, an erosional shore zone feature. The objectives of this paper are to characterize the geomorphology and coastal setting of these three submerged coastal features and to better understand the conditions under which the submerged shorelines developed and the extent to which they resemble the modern coast. Our description of the submerged shorelines on eastern Baffin Island is based primarily on geomorphic analysis from multibeam sounding and subbottom acoustic profile records, video imagery and grab samples.

Previously, the only documentation of the early Holocene submerged shoreline of eastern Cumberland Peninsula was from single-beam seabed profiles of submerged terraces, 28-38 m below sea level (bsl), along the northeastern coast (Miller and Dyke, 1974; Miller, 1975).

3.1.1 Regional Setting

Cumberland Peninsula is the easternmost landmass in the Canadian Arctic Archipelago (Fig. 3.1A). It comprises mountainous terrain as a result of uplift after the late Cretaceous to early Tertiary rifting of North America from Greenland (Jackson and Taylor, 1972). The physiography of the landscape has since been carved by glacial and fluvial erosion throughout the multiple glacial cycles of the Quaternary (Miller et al., 2005). The Last Glacial Maximum (LGM) brought the Foxe sector of the Laurentide Ice sheet to its limit along the northeastern coast of Baffin Island and onto the adjacent continental shelf (Marsella et al., 2000; Dyke et al., 2002; Miller et al., 2005). Northern Cumberland Peninsula was influenced by the expansion of the Penny Ice Cap (PIC) and alpine glaciers, as the Laurentide Ice Sheet (LIS) coalesced with the PIC (Margreth, 2015).

Recession from LGM ice limits began by 15 ka on eastern Baffin Island, but the fiord heads of northern Cumberland Peninsula did not experience rapid deglaciation until after 11.7 ka following the Younger Dryas (YD) re-advance (Merchant's Bay; Dyke et al., 2003; Miller et al., 2005; Briner et al., 2009; Margreth, 2015). During two early Holocene re-advances – the Cockburn Substage (9.5-8.5 ka) and the 8200-year cold event – ice from the PIC and local valley glaciers reached fiord heads (Miller, 1975; Andrews and Ives, 1978; Miller et al., 2005; Briner et al., 2009). Increased sea-ice cover after 5 ka marked the beginning of Neoglaciation, which intensified between 1.9 and 1.1 ka (Margreth et al., 2014). On Cumberland Peninsula the Little Ice Age began after 0.8 ka with a succession of alpine glacial expansions (Margreth et al., 2014).

For most of Baffin Island, the relative sea-level (RSL) history throughout the mid- to early Holocene has been controlled predominantly by uplift and coastal regression (seaward advance of the shoreline). Glacial recession following the LGM resulted in differential glacial-isostatic adjustment (GIA), which created a complex sea-level history in peripheral regions, including Cumberland Peninsula. Radiocarbon-dated raised shorelines were used to reconstruct RSL history for southwestern Cumberland Peninsula (Dyke, 1979). Sea-level curves were extrapolated from the sparse RSL dataset and interpreted as J-shape curves along the central peninsula and continuously submerged below present level along the eastern coast (Pheasant and Andrews, 1973; Miller, 1975; Dyke, 1979; Andrews, 1980; Clark, 1980; Andrews and Miller, 1985; Dyke et al., 2002; Miller et al., 2002; Briner et al., 2009). Preliminary evidence for a submerged RSL record was provided for Boas and outer Padle fiords by seabed profiles of flat-topped features (28-38 m bsl) with steep seaward slopes, interpreted as submerged deltas (Miller and Dyke, 1974; Miller, 1975). Eight submerged deltas have since been mapped in high-resolution (including those above), providing geomorphic evidence for the spatial distribution of the postglacial submergence (Chapter 2).

Over the past millennium or so, eastern Baffin Island has been experiencing a RSL rise known as the Canso Channel Transgression. England and Andrews (1973) described submerged shingle ridges (9 m bsl) and deeply incised bedrock gorges blocked by modern shingle barrier ridges off the eastern coast of Broughton Island (Pheasant and Andrews, 1973). Canso Channel and Qikiqtarjuaq have buried peat dated at 930 ± 100 BP (Gak-3096) and 810 ± 80 BP (SI-2549), suggesting that the transgression began at least by ca. 1 ka (Pheasant and Andrews, 1973; Brigham, 1982). Other dated samples constrain the onset of the transgression to at least 1.2 ka for the northeastern coast (Pheasant and Andrews, 1973; Dyke, 1979; Andrews and Miller, 1985). The evidence for transgression along northern Cumberland Peninsula further adds to the postglacial submergence trend extrapolated from the sea-level curves. Recent evidence from the tide gauge and GPS station at Qikiqtarjuaq (established in 2004), however, suggests a modern emergence trend contrary to this recent geological record. Furthermore, sea-level projections for Qikiqtarjuaq describe a RSL fall between now and 2100, attributed to the ongoing uplift and suppressed RSL rise from the close proximity and gravitational effects of the Greenland Ice Sheet and smaller glaciers in the Canadian Arctic Archipelago (James et al., 2014).

3.1.2 Study Area

The study area for this project encompasses three geographic localities: Broughton Channel (west of the Hamlet of Qikiqtarjuaq), Boas Fiord and Akpait Fiord (Fig. 3.1). These sites were chosen based on the discovery of four types of submerged shoreline features: a boulder barricade, delta terrace, sill platform, and two spits. The fiord-head delta in Boas Fiord was chosen to represent the geomorphology of typical submerged deltas in the region (Chapter 2). In each locality, the geomorphology of the modern shoreline is classified and mapped for comparison with the surveyed submerged shoreline features.

3.1.2.1 Broughton Channel

The Hamlet of Qikiqtarjuaq, Nunavut (formerly known as Broughton Island) is located on Broughton Island at the north end of Broughton Channel, on northwestern Cumberland Peninsula (Fig. 3.1B). Qikiqtarjuaq has semi-diurnal tides with a mean range of 0.9 m, and a maximum spring tide range of 1.32 m (Canadian Hydrographic Survey, 2014), with sea ice present between October and July (Mallory et al., 2006). The island is separated from the mainland of Baffin Island by Broughton Channel, a shallow marine channel carved by glacial outflow from an expanded PIC throughout the Late Quaternary (Pheasant and Andrews, 1973; Brigham, 1982).

The study area encompasses the coastal waters and shores of Broughton Channel, including those of the Hamlet of Qikiqtarjuaq, NU. The shorelines surrounding the channel are varied. Opposite the hamlet on the western (mainland Baffin Island) shore, a gravel barrier forms a tombolo connected to a bedrock island, partially closing the entrance to the channel (Fig. 3.1B). To the north of the tombolo, the coast is fully exposed to Baffin Bay. Within the channel, the beaches that line the eastern and western coasts are protected from Baffin Bay, but are influenced by local currents. Surface currents of 0.5-0.8 m/s cause ice breakup several weeks earlier than in adjacent regions and winnow the seabed, leaving behind a boulder lag within a sand and gravel matrix (Gilbert, 1980). Broughton Channel reaches a depth of 60-70 m below sea level, south of the community, and deepens to more than 300 m in the Kingnelling Fiord trough at the south end (Gilbert, 1980). The channel is shallowest (16 m bsl) between the tombolo and the community (Gilbert, 1980). Gilbert (1980) profiled a submerged terrace 2-5 m below sea level along the east and west coast of the channel, south of the community of Qikiqtarjuaq, NU. The terrace was interpreted to have formed by seasonal sea-ice erosion of the glacial sediment, and possibly analogous to the Frobisher Bay and Cumberland Sound tidal flats (Gilbert, 1980).

The PIC (6000 km^2) lies 50 km to the southwest and has fed ice through Qikiqtarjuaq onto the continental shelf during the Quaternary. During two pre-LGM glaciations, ice from the southern glacial system advanced onto the continental shelf beyond Cape Broughton (Brigham, 1982). During the early Foxe Glaciation (>54 ka

BP) the ice limit extended to the present tombolo and community of Qikiqtarjuaq and relative sea level was +72 m (Brigham, 1982).

3.1.2.2 Boas Fiord

Boas Fiord extends 34 km north-south and reaches >300 m depth at the fiord mouth, where it enters Merchant's Bay from the south (Fig. 3.1C). Boas Fiord hosts cirque and local valley glaciers within the fretted mountains of its drainage basin (Hawkins, 1985). In front of the modern glaciers is a suite of late Foxe recessional moraines marking much more extensive ice within side-valleys of the fiord (Miller, 1975; Hawkins, 1985; Margreth, 2015). It was the absence of late Foxe raised marine features and the proximity to the coastline of late Foxe morainal deposits that led Miller (1975) to hypothesize that the postglacial shoreline features are presently below sea level, adjacent to the moraines. Glacial ice occupied Boas Fiord during the YD at ca. 11.7 ka, after which glaciers receded up-valley into the central peninsula (Margreth, 2015). Pulses of glacial expansion returned low-gradient valley ice to the fiord head during the Cockburn Substage (9.5-8.5 ka BP) and again at the 8200-year cold climate event (Andrews and Ives, 1978; Miller, 1975; Miller et al., 2005; Briner et al., 2009; Margreth, 2015).

Miller (1975) explored Boas Fiord (previously Kangetokjuak Fiord) with a single-beam echosounder and documented bathymetric profiles of submerged deltas at the fiord head and side-entry valleys. Along with a documented submerged delta in outer Padle Fiord (Miller and Dyke, 1974), these features provided the first evidence of submerged shorelines in Cumberland Peninsula and targets for recent multibeam mapping (Chapter 2). The geography of Boas Fiord has been outlined in Chapter 2 as the study area of two submerged deltas at 33 and 37 m bsl. Multibeam imagery and a subbottom profile of the submerged delta at the fiord-head were acquired for this study in 2012. These deltas were deposited below present sea level adjacent to presumed late Foxe moraine deposits in the glacial valleys (Miller, 1975). The subbottom profile of the fiord-head delta terrace showed the tripartite structure of a Gilbert-type delta, and was used to determine the sea level during delta deposition.

3.1.2.3 Akpait Fiord

Akpait Fiord is the easternmost location mapped during the multibeam surveys of 2013 and 2014 (Fig. 3.1D). It is a 16-km-long, east-west oriented fiord that opens into Baffin Bay north of Cape Dyer. At present, remnant cirque and valley glaciers are situated up-valley from the fiord-head, feeding meltwater onto a small glaciofluvial outwash plain. Remnant cirque glaciers, with proximal moraine deposits, line the high elevation plateau at the fiord mouth, adjacent to Baffin Bay (Dyke, 2013C).

The LIS did not extend to the Cape Dyer area during the LGM; instead Cape Dyer was influenced by local glacial ice (Locke, 1980; Margreth, 2015). Evidence of high sea-level strandlines on the outer coast can be found 25-30 m and ~70 m above sea level (asl), correlated to glacial expansions at ca. 70 ka and >110 ka (Locke, 1987). Sonar profiles document a possible wave-cut platform at 56 m bsl towards the head of

Sunneshine Fiord correlated with 9 ka moraines and raised deltas on western Cumberland Peninsula (Miller, 1975; Dyke, 1979; Locke, 1980). Since this potential lowstand, RSL has risen to its present elevation at the postglacial marine limit.

3.1.3 Shoreline Geomorphology

Three main submerged shoreline features have been documented in the study region: a boulder barricade, eight delta terraces, and a sill platform. The literature on these features is outlined below to summarize their geomorphology and relation to sea-level.

3.1.3.1 Boulder Barricade

Boulder barricades were first described as an ice-deposited landform and observed by Lyell (1854) in Labrador and the Baltic Sea. It was not until 1902, however, that the term *boulder barricade* was first formally used by R. Daly (Rosen, 1979). Since then there has been extensive documentation and research of boulder barricades in the arctic and subarctic regions, especially in Canada, Scandinavia and the Baltic Sea (Lyell, 1854; Tanner, 1939; Løken, 1962; Bird, 1967; Rosen, 1979; Gray et al., 1980; McCann et al., 1981; Gilbert et al., 1984; Aitken and Gilbert, 1989; Forbes and Taylor, 1994; Dionne, 1998; 2002; Forbes and Manson, 2008).

At present, the term boulder barricade refers to an elongate ridge of boulders emplaced at the outer edge of a low gradient intertidal zone (low-tide level), parallel to the coastline (Rosen, 1979; Dionne, 2002). These barricades can be seen at mid-to low-tide level and result from ice rafting of intertidal boulders (Fig. 3.2A). The formation of the boulder barricade at low-tide level has been related to the spring break-up of ice on the tidal flats prior to breakup of the shorefast sea ice in deeper water (Rosen, 1979; Forbes and Taylor, 1994).

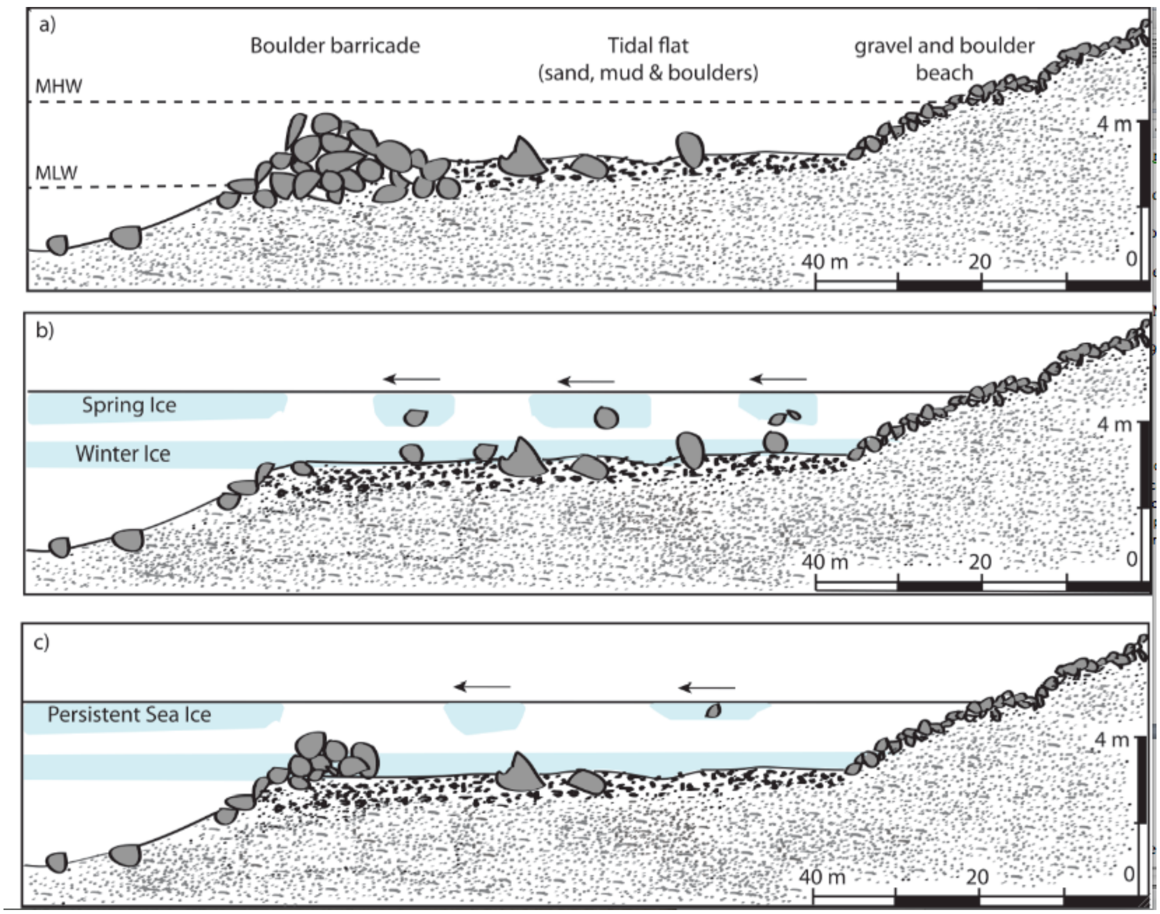

Figure 3.2: Schematic diagram of boulder barricade formation through seasons and over time. A) Geomorphic characteristics of a boulder barricade in the intertidal zone. B) During the winter, intertidal boulders are transported through the ice. During the spring melt, the intertidal ice breaks and rafts boulder-laden ice to the limit of persistent sea ice. C) Over time, the ice rafts melt and boulders become emplaced at the mean low water level. Modified from Kelletat (1995).

In Arctic regions, the combined effects of downward freezing at low tide and surface melt of intertidal ice during the late winter result in the migration of boulders up through the ice (Fig. 3.2B), resulting in boulder-laden intertidal ice (Rosen, 1979; 1982). The intertidal ice breaks up before the persistent sea ice in the spring, facilitated by tidal cracks from the lower albedo of sediment-laden ice (Rosen, 1982). Persistent sea ice prevents the seaward migration of the boulder-laden ice rafts during the spring melt (Fig. 3.2C; Aitken et al., 1988; Forbes and Taylor, 1994). As the grounded ice rafts melt, the boulders are deposited and concentrate over subsequent seasons as a ridge, which helps to entrap ice rafts in successive years.

Rosen (1979; 1982) identified three conditions necessary for the formation of a boulder barricade: a) a rocky coastal setting as the source of the boulders, b) sufficient winter ice and water level fluctuations to encase the boulders in the ice, and c) a distinct break in slope in the nearshore zone. Without the third condition, the boulders deposit as random, bouldery flats.

Boulder barricades represent phases of sea-level stability (Gray et al., 1980), and raised barricades have provided evidence of regional emergence as an indicator of former higher sea level (Løken, 1962). Løken (1962) interpreted the highest boulders of the raised barricade in northern Labrador to indicate high tide level. He recommended this method for determining palaeo-sea level position be applied only in regions with a low tidal range. Gray et al. (1980) concluded that the elevations of raised barricades found in Ungava correlated with coastal terraces.

On eastern Baffin Island, the tidal flats of Pangnirtung host a modern boulder barricade as well as an inactive inner ridge that was abandoned by coastal emergence (McCann et al., 1981; Gilbert et al., 1984). Forbes and Manson (2008) observed a poorly developed boulder barricade at Clyde River, along with an outer barricade interpreted as recently submerged by rising sea levels–the only reported case in the literature.

3.1.3.2 Delta Terrace

Deltas are coastal geomorphic features that are found worldwide in various forms and within different settings. Deltas are depositional features formed where fluvial outflow intersects with large bodies of water and sediment accumulates above and below sea level (Suter, 1994). Fluvial sediment supply controls the progradation of deltas, which deposit in three main environments: the fluvially-dominated delta plain, the delta front and the prodelta (Suter, 1994). Discharge from a channel mouth into a deep basin results in the radial deposition of coarse-grained sediments on steeply dipping foreset beds that prograde into the finer-grained, low-angle, bottomset beds of the prodelta. At sea level, the foreset beds are eroded and truncated by the migrating distributary channel as low-angle topset beds are deposited. This tripartite delta formation, associated with coarse sediments, was first described by Gilbert (1890), and has since been labeled a 'Gilbert-type' delta, in contrast to larger deltas with higher proportions of fine-grained sediments (Suter, 1994).

During progradation, coarse-grained sediments are deposited as topset beds on the delta plain in a complex setting of migrating distributary or braid channels. The truncation of foresets by the topsets forms an erosional unconformity known as the transgressive surface, which records the lowest erosional limit of delta plain channels and therefore the lowest water level (van der Straaten, 1990; Bell et al., 2003; Gutsell et al., 2004). Wave and tidal dynamics rework the delta front during and following progradation. The prodelta is proximal to the delta front within the fiord basin, where sediment is deposited through suspension, turbidity flows, or mass transport processes (Suter, 1994). The bottomset beds that make up the prodelta setting are near-horizontal, and provide the base for the upward-coarsening signature that is characteristic of prograding deltas (Suter, 1994).

Deltas are found at the heads and along the sidewalls of the coastal fiords on Baffin Island. Fiord-heads are the main setting for the formation of extensive deltas and outwash plains (sandurs) due to the large sources of glaciofluvial sediment in fiord-head drainage basins. Glaciofluvial point sources are also present in side-entry valleys along fiord sidewalls, where deltas, outwash fans, and submarine fan deltas can be found (Syvitski et al., 1987; Prior et al., 1990). Side-entry deltas are usually triangular-shaped due to the unrestricted basin in which they are deposited. The triangular shape contrasts with the characteristic rectangular shape of fiord-head deltas, which are confined by straight, steep sidewalls and build straight progradational fronts due to high sedimentation fluxes.

Radiocarbon dating methods can be used to determine the age of deposition of a delta if *in situ* bioclasts (e.g. marine bivalves) are collected from associated sediments (Andrews & Peltier, 1989). Submerged deltas represent a particular challenge for bioclast sample retrieval as sediment coring is the only reasonable sampling approach and sediment texture determines the success of core penetration. Coarse sediments (e.g., sand and gravel, diamicton) resist standard coring techniques (i.e. gravity, piston) and therefore the only viable target is the finer grained delta bottomsets in the prodeltaic environment (Berne et al., 2007). Bioclasts from bottomsets should provide radiocarbon results that date the RSL position represented by the transgressive delta surface (Sutherland, 1983). An alternative but less informative strategy is to core the post-submergence mud draping the delta terrace and topsets. A radiocarbon date on basal bioclasts should provide a minimum age estimate on the abandonment and submergence of the delta.

Submerged deltas, representative of a postglacial lowstand, have been studied within the coastal waters of Newfoundland. It was from these studies that three important factors were outlined for the formation and preservation of a lowstand delta: a) a regression to a minimum sea level, b) glacial deposits for fluvial downcutting or a proximal glacial source for sediment supply, and c) a sheltered environment (Shaw and Forbes, 1995). At the lowstand, glacial deposits were downcut by glaciofluvial systems to form Gilbert-type deltas graded to sea-level (Shaw and Forbes, 1995; Shaw, 2005). The depth of the transgressive surface as well as the transitional lip between the delta plain and the delta front have been used to record the lowest water level of the postglacial lowstand (Shaw and Forbes, 1995; Bell et al., 2003; Gutsell et al., 2004). Along the coasts of Baffin Island, eight lowstand deltas have been mapped in detail within the fiords of northeastern Cumberland Peninsula (Miller and Dyke, 1974; Miller, 1975; Chapter 2).

3.1.3.3 Submerged Fiord-Sill Platform

St. George's Bay is one of the sites in Newfoundland where submerged deltas were reported, graded to a -25-m-deep early Holocene lowstand (Shaw and Forbes, 1992). Along with lowstand deltas, the mouth of the bay is partially blocked by a submerged morainal bank, much like a fiord-mouth sill, which has been reworked by wave action to form a flat barrier platform and landward spillover deposit, graded to the -25 m postglacial lowstand (Shaw and Forbes, 1992; Shaw and Courtney, 1997). This submerged barrier platform is similar to that which was found at the mouth of Akpait Fiord in the study area. St. George's Bay has therefore been used as an analogue for the interpretation of the submerged feature in Akpait Fiord.

St George's Bay is a glacially over-deepened valley with an emplaced morainal bank, over which a spillover wedge has prograded into the basin. At the entrance to St.

George's Bay from the Gulf of St. Lawrence, the morainal bank is a flat-topped sill, at depths of 20-25 m below sea level with an overall relief of 30-45 m above the adjacent seafloor (Shaw and Courtney, 1997). The spillover is made up of gravel and sand that prograded landward into the basin with a convex upwards slope.

During the postglacial lowstand, the morainal bank was subaerially exposed and formed a peninsula, which blocked off the inner bay from the Gulf of St. Lawrence. Following the lowstand, a Holocene transgression submerged the moraine, when wave action controlled erosion and redistribution of surface sediments (Shaw and Forbes, 1992). Wave action planed off the surface of the morainal bank, where glacial sediments were redistributed across the shallow sill and deposited into the landward basin. The landward redistribution of glacial sediments formed a postglacial prograded wedge, or a 'spillover deposit' with steeply landward-dipping (20°) internal reflectors (Shaw and Forbes, 1990; Shaw and Forbes, 1992; Shaw and Courtney, 1997). The result is a relatively smooth sill platform with extensive gravel ripples and scattered sand waves (Shaw and Forbes, 1990).

3.2 Methods and Materials

Underwater mapping surveys and sampling for this study were conducted within the coastal waters of Boas Fiord, Akpait Fiord, and Broughton Channel (Hughes Clarke et al., 2015), along with characterization of the adjacent shoreline, and coastal mapping surveys in Broughton Channel. Five data sources were examined for characterization of the submerged palaeo-shoreline geomorphology in relation to the modern setting: 1) multibeam bathymetric mapping of the seafloor; 2) single-beam bathymetric mapping of the littoral zone within Broughton Channel; 3) subbottom acoustic profiles of the seafloor features; 4) classification of the adjacent modern coastline with aerial photographs, topographic and surficial geology maps; and 5) ground-truth of the modern coastline and submerged setting through sediment textural analyses, real-time kinematic (RTK) surveys and underwater video characterization. Multibeam and subbottom profiles were obtained during cruises aboard the *MV Nuliajuk* through a partnership with the Government of Nunavut, the Ocean Mapping Group (University of New Brunswick), and Memorial University of Newfoundland in 2012-2014. Field data from the modern shore-zone of Broughton Channel were acquired during the fall of 2013.

3.2.1 Multibeam Bathymetry

The *MV Nuliajuk* was equipped with a Kongsberg EM3002 multibeam echosounder (300 kHz) during the 2012-2013 surveys and was refitted with a Kongsberg EM2040 multibeam echosounder (200 kHz) for the 2014 survey (Brucker et al., 2013; Hughes Clarke et al., 2015). The multibeam echosounders cover a seabed footprint with a track width of about four times the water depth. To acquire complete coverage, each survey was run in a systematic grid pattern, with ~50% overlap of adjacent swath lines. The final products were a series of raster depth and backscatter (intensity of seafloor acoustic reflectance) datasets of the ocean floor. The horizontal datum are with respect to the WGS84 ellipsoid, and the vertical depths were referenced to mean sea level (MSL). For a full description of the *MV Nuliajuk* system and data processing, see Brucker et al. (2013). Additional surveys were conducted in Akpait Fiord in 2014 with the *CCGS Amundsen*.

3.2.2 Subbottom Echosounder

A shallow-water Knudsen 3.5 kHz chirped subbottom profiler was hull-mounted to the *MV Nuliajuk* during the multibeam surveys, with a beam width of 80°. The profiles were generated through the penetration of acoustic energy into the seafloor substrate, and its reflection off boundaries between units of contrasting acoustic impedance. The subbottom echosounder was run in tandem with the multibeam to record the subbottom profiles of the seabed. Profiles were viewed with SegyJP2Viewer (Courtney, 2012). The generated profiles help to interpret the depositional facies and sediment distribution of the submerged shoreline features.

3.2.3 Single-beam Sonar

For further study of the shallow shore-zone in Broughton Channel, a single-beam Lowrance HDS-7 Gen2 echosounder was attached to the transom of a local freighter canoe to profile shallow bathymetry beyond the safe water depth limit of the *MV Nuliajuk* (<10 m water depth). This system used an external Lowrance Global Positioning System (GPS), mounted directly on top of the transducer for positioning and was corrected for tidal variations with Arctic WebTide Model (v.0.7.1), resulting in depths referenced to MSL.

Transects along the eastern and western shores of Broughton Channel provided shore-normal profiles of the littoral zone. These were positioned to extend offshore beach profiles acquired through real-time kinematic (RTK) GPS surveys onshore.

3.2.4 Coastal Classification

The objective of classifying the modern shore-zone was to catalogue the characteristic coastal geomorphology of northeastern Cumberland Peninsula, in particular in the regions where submerged shorelines have been documented. Aerial photographs from the National Air Photo Library, along with topographic maps and surficial geology maps (Dyke, 2013A, B, C), were used for qualitative characterization of the shore-zone. The aerial photographs available for these regions are from 1956, at a scale of 1:60,000. The small scale of the photographs limits the visibility of fine-scale shore-zone morphology.

The modern coastline is important as a potential analogue of the submerged palaeo-shoreline. The parameters chosen for this study were selected on the basis of distinctive features of the submerged shoreline but were broadly representative of the overall coast in this region. In each area, a shoreline map was generated depicting the form and material of the modern shore zone.

Magellan Ashtech survey-grade RTK GPS receivers were used to conduct beach profiles of the beaches within the vicinity of Broughton Channel for comparison with bathymetric profiles over the submerged shore zone. Broughton Channel was prioritized due to its proximity to the Hamlet of Qikiqtarjuaq and ease of small boat access. Similar surveys were not undertaken in Boas and Akpait fiords due to vessel priorities and time constraints. The results of these RTK surveys (Appendix B; Table B.1) together with sediment texture analysis (Appendix B; Table B.2) were used as quantitative input to the coastal classification.

The qualitative data were input into the Geological Survey of Canada (GSC) Coastal Information System (CIS), which segments the coastline based on geomorphic form and material of nearshore, foreshore and backshore zones. Because of the low resolution of the source data, the nearshore could not be properly classified. Therefore the coastal classification for this study was confined to the foreshore and backshore. The foreshore is defined as the zone of the shore that lies between the crest or the upper limit of swash at high tide and the low tide line. This is the zone that is influenced by the marine interface and is regularly washed by tidal and wave processes (Couture et al., 2015). The backshore is the 'dry' zone of the shore landward of the high-water line, influenced by storm wave run-up or storm surge flooding. The backshore is divided from the foreshore by the crest of the most seaward berm (Couture et al., 2015). Sloped coasts were separated into three classes: cliff, outcrop and slope. Features classified as 'cliff' are characterized by a sloped face steeper than 40°. Low to moderately sloping (<40°) bedrock coasts were classified as 'outcrop.' The term 'slope' was adopted for gently sloping (< 40°) unlithified deposits in the backshore (Couture et al., 2015).

The data are stored as lines and points spatially referenced with the dynamic segmentation feature in ArcGIS (v.9.0). Each segment is defined with a coastal feature from a hierarchical coastal feature classification system. The coastal features are classified based on two themes: form and material, at four hierarchical levels.

3.2.5 Seabed Imagery and Samples

A Deep Blue 'Pro-Colour' underwater camera was deployed over the submerged delta terraces and shorelines. Video footage was required to ground-truth the sonar dataset for grain-size and characterization of the submerged geomorphic features. Video imagery was acquired across the delta terraces and other features of interest. Ten transects were recorded perpendicular to the submerged boulder barricade on the eastern shore of Broughton Channel. The video was run simultaneously with the single-beam sonar, to provide a seabed profile and positioning with the video data. From the video log, still screen shots were taken at approximately 30-second intervals, or when the camera steadied shortly after; these were time stamped and correlated to the offset time of the sonar logs for positioning. The grain size and seabed features along each transect were logged, and the still shot locations were compared to the multibeam raster in ArcGIS. For the complete set of video logs see Appendix B.1: Figure B.6.

Sediment samples were taken with a Wildco Ponar grab sampler throughout the surveys along eastern Broughton Channel. The sediments were analyzed with dry sieve techniques and a Horiba L-950 grain analyzer at the Earth Sciences Department at MUN. Grain-size analysis was also undertaken on the beach sediments along each RTK profile. This involved dry sieve analysis on the sample matrix (following the procedures set out by Bernhardt, 1994) and gravel to boulder clast measurements in the field. Clast measurements involved measuring the three axes (a, b, c) of fifty clasts located at 10 cm intervals along a 5 m transect parallel to the water line, where the b-axis was then used for further grain-size analysis. Moments for each sample were calculated from the proportions in each sieve or class using phi units ($D_{phi}=-\log_2 D_{mm}$) with GRADISTAT v.8.0.

3.3 Results

This study presents a geomorphic classification of modern and submerged shore zones at three localities on Cumberland Peninsula: Broughton Channel, Boas Fiord and surrounding Akpait Fiord. The characteristics of the modern shore zones are presented, followed by the results of the sonar surveys.

The submerged shoreline was not mapped in its entirety, but geomorphic indicators of the relict coast were identified and mapped in many localities. The results of the bathymetric surveys, video imagery and sediment texture analyses are presented to characterize the geomorphology of these submerged shoreline features and identify their relation to RSL.

3.3.1 Broughton Channel

3.3.1.1 Modern Shoreline

In this region the modern coastline is made up of fringing and pocket beaches in the foreshore, with discontinuous sloped and outcrop backshores (Fig. 3.3). From the RTK surveys and sediment analysis, the shorelines surrounding Broughton Channel are found to vary from continuous low angle sand-pebble-cobble beaches (Fig. 3.4A) to non-continuous pocket sand-pebble-cobble-boulder beaches between bedrock outcrops (Fig. 3.4B). A summary of the five beaches that were surveyed as ground-truth for the CIS coastal characterization is presented in Appendix B.1. No boulder barricades were observed in the vicinity of Qikiqtarjuaq.

The factors that characterize the surveyed beaches are: wave energy, orientation, sediment source, bedrock, backshore and slope, sediment type, and beach width. The beaches to the north, which are directly exposed to waves from Baffin Bay, are wider than those along the eastern and western shores of Broughton Channel. This is also attributed to the more steeply sloping backshore in Broughton Channel, compared to the planar backshores to the north.

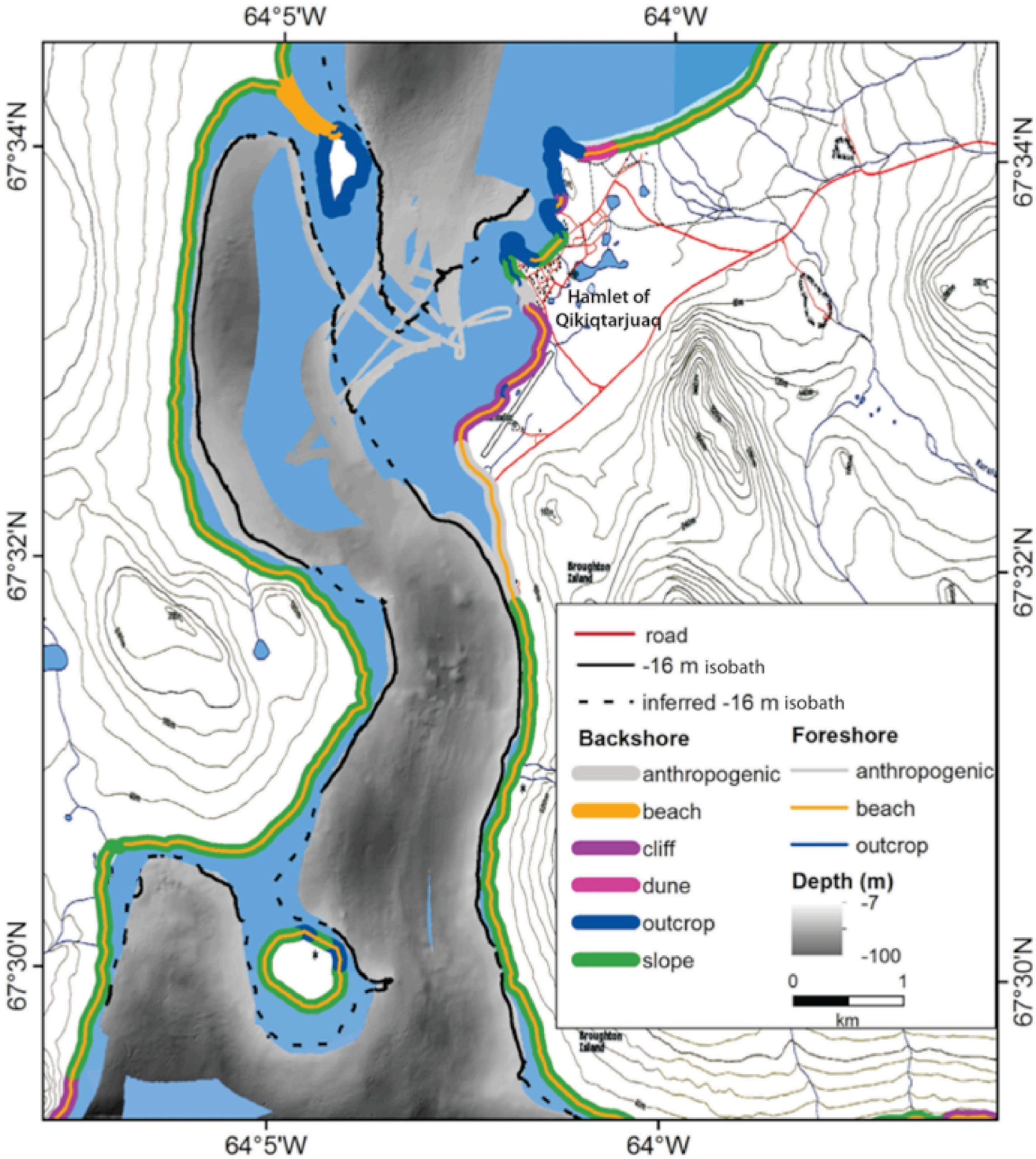

Figure 3.3: Modern coastal foreshore and backshore classification. Bathymetry is displayed in grayscale to simplify the image. Foreshore features overlay backshore features and both are classified according to coastal type. At a depth of 16 m bsl, a relict shoreline was reconstructed based on the -16 m isobath. Dashed lines are interpreted from Canadian Hydrographic Service surveys 1960-1961.

Figure 3.4: A) Continuous sand-pebble-cobble beach along the south shore of the tombolo barrier at the north end of Broughton Channel, looking west. B) Photograph of a pocket beach between bedrock outcrops along the eastern shore of Broughton Channel, looking north. Photography by B. Cowan, 2013.

3.3.1.2 Submerged Shoreline

A continuous ridge of boulders about 1.8 km long is situated on average 120 m off the eastern shoreline of Broughton Channel. Interpreted as a relict boulder barricade (grey line in Fig. 3.1B-inset), it lies in a depth range of 16-18 m bsl (grey bar in Fig. 3.5), based on the multibeam bathymetry. Depth soundings reveal the occurrence of a terrace (5 m bsl), previously documented by Gilbert (1980), and a discontinuous break in slope between 15 and 18 m bsl in the nearshore of the eastern coast.

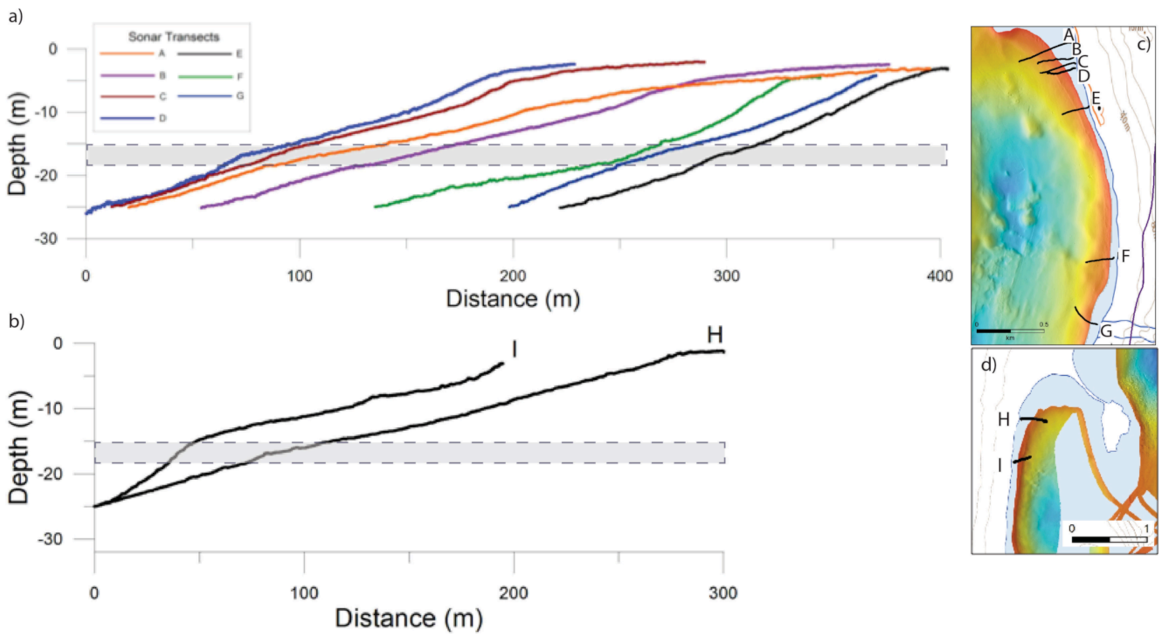

Figure 3.5: A) Sonar profiles of eastern Broughton Channel, lines run from offshore perpendicular towards the coast. The depth range of the boulder barricade (16-18 m bsl), as interpreted from the multibeam data, is outlined by dashed grey line. B) Sonar profiles of western Broughton Channel transects. Vertical exaggeration: 3.4X. C) Locations of transects A-G from Fig. 3.1b. D) Locations of transects H and I from Fig. 3.1b.

Within the region of a distinct barricade visible in the multibeam bathymetry, the sonar dataset records a shallow offshore gradient (mean slope about 7°) until a break in slope at a depth of 16-18 m. Seaward of the break in slope, the seafloor continues down into the channel basin (-65 m) at a gradient of about 10−12°. The break in slope is not continuous or always present along the submerged barricade. Where the barricade is no longer present, towards the north, the offshore gradient (transect A) becomes shallower and continuous (about 4°; Fig. 3.5A). Similarly, in the south where the barricade is less evident in the multibeam, though still present, transect G has a more continuous shallow slope (6°), with a convex profile instead of the break in slope (Fig. 3.5A). Transects A and G are located adjacent to modern seasonal drainage outlets, which are sources of sedimentation and deposition.

Along the western shore, the multibeam bathymetry does not show a boulder ridge as observed along the opposite side of the channel. The littoral zone incorporates a narrow terrace at 8 m bsl, which drops about 150 m offshore onto a gently sloped (3°) terrace between 10 and 15 m bsl (Fig. 3.5B; Transect I). Three hundred metres offshore, at a depth of approximately 15 m, the terrace drops at a steeper angle (14°) to the basin floor, 67 m bsl. The offshore gradient becomes more constant and linear (5°) towards the north as the coast curves behind the tombolo barrier beach (Fig. 3.5B; Transect H), with a minimal change in slope at 16-18 m bsl.

The backscatter return of the boulder barricade is higher than the surrounding seabed, highlighting the presence of a harder substrate (Fig. 3.6). The high backscatter region delimits the boulder concentration on the seafloor that starts landward of the nearshore break in slope (16-18 m bsl) and continues offshore.

The underwater video log provides ground-truth of the multibeam and sonar datasets along the eastern littoral zone. Representative still screen shots are presented in Figure 3.7 to describe the patterns observed on the eastern seabed (for further detail of each transect, see Table B.4 & Fig. B.6). In the shallow water, landward of the barricade, the seabed is dominated by various species of marine

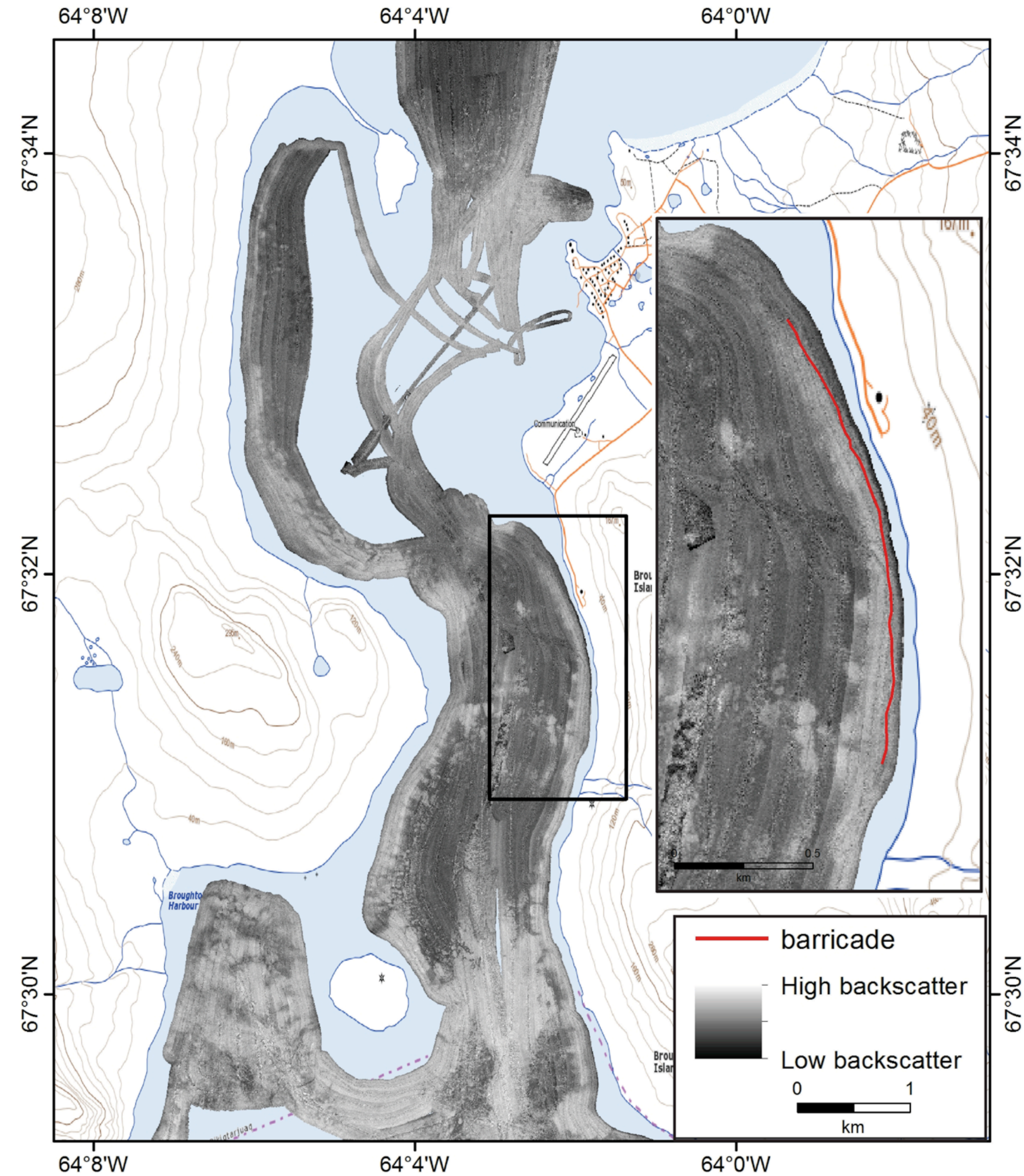

Figure 3.6: Backscatter data for Broughton Channel. Inset image marks the upper limit of the submerged boulder barricade with red line. The backscatter record, sonar transects and video reveal that the boulder ridge marks the shallowest edge of continuous boulder cover on the seabed as represented by the region of high backscatter parallel to the coast.

algae that obscure the view of the sediment surface (Fig. 3.7A). Where sediment patches could be observed, the substrate was made up of sand with shell hash. The sediment at, and landward of, the boulder boundary was measured from grab samples to be fine to very fine sand.

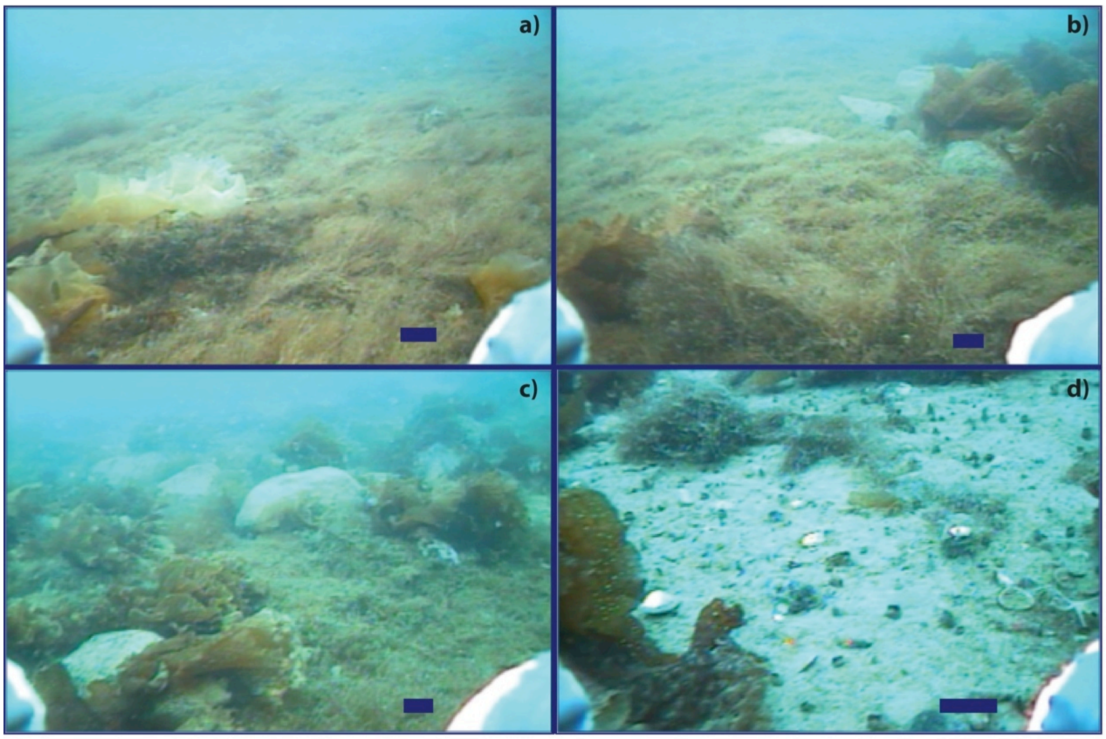

Figure 3.7: Screen shots along a video transect proceeding seaward over the submerged boulder barricade. A) shallow water, landward of boulder ridge; B) transition zone between seaweed covered seabed, and boulder clusters; C) extensive boulder ridge; D) sand patches observed between boulder clusters. Scale bar is indicative of 10 cm within the field of view.

Scattered boulders appear closer to the barricade. In most transects, the ridge observed on the multibeam was the boundary between algae and boulder concentrations, while in others there was a more gradual transition into boulder concentrations (Fig. 3.7B). This ridge also locates the first concentration of boulders (Fig. 3.7C). The boundary between seaweed and boulders is linear and runs roughly parallel to the shoreline. The boulders form clusters seaward of the boundary and are holdfasts for kelp species. The lithology of the boulders cannot be determined, as their surface is obscured by the presence of kelp or pink calcareous algae. The boulders are rounded to sub-rounded, with a rare occurrence of sub-angular clasts, and range in diameter from 20 to 130 cm (n=20; mean of 70 cm). Between the boulder clusters are sand patches with scattered pebble, strewn with shell hash and clam siphons (Fig. 3.7D). The kelp covered boulder clusters continue at the same concentration offshore into depths >25 m bsl.

3.3.2 Boas Fiord

Submerged deltas were initially documented in Boas Fiord by Miller (1975), and then subsequently mapped in high-resolution (Chapter 2). These deltas are located at the fiord-head and at the mouth of a mid-fiord side-entry valley. The head of Boas Fiord is outlined below as a representative locality for the geomorphology of the eight submerged deltas previously mapped (Chapter 2).

3.3.2.1 Modern Shoreline

The majority of the modern coastline in Boas Fiord is made up of narrow fringing beaches at the base of rock cliffs and sloping bedrock, overlain to varying extent by colluvium (Fig. 3.8). Talus is present at the base of steep cliffs, with small alluvial fans graded to sea level along the sidewalls. The modern fiord-head sandur is about

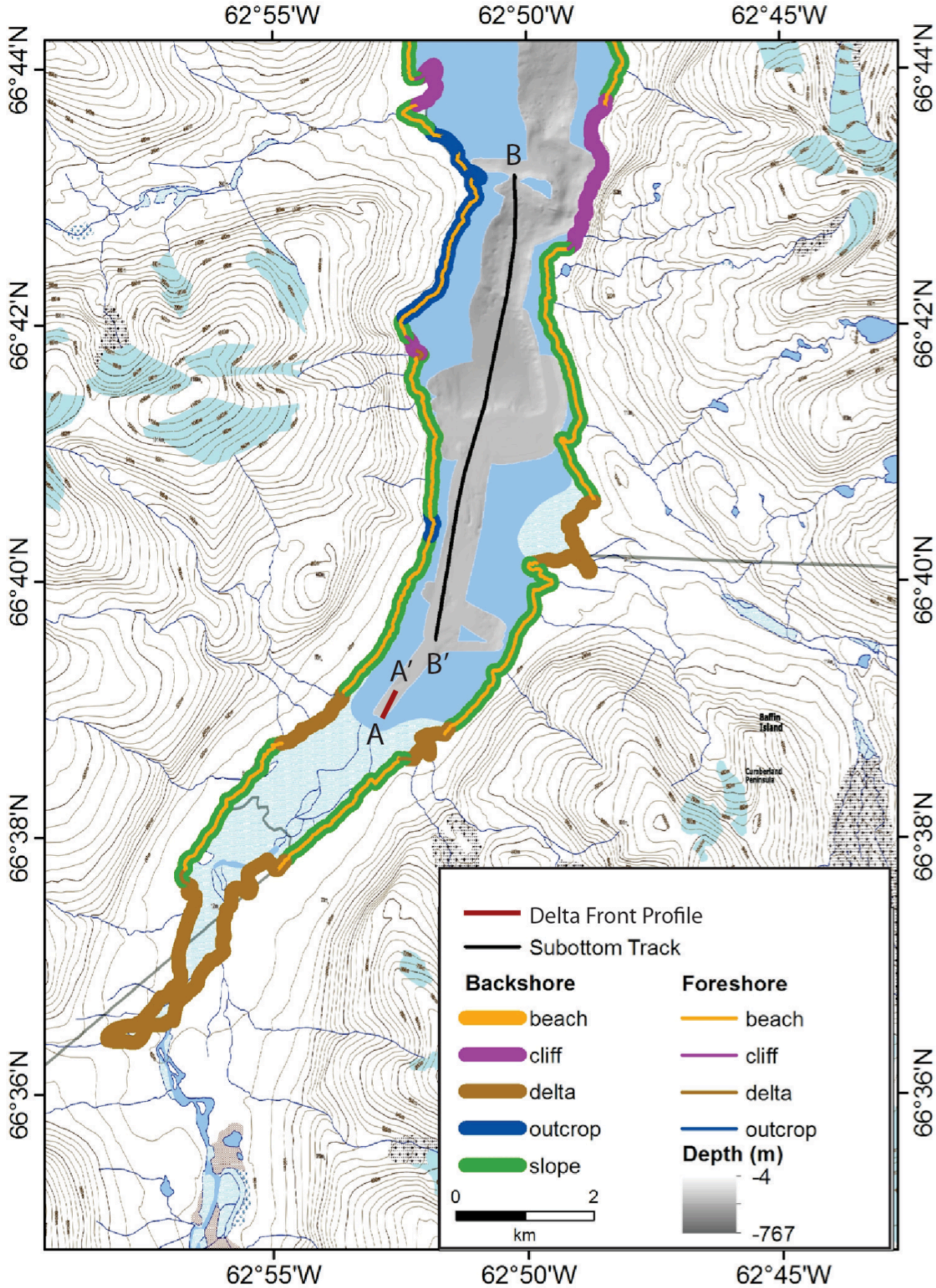

Figure 3.8: Multibeam imagery of Boas Fiord-head delta terrace at 33 m below sea level. Modern delta front A-A’ is profiled in Figure 3.9. Subbottom profile B-B’ is interpreted in Figure 3.10. Modern shoreline classification is outlined by CIS with respect to backshore and foreshore geomorphology.

4.5 km long and 1.4 km wide at its widest point, and extends along the eastern sidewall. Two main valley glaciers along with several smaller cirque and tributary valley glaciers feed meltwater and sediment to the sandur. With a basin area of 631 km^2, the main drainage route follows a 20-km-long path from present-day glaciers to sea level (Fig. 3.1C). To the east of the sandur mouth and 4 km down-fiord are alluvial fans, which extend out onto the submerged delta terrace.

The modern fiord-head sandur was formed by transgressive back-flooding of the sandur plain. In contrast to the submerged delta, the extent of multibeam coverage reveals a very shallow modern delta-front slope (~2°; Fig. 3.9) that converges asymptotically with the submerged delta terrace slope, forming a concave-upward profile to a distance of about 500 m offshore. Asymmetric, seaward-oriented, low

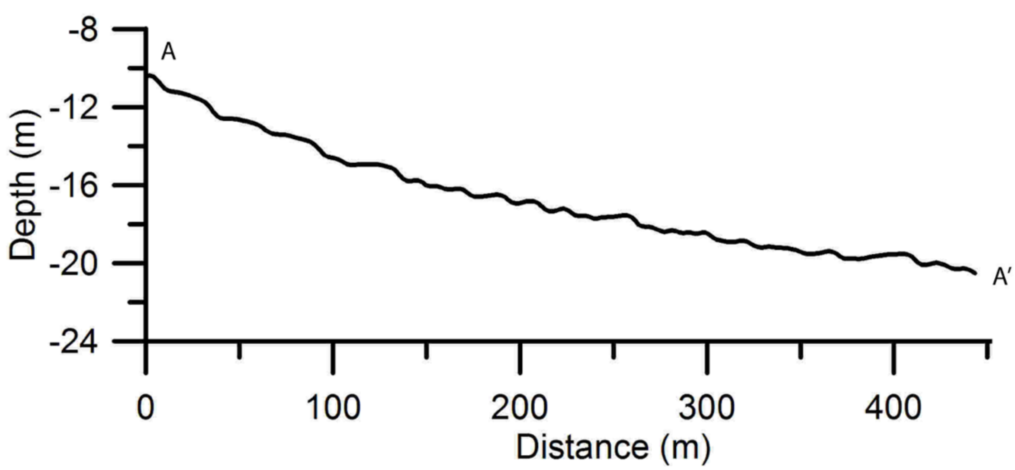

Figure 3.9: Depth profile A-A' taken from bathymetry data of modern delta front slope and bedforms. Profile track is shown in Figure 3.8. Vertical exaggeration: 9X.

amplitude bedforms, with crest to trough relief of 0.1-0.5 m and wavelength of 20-70 m, are present up to 700 m offshore on the proximal delta front slope (Fig. 3.9). Modern deposition is on the submerged terrace, resulting in post-depositional sediment (about 2.5 m thick) that pinches out toward the lip of the submerged delta (Fig. 3.10).

3.3.2.2 Submerged Shoreline

Boas Fiord-head is the site of an extensive submerged sandur plain (33 m bsl) that extends down-fiord 5 km from the present subaerial limit of the modern fiord-head sandur (Fig. 3.8). The delta front curves along the eastern sidewall, where a side-entry valley with cross-valley moraines enters into the fiord-head. The delta front includes chute remnants, slump scars and mass transport deposits.

Figure 3.10 presents the acoustic subbottom profile and associated interpretation along the survey track B-B' highlighted in Figure 3.8. Note that the track runs from the proximal slope of the inner basin sill, across the basin, prodelta slope and outer delta, landward to the inner part of the submerged delta. Acoustic penetration through the subbottom stratigraphy is limited, more so for the submerged delta than the basin-fill deposits. Five acoustic units are identified. The lowermost unit (A), appearing only beneath the sill slope, is acoustically massive (shows no structure) with a strong surface reflection. It represents the acoustic basement and is

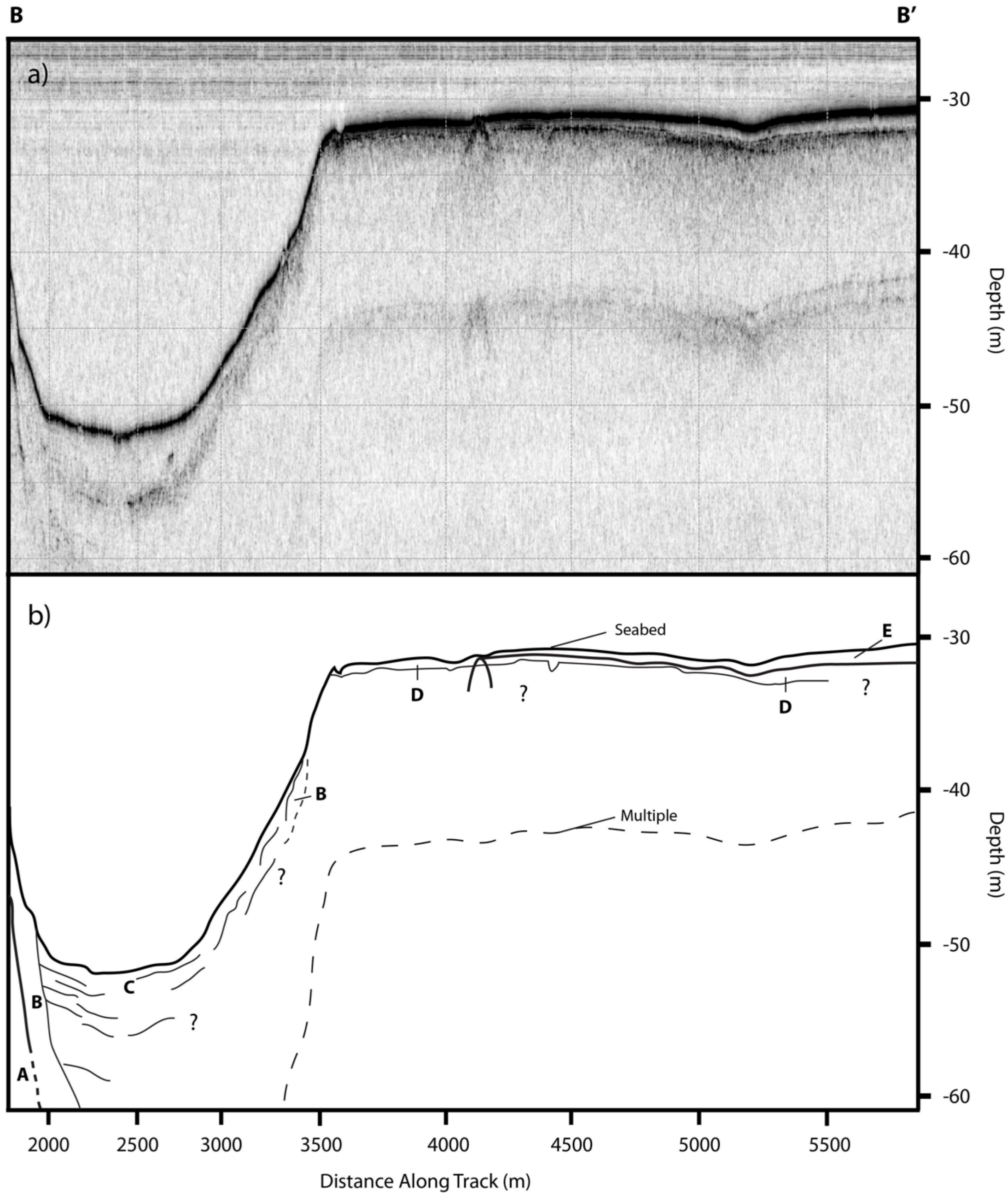

Figure 3.10: Subbottom profile B-B' of Boas Fiord-head delta from Fig. 3.8. A) 3.5 kHz acoustic record of the delta front (depth is based on an acoustic velocity of 1500 m/s in water). B) An interpretation of the acoustic stratigraphy. Acoustic units: A) Bedrock or till basement; B) Mass transport deposits; C) Basin fill; D) Horizontal delta topset beds; E) Post-submergence mud drape.

interpreted to be bedrock or till. Draping this unit is another acoustically massive unit (B) that grades into chaotically structured sediment at the bottom of the slope. This unit is interpreted to represent a series of mass transport deposits on the inner sill slope that appear mounded at the base of the slope but massive or poorly structured higher up the slope. A similar unit, also designated B, is identified on the upper delta slope between water depths of 35 and 45 m. Here the uneven seabed reflects the irregular surface of the mass transport scars and deposits, while the acoustic stratigraphy appears mounded and discontinuous. There is insufficient penetration through this unit to characterize a lower sedimentary contact or bed. Unit C represents an acoustically transparent to weakly stratified unit that abruptly onlaps Unit B against the sill slope but grades upslope into Unit B on the delta foreslope. The acoustic stratigraphy suggests that Unit C is a basin fill, composed of stratified sediments that partially originate from the delta slope and accumulate against the inner slope of the sill. There is likely a suspended sediment component to the basin fill, reflecting the evenly draped nature of the stratification, at least in the upper half of the unit.

Units D and E are only found on the delta terrace. Strong, horizontally stratified, acoustic reflectors that return much of the acoustic signal represent unit D. The surface of this unit is irregular in places, forming depressions. Although limited in exposure on the acoustic record, this unit is tentatively interpreted to represent the uppermost topset beds of the delta. It would likely be composed of gravel beds and this would explain the lack of acoustic penetration. The irregular contact may reflect the uneven surface of a typical braid plain, as well as the possibility of infilled kettle holes.

The overlying unit E is acoustically transparent and several metres thick, thinning towards the delta lip. It drapes the underlying uneven contact and probably represents a fine-grained suspension deposit composed of mud. Thinning of the unit towards the lip reflects winnowing of the fine-grained sediment by stronger bottom currents near the delta edge. A similar pattern of sediment distribution was observed by video on a submerged delta in nearby Kangert Fiord (Fig.2.4). Unit E is interpreted to be mud deposited after abandonment and submergence of the delta due to rising RSL.

3.3.3 Akpait Fiord

3.3.3.1 Modern Shoreline

Situated on the eastern coast of Cumberland Peninsula, Akpait Fiord is exposed to the open waters of Baffin Bay. The majority of the coastline in this area is made up of bedrock cliffs in the backshore with foreshore fringing beaches (Fig. 3.11). Talus cones and colluvium are common along the base of steep sidewalls.

While at first glance the coastline within the vicinity of Akpait Fiord appears to be sediment starved, more detailed analysis of aerial photography reveals a number of

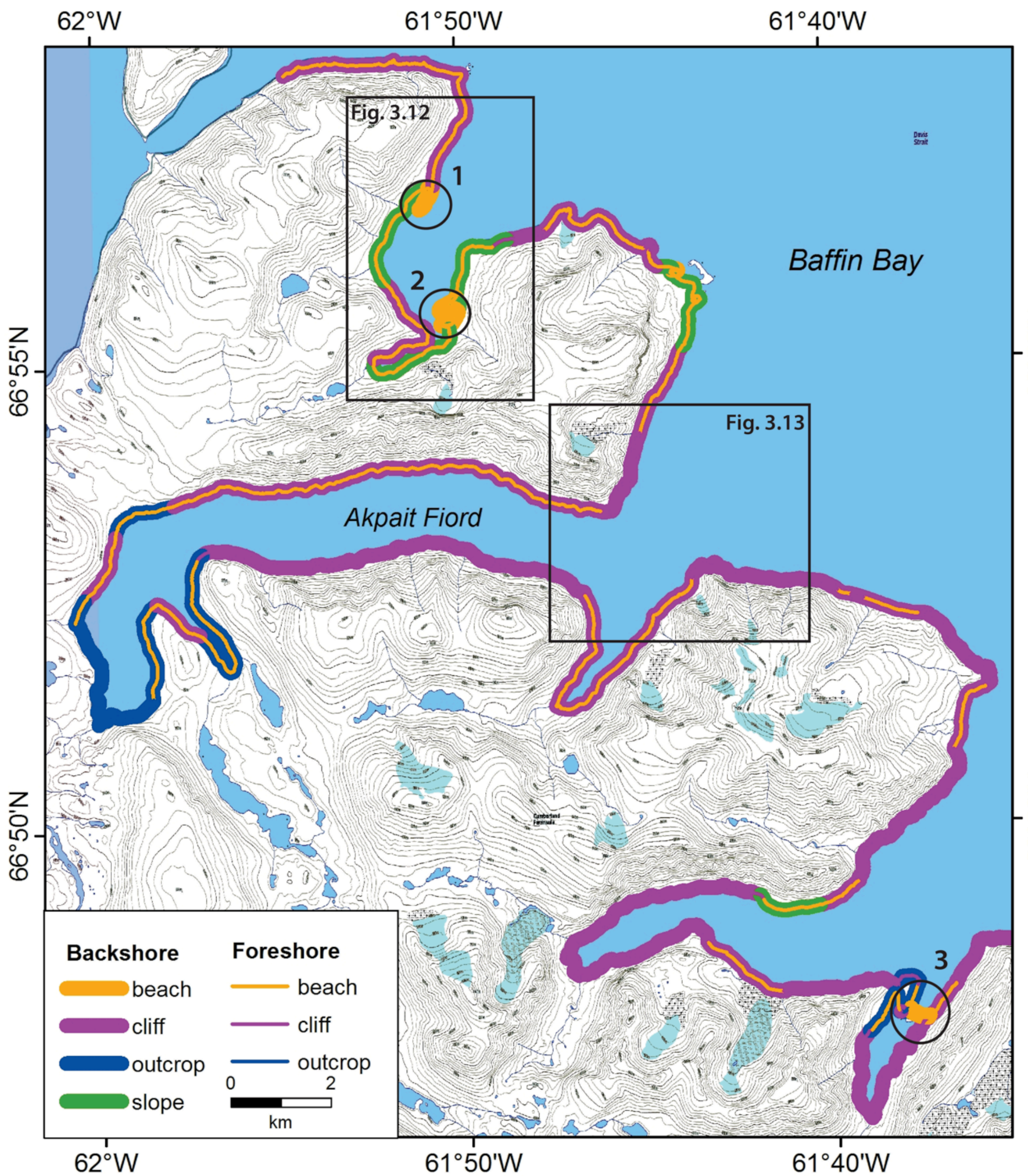

Figure 3.11: CIS classification of the backshore and foreshore coastal geomorphology surrounding Akpait Fiord on eastern Cumberland Peninsula. The two embayments to the north and south of Akpait Fiord display barrier beaches (2 and 3) and active spit formation (1, 2). Black boxes outline the locations of an aerial photograph of the northern coast (Fig. 3.12) and the submerged sill platform at the mouth of Akpait Fiord (Fig. 3.13).

small-scale barrier beaches and spits attesting to longshore sediment transport (Fig. 3.11; 1-4). Two spits and a breached barrier beach are located within the embayment to the north of Akpait Fiord-mouth (Fig. 3.12; 1, 2), and one barrier beach is located to the south (Fig. 3.11; 3). The attached spits range in width from 20 to 100 m and in length from 100 to 450 m. The longest spit (1) extends shore

Figure 3.12: Aerial photograph (NAPL A15467-104; 1956) of the coastline north of Akpait Fiord, located in Fig. 3.11. Active spits (circled) are located at two sites proximal to sediment sources. Spit 1 is sourced from sediment to the north along an active wave-cut cliff (outlined with a dashed line), in colluvium. Site 2 comprises both a wide, low spit and a breached barrier beach.

parallel, towards the southwest. The two barrier beaches (2, 3) are oriented east-west along the southern coast of their embayments. The barrier beach at site 3 is the longest at about 400 m and is roughly 65 m wide. This beach encloses a lake in the side valley, which could be either freshwater or brackish dependent on the frequency of storm washover events and the drainage rate of freshwater seepage. Without field data on water quality or barrier beach characteristics the salinity levels of the enclosed lake is unknown and may be seasonally variable. These depositional shore-zone features have been built out from coasts dominated by colluvium or till veneer overlying sloped and cliffed backshores (Fig. 3.11). Sediments in spit #1 are sourced from an active wave-cut cliff in colluvium (Fig. 3.12).

3.3.3.2 Submerged Shoreline

A side-entry valley, which enters the head of Akpait Fiord from the south, has a submerged terrace with a break in slope at 51 m bsl (Fig. 3.1D). A sill at the fiord mouth forms an extensive platform between 50 and 52 m bsl, with 72 m of relief above the adjacent inner basin floor (Fig. 3.13A). The inner slope of the sill is steeper and displays more evidence of mass transport compared to the outer slope. The inner slope has a convex-up profile (Fig. 3.14A). The sill surface is relatively free of ice scour compared to the seabed offshore. Generally, the sill platform has medium to low backscatter, with two inner crescent-shaped patches of high return (Fig. 3.13B).

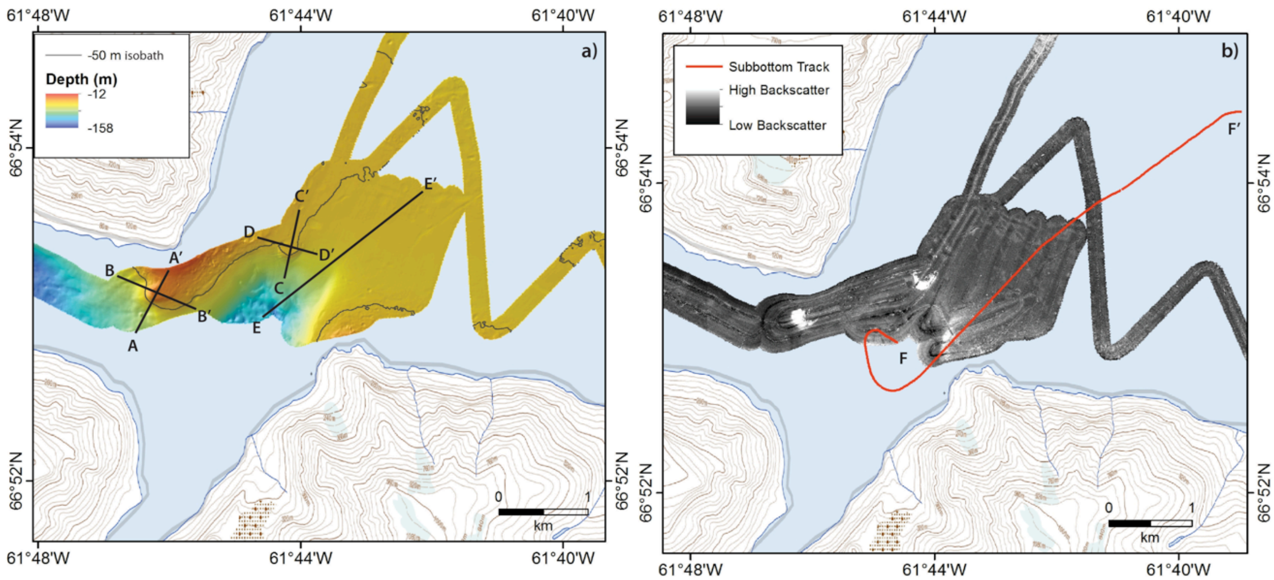

Figure 3.13: A) Multibeam bathymetry with the -50 m isobath outlined in grey and location of bathymetric profiles shown in Fig. 3.14. B) Backscatter intensity of the sill platform with the location of the subbottom track F-F’ in Figure 3.15.

Underwater video showed that the platform is draped by fine sediment (Fig. 3.15A), accounting for the low acoustic backscatter return; the two high- backscatter patches are characterized by slightly imbricated round to sub-rounded cobble gravel (direction of imbrication cannot be discerned from video footage; Fig. 3.15B). The gravel deposits are roughly 200 m wide and make up remarkably flat terraces at 50m (closest to sill platform) and 30 m bsl (west of sill). Both deposits appear to have built southwestward into the fiord and on the basis of what is observed of modern littoral processes, they are interpreted as gravel spits formed by longshore drift on shorelines well below present sea level.

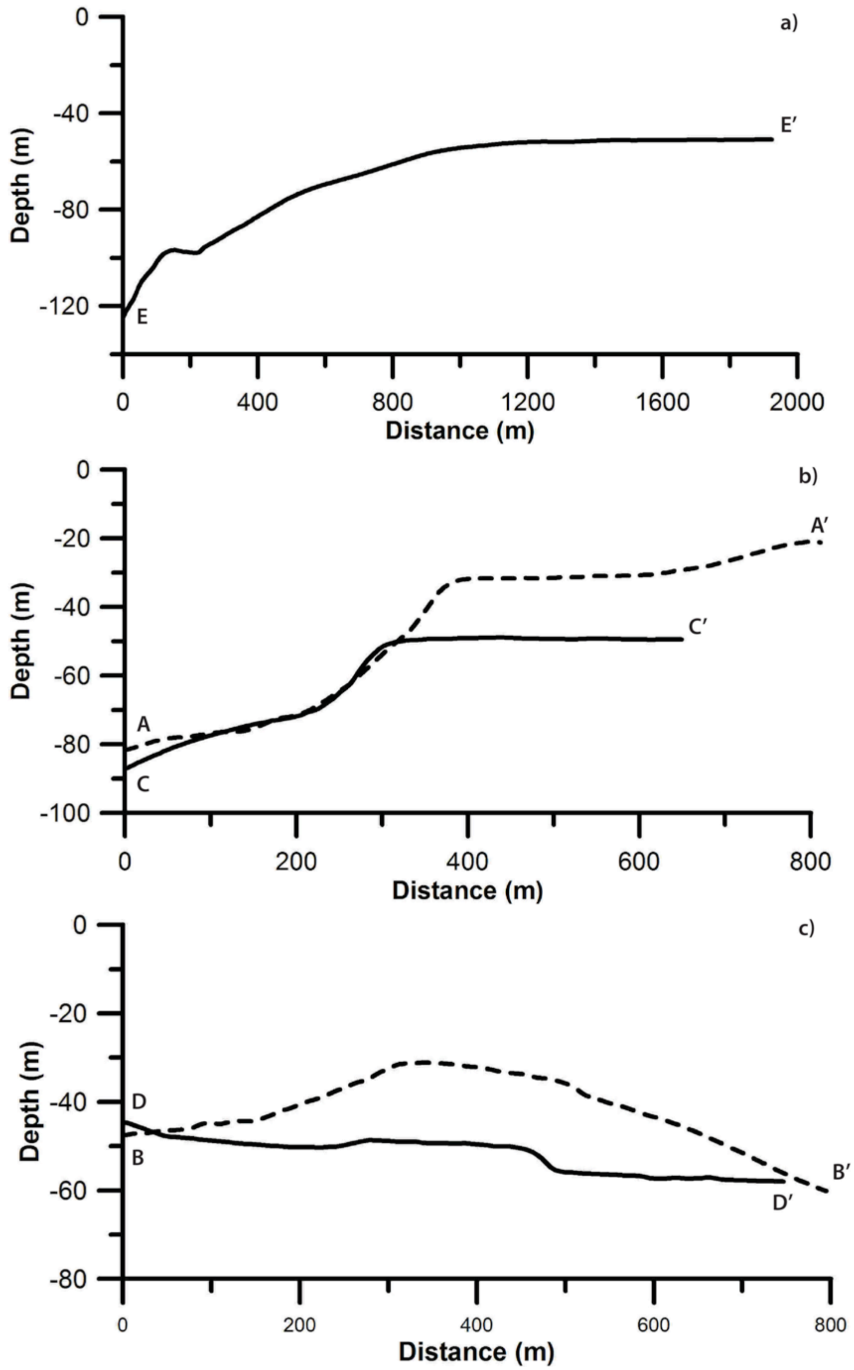

Figure 3.14: A) Convex axial profile E-E′ of sill platform; vertical exaggeration: 6.9X. B and C) Cross-profiles of the high backscatter gravel terraces; vertical exaggeration: 2.8X. The locations of profiles are shown in Figure 3.13.

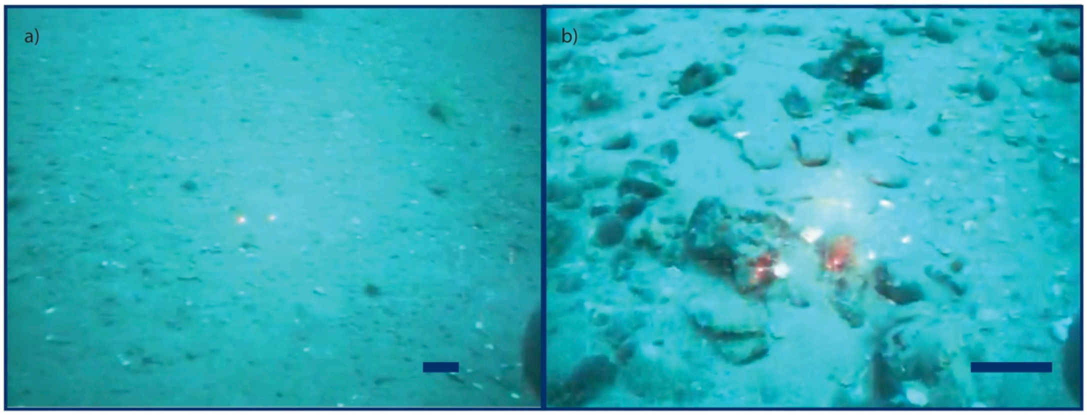

Figure 3.15: Still screen shots from the mouth of Akpait Fiord. A) Surface of submerged sill platform. B) Surface of -50 m submerged spit. Scale bar and distance between red laser points are indicative of 10 cm within the field of view.

A field of symmetrical tidal bedforms is documented 6.5 km to the north of the sill platform, with crests normal to the coast (Hughes Clarke et al., 2015). These attest to active sediment transport at about 60 m bsl in that exposed offshore location. Meanwhile, the surface of the sill platform does not include bedform features, but is instead made up of sandy gravel draped by fine-grained sediments.

The mouth of Akpait Fiord is characterized by the sill platform and landward basin acoustic stratigraphy. The acoustic subbottom profile and associated interpretation (Fig. 3.16) run along a survey track F-F' that traces seawards from the inner fiord-mouth basin, with a turn in the ship track, before continuing over the sill platform. The subbottom track crosses the base of the northern slope as the ship turns to run perpendicular to the proximal slope of the fiord-mouth sill and over the sill platform (Fig. 3.13B). Five acoustic units are identified. The acoustic basement unit (A),

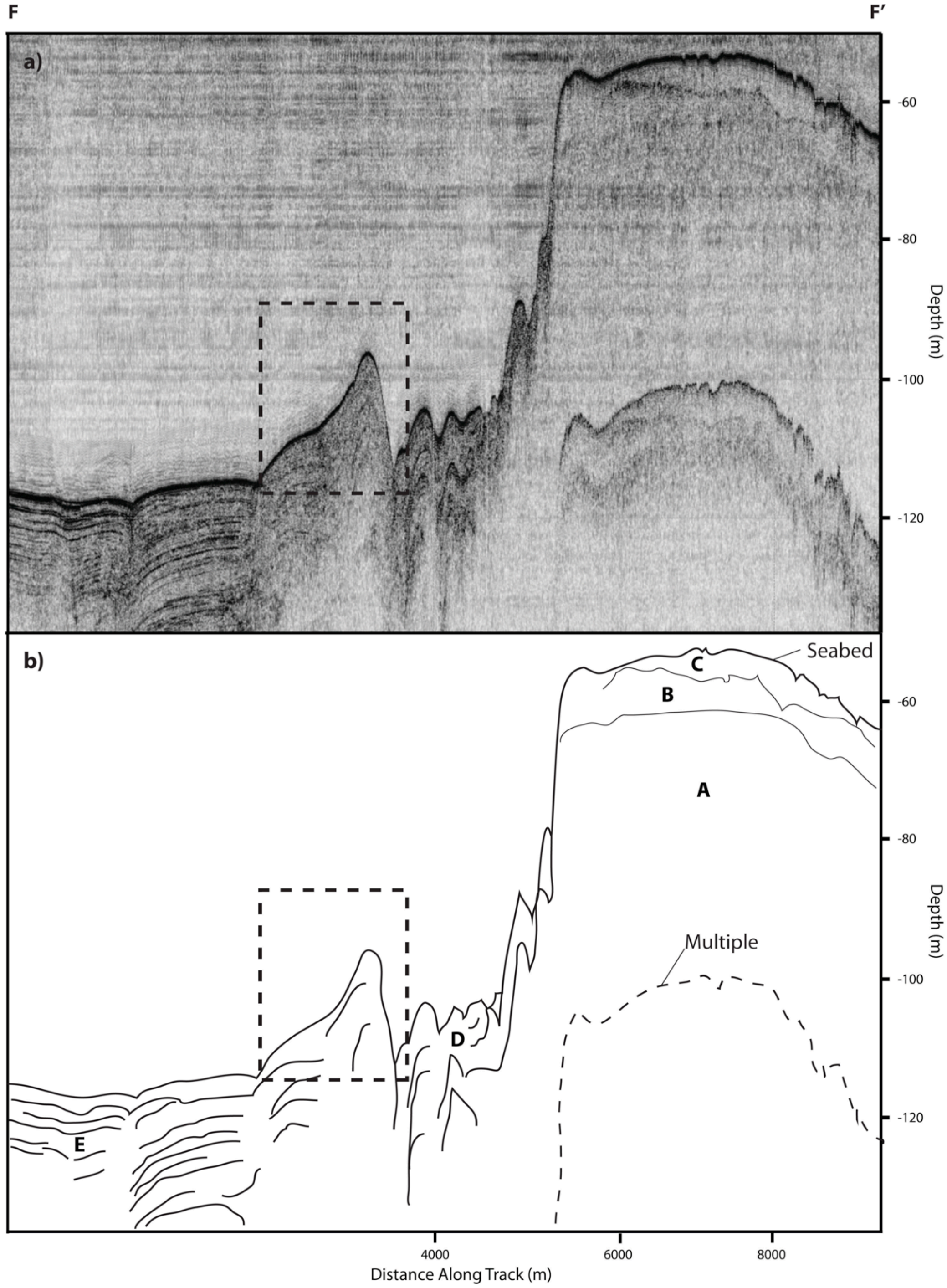

Figure 3.16: A) A 3.5 kHz acoustic record of a cross profile of the sill platform in Akpait Fiord (see Fig. 3.13 for location of profile track F-F'; depths based on an acoustic velocity of 1500 m/s in water). The profile is centred on the steep inner slope of the sill. B) Interpretation of acoustic facies; see text for discussion. Dashed box outlines the sloped feature that resulted from the turn in the ship track along the base of the inner sill slope before it continued perpendicular to the platform.

makes up the majority of the sill, is acoustically massive (no structures) and has an irregular, weak surface reflector (Fig. 3.16). It is interpreted as the fiord-mouth moraine deposited prior to the postglacial regression. Overlying Unit A is another acoustically massive unit (B), approximately 5 m thick, bounded by a strong, irregular surface reflector. Unit B is thickest towards the landward side of the platform but is discontinuous, and thins seawards. This unit is interpreted to represent the redistributed sill sediment that formed a wedge-shaped overwash deposit on the landward edge of the sill. Draping Unit B on the sill terrace is a faintly stratified unit (C), up to 5 m thick, with a convex upward strong, surface reflector. Unit C thins towards the landward edge of the sill. Similar to the post-submergence deposit on the delta surface at the head of Boas Fiord (Fig. 3.10), the thinning of Unit C towards the landward edge reflects the winnowing of fine-grained surface sediments at the edge of the platform. Iceberg scours are evident in the seabed reflector on the seaward extent of the platform. This unit represents a fine-grained deposit that probably draped the sill platform after abandonment and throughout the postglacial transgression.

Disrupted parallel reflectors (D) are mounded at the landward base of the sill platform, indicative of mass transport deposits. The acoustic unit (E) encompasses sub-parallel, horizontal reflectors (15 m thick). These finely stratified reflectors are characteristic of basin fill that accumulate through suspension and drape the basin floor.

3.4 Discussion

3.4.1 Postglacial Sea Level Indicators

Sea-level indicators are coastal geomorphic features formed with a known relation to past sea level, either above or below present sea level. The four submerged shoreline features presented in this paper each constrain sea level to different degrees. Furthermore, the utility of a sea-level indicator as an index point depends on the ability to date the sea level that the feature constrains. At present, the submerged deltas are the only feature of the four with the potential to date the occurrence of lower RSL on Cumberland Peninsula.

Observations of Gilbert-type deltas on the seafloor provided initial evidence for a postglacial lowstand in eastern Cumberland Peninsula. Chapter 2 identified the transgressive surface within the acoustic profile of the fiord-head delta in Boas Fiord. The transgressive surface, 2 m below the mean depth of the terrace lip, is indicative of the lowest low water level during the RSL lowstand. Assuming a micro-tidal range (<2 m) similar to present, the mean sea level position for the lowstand at the head of Boas Fiord was approximately 34 m bsl (Chapter 2).

Submerged deltas include stratigraphic sequences that delimit sea level at the transgressive surface, and should be a primary target for dating the lowstand along Cumberland Peninsula. The prodeltaic sediments are fine-grained and should provide long cores and bioclast material preserved within the prodelta deposits should be suitable for radiocarbon dating.

The submerged boulder barricade does not provide an index point for palaeo-sea-level; however, it does constrain the depth of sea level during its formation. The submerged barricade identified at Qikiqtarjuaq is found at a seaward transition from predominantly sand and algae to boulder concentrations at a marked break in slope. Assuming no change in the micro-tidal range of Broughton Channel, the highest boulder line can be used to mark the high tide. The submerged boulder barricade was recorded within a depth range of 16 to 18 m bsl, which constrains the average high-tide level to 16 m bsl. The age at which this feature was formed cannot be determined independently; however, as demonstrated by Gray et al. (1980) in Ungava Bay, the age of boulder barricades can be constrained through extrapolation of shoreline gradients from dated features. If the RSL lowstand in eastern Cumberland Peninsula is eventually confirmed to be a synchronously formed shoreline during the recession of the Cockburn Substage (cf. Chapter 2; ca. 8.5 ka) and the boulder barricade at Qikiqtarjuaq is considered to be part of the lowstand shoreline, then we can assign a correlative age to the barricade.

The submerged sill platform in the mouth of Akpait Fiord forms a remarkably flat feature at 51-52 m present water depth. It is interpreted using the barrier platform in St. George's Bay, Newfoundland as an analogue (cf. Shaw and Forbes, 1992). In this context, the sill at the mouth of Akpait Fiord was likely reworked when the sill crest (Unit A; Fig. 3.16B) was first exposed to wave action and a wedge of spillover deposits (Unit B) was produced that recurrently failed on the steep inner sill slope, resulting in mass transport deposits (Unit D) into the landward basin. Marine fine-grained sediments have draped the sill platform since submergence (Unit C).

Supporting evidence for a RSL lowstand of 51-52 m bsl comes in the form of a fiord-head terrace at 51 m bsl and the deeper of the two gravel spits at 50 m bsl that extend southwestward from the sill platform and has a relief of 1-2 m above the platform. The subaerial component of the spit was likely reworked during the Holocene transgression, resulting in a morphology that is wider than modern spits found to the north of Akpait Fiord (Fig. 3.11; Fig. 3.12).

The sill platform stratigraphy provides several opportunities for dating the RSL lowstand, though none are precise. One strategy would be to sample and date organics in the spillover deposits (Unit B; Fig. 3.16) or the related mass transport deposits (Unit D; Fig. 3.16). There is a risk of dating reworked organics as these deposits are by definition remobilized older sediments. Care would be required to select only *in situ* organics living in these depositional environments. Given the coarse nature of the deposits, sediment core penetration and retrieval may also be a challenge (potentially require vibracoring processes). Another strategy is similar to what was suggested for submerged deltas; that is, retrieval and dating of basal organics from post submergence sediments on the sill platform (Unit C; Fig. 3.16).

The St. George's Bay platform was interpreted to have been subaerial at the RSL lowstand (Shaw and Forbes, 1990), a similar situation cannot be confirmed at this time for Akpait Fiord. The implication of such an interpretation, however, is that the fiord basin behind the sill would have evolved into a freshwater/brackish environment at the RSL lowstand, a condition that should be reflected in the biostratigraphy of fiord basin sediments. For example, foraminiferal or diatom analysis should distinguish fresh/brackish assemblages in basin sediment cores that would help target organic samples for radiocarbon dating. In this way, the age of the lowstand RSL position can be bracketed using the period of marine isolation.

The shallower submerged spit, at a depth of 30 m bsl, is most similar in size and orientation to modern spits (see #1, Figs. 3.11 and 3.12). As the subbottom profiles do not penetrate below the cobble gravel of the spit, it is unclear as to how the spit relates to underlying substrate. The formation and preservation of the -30 m spit attests to either a standstill during overall Holocene transgression, or the opportunistic availability of gravel through erosion and longshore drift of coastal sediment along the northern coast of Akpait Fiord mouth.

3.4.2 Palaeo-Coastal Setting

The bathymetry of the study areas record relict coastal settings that differ in many respects from the modern shore zone. The submerged shorelines were subjected to marine dynamics and sediment loads different than those observed along the modern coastline. Both Broughton Channel and Akpait Fiord may have been isolated from Baffin Bay by shallow sills, resulting in marked changes in palaeo-geography and coastal environments.

3.4.2.1 Broughton Channel

The boulder barricade mapped in the nearshore zone of eastern Broughton Channel provides evidence for a past sea level stand, 16 m lower than present. A boulder barricade is not observed in the modern shore zone, which indicates that the coastal setting has evolved since the postglacial lowstand.

From the extent of the available multibeam bathymetry, the -16 m palaeo-shoreline can be mapped for much of Broughton Channel using the -16 m isobath (depth contour; Fig. 3.3). An examination of the configuration of this isobath demonstrates that Broughton Channel was closed off from Baffin Bay to the north. The shallow platform between the tombolo and the community is likely the remnant of a moraine deposited at the ice limit of the early Foxe glaciation (>54 ka BP; Brigham, 1982) and reworked during subsequent lower RSL, the most recent during the Holocene. The -16 m isobath reveals an additional submerged shoreline, a tombolo that extended to the south in Broughton Harbour. This feature is interpreted from the -16 m isobath drawn from the combined multibeam and Canadian Hydrographic Service datasets. The subaerial beach that made up the tombolo feature was reworked during the following transgression, such that a widened platform is discernable on the seabed between the modern island in Broughton Harbour and the mainland.

Isolated and protected from Baffin Bay during the lowstand, Broughton Channel would have formed a tidal embayment with currents, tidal regime, sediment transport processes, and ice dynamics that differ from the present day. The scenario that Broughton Channel was closed off from Baffin Bay may explain the formation of a boulder barricade at that time and the absence of boulder barricade development along the modern coast. The semi-enclosed tidal basin was not influenced by the same currents that run through Broughton Channel today (0.5-0.8 m/s), which cause earlier ice breakup than nearby regions (Gilbert, 1980). The sheltered setting of the semi-enclosed tidal basin would have promoted the persistence of landfast ice over the main basin during spring thaw, providing a barrier to the drift of intertidal ice rafts and promoting the deposition of boulders in a ridge at the margin of the intertidal zone. The basin ice does not persist into the spring thaw because of the modern tidal exchange through Broughton Channel. Under these conditions, ice-encased boulders may be rafted into deeper water (>25 m bsl), where they are dispersed randomly across the seabed, contributing to the winnowed boulder lag observed in the deeper waters of the channel (Gilbert, 1980).

The submerged boulder barricade at Qikiqtarjuaq has less relief and is more dispersed than might be expected from typical barricade forms today. The somewhat poor development may reflect the limited tidal range, which, although it may not have been identical to today, is unlikely to have been substantially greater than 2 m.

3.4.2.2 Boas Fiord

The majority of the shallow waters mapped in Boas Fiord were at the fiord-head, on a side-entry delta, and at the mid-fiord sill. At a sea level 34 m below present, most of the sill was subaerially exposed with a shallow marine channel to the east (Fig. 3.10). The head of Boas Fiord became a semi-enclosed basin with restricted inflow and outflow processes. The submerged fiord-head delta was exposed to a confined marine influence, which increased during the subsequent transgression.

The deposition of the submerged sandur was influenced by two sediment sources: the main fiord-valley glacio-fluvial outwash, and discharge from an eastern side-valley that eventually amalgamated with the prograded sandur. The main difference between the modern and submerged fiord-head deltas is the volume of sedimentation that took place. The submerged delta has a relief of 57 m off the basin floor, extends 7.5 km from the modern delta terrace and has an average width of 1.8 km. The modern sandur is built on top of the submerged delta, with a relief of 33 m over 7.5 km axial distance. It is 1.4 km wide and about 4.5 km long. The thickness of post-transgressive sediment over the submerged sandur surface, at the southernmost extent of our subbottom profile (~3 km from the modern delta front) is approximately 2.5 m. The modern delta presents a significantly smaller volume of sediment compared to the quantity of proglacial or early paraglacial sedimentation during the deposition of the submerged delta.

The fiord-head coastal setting and style of sedimentation in Boas Fiord has evolved since the submerged delta was deposited in the early Holocene. Proximal valley glaciers deposited the submerged delta. The uneven surface of the acoustic Unit D may indicate a braid plain or infilled kettle holes. Kettle hole features would indicate that this submerged delta was deposited in contact with the valley glaciers and mark the ice margin for the age of deposition.

The sediment source for the submerged delta was controlled by the main fiord-valley glacial system and a side-entry system. These glacial systems were the source of sediment for the submerged sandur, which amalgamated to extend the lowstand delta terrace along the eastern sidewall. At present, an alluvial fan is being deposited over the submerged sandur. The modern glacio-fluvial drainage route to the head of Boas Fiord is longer than in the past and deposits sediment into a shallower basin without a side-valley sediment source, on the extensive submerged delta terrace at the fiord-head. Delta front dynamics are not observed at present because the drainage system lacks the sediment load and an open basin for progradation. The modern delta front is open to marine dynamics, which combined with fluvial influx form unidirectional bedforms on the shallow upper delta front.

3.4.2.3 Akpait Fiord

The relict postglacial sill platform at the mouth of Akpait Fiord provides a poor constraint on its associated lower sea level. The lower RSL was undoubtedly within the range of wave base over the 51-52 m bsl platform, but the exact depth is uncertain. Two associated submerged landforms serve as sea-level indicators.

The first is the -51 m depositional terrace near the head of Akpait Fiord – this indicates a sea level either at -51 m, or lower if the sill became subaerial and a delta built out into a lake basin. A subaerial sill would isolate Akpait Fiord from Baffin Bay and its dynamic marine influence on the inner coastal setting. Basin cores could detail the environmental shift from marine to freshwater and back to marine that would occur at the time of delta formation and through subsequent transgression. Foraminiferal and diatom assemblages may constrain this environmental shift, and present ages for sedimentation rates in the fiord basin.

The crescent-shaped gravel spit at -50 m provides a second indicator of lower RSL. The -50 m isobath runs parallel to the northeastern coast of the fiord-mouth, and around the spit extension (Fig. 3.13A). During the formation of a subaerial spit at -50 m the fiord basin was influenced by restricted marine inflow and outflow. Spits are formed on coasts characterized by sustained erosion and longshore drift. If Akpait

Fiord was isolated from Baffin Bay by the sill platform, the -50 m spit may indicate the renewed influence of Baffin Bay inside the fiord-mouth after initial submergence of the platform. The southwestward extension of the spit deposit up-fiord is analogous to the modern spit #1 to the north sustained by erosion of wave-cut colluvium from the northeast (Fig. 3.12).

A subaerial barrier platform at the mouth of Akpait Fiord would be influenced by storm wash and coastal dynamics, likely resulting in overwash deposits. Acoustic penetration through the subbottom stratigraphy is limited, but Unit B forms a wedge-shaped deposit that thins seawards. Steeply dipping clinoformal reflectors indicative of a spillover deposit (Shaw and Forbes, 1992; Shaw and Courtney, 1997) were not identified in Unit B or on the landward slope of the sill platform; however, the wedge-shape of Unit B, in addition to the mass transport unit (D) at the base of the steep landward slope may suggest overwash of sediments on the sill platform at a lower RSL.

The acoustic unit (A) interpreted as the fiord-mouth moraine has a planed surface reflector, which may mark the wave-base during regression that redistributed sediments into a planar feature. In this interpretation, RSL lowered below the surface of Unit A (60-55 m bsl) to form a subaerial platform for overwash deposits (Unit B) to form. This interpretation may be constrained further by piston cores from the mass transport deposits (Unit D). Radiocarbon ages of organic material and analysis of foraminiferal and diatom assemblages from these cores could constrain the overwash and sediment transport over the sill platform if the platform was breached by marine influx. The submerged shoreline features present in Akpait Fiord and the palaeo-shoreline they represent, constrain the early Holocene RSL between 60 and 50 m bsl.

3.4.3 Predicting Submerged Shorelines

This chapter has revealed four types of submerged shoreline features preserved on the seafloor in northeastern Cumberland Peninsula. Submerged deltas have been identified throughout Cumberland Peninsula, but the formation and preservation of a submerged boulder barricade, sill platform and spits are the result of specific environmental conditions that rarely coincide. A boulder barricade is situated in a setting with a break in the nearshore slope at the low-tide limit, where sea ice formation is prevalent and persistent, and there is a boulder source in the intertidal zone. The palaeo-geography and submerged boulder barricade mapped in Broughton Channel revealed the addition of an oceanographic constraint on their formation. Surface currents affect ice breakup and the migration of boulder-laden ice. Since the opening of Broughton Channel to Baffin Bay and the initiation of strong currents through the channel, the occurrence of a boulder barricade in the shore zone has disappeared.

The southwestward spits at the mouth of Akpait Fiord require sustained erosion and longshore drift, which have not been mapped elsewhere in the submerged setting but are observed along the modern coast (Fig. 3.12). The sill platform, on the other hand, is formed by a remnant fiord-mouth moraine deposit, with a relief that brings its surface in contact with the wave base during or leading up to the lowstand. If all these physical, oceanographic, and sea-ice conditions are met, there is a possibility that similar submerged shoreline features are present elsewhere in Cumberland Peninsula. It is unlikely that the conditions required for the formation of boulder barricade and sill platform features are reflected in many other locations. For example, the fiord-mouth directly south of Akpait Fiord was mapped as a potential site of another sill platform, as it appears to be geographically analogous to Akpait. In the absence of a moraine sill at the fiord-mouth, however, a sill platform did not develop at this location.

The submerged boulder barricade and sill platform presented in this paper have been plotted in relation to the early Holocene shoreline gradient developed in Chapter 2 (Fig. 3.17). Figure 3.17 shows the eastward tilt of the postglacial submerged deltas and demonstrates that the boulder barricade and sill platform fit closely on the linear shoreline gradient. Note that site 4 is the submerged delta at the head of Boas Fiord, also discussed in this paper. The tight fit of the submerged shoreline features on the linear trend can be utilized to determine the depth at which additional submerged shoreline sites are expected as a function of longitude in northern and eastern Cumberland Peninsula.

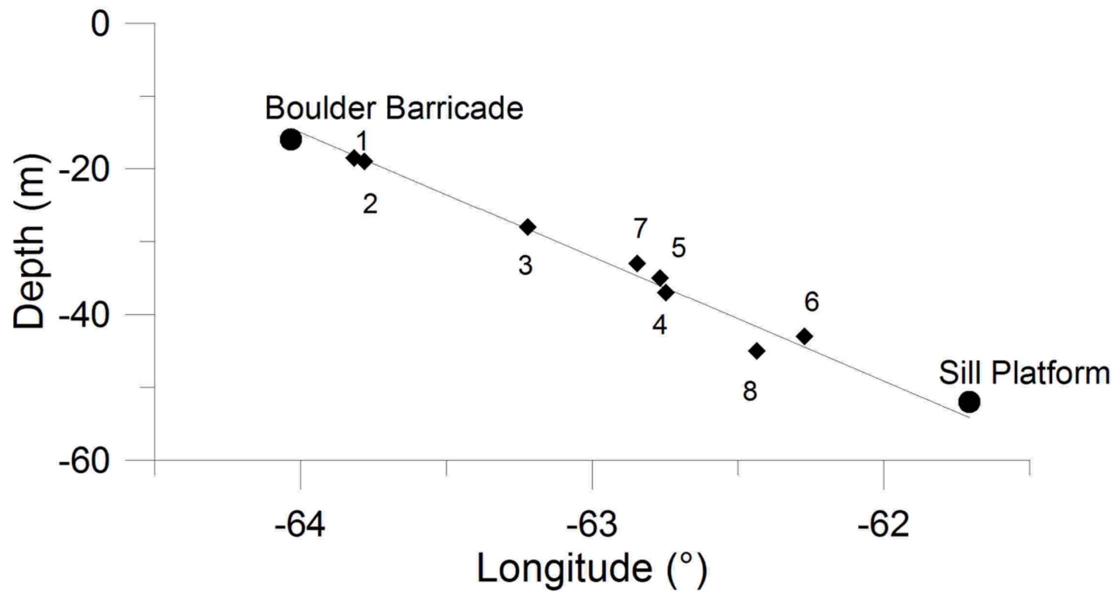

Figure 3.17: The depths of the submerged boulder barricade in Broughton Channel and sill platform in Akpait Fiord (black circles) are graphed in addition to the lowstand shoreline gradient through submerged deltas of Chapter 2: 1) Head of Kingnait Fiord; 2) Kingnait Fiord side-valley; 3) Outer Padle Fiord; 4) Head of Boas Fiord; 5) Boas Fiord side-valley; 6) Inner Durbhan Harbour; 7) Mermaid Fiord side-valley; 8) Outer Clephane Fiord.

Few transgressive relict shoreline features postdating the early Holocene submerged shoreline have been found in this region. The abandoned spit at -30 m in the mouth of Akpait Fiord is the most obvious. A side-entry delta in Boas Fiord has a fan deposited over it, but the associated relative sea-level is difficult to discern (Chapter 2). The undated, small-scale gravel barriers at -9 m on the east side of Broughton Island (England and Andrews, 1973) and buried peat below present high tide in the region of Qikiqtarjuaq (Pheasant and Andrews, 1973; Brigham, 1982) attest to recent transgression, as do a scattering of features along the modern coast: the barrier beach mapped south of Akpait Fiord (site 3; Fig. 3.11) and the modern gravel barrier forming the tombolo at the north end of Broughton Channel (Fig. 3.3), among others.

3.5 Conclusion

New high-resolution bathymetric and backscatter maps of submerged shoreline features (-16 to -50 m bsl) offshore of northern and eastern Cumberland Peninsula, combined with sediment samples and seabed video imagery, have made it possible to compare the modern and postglacial submerged shore zones at several study sites. In some cases, analogous features are present in close proximity on the modern and submerged shorelines: examples include the modern and relict spits in the vicinity of Akpait Fiord, modern and relict tombolos in Broughton Channel, and fiord-head deltas in Boas Fiord. In some cases the immediately adjacent modern shoreline is a poor analogue for the features found on the early Holocene coast. Boulder barricades, for example, are not found on the modern coast in the vicinity of Broughton Channel, but a relict barricade has been mapped 16 m bsl in this locality. Similarly, there is no modern analogue for the sill platform at Akpait Fiord.

During the postglacial lowstand, Broughton Channel was a semi-enclosed tidal basin, protected from the influence of Baffin Bay. In Boas Fiord, a mid-fiord sill with a shallow channel restricted the marine influence at the head of the fiord. In Akpait, a fiord-mouth sill may have been emergent at the lowest sea level. The semi-enclosed basin of Broughton Channel at -16 m RSL protected the contemporaneous coastal setting from the strong tidal currents that prevail today. This promoted the persistence of landfast ice, which provided a barrier to drifting intertidal ice, leading to the deposition of a boulder barricade at the margin of the intertidal zone. In

Akpait Fiord, a RSL ranging from 60 to 50 m bsl brought the wave base in contact with the fiord-mouth moraine deposit, resulting in the planation and possible emergence of the sill to isolate the fiord basin from marine influence.

This paper presents the first documentation and characterization of submerged shoreline features from the early Holocene lowstand in northern and eastern Cumberland Peninsula. It also reports the first record of a submerged boulder barricade in the literature. The post-lowstand Holocene transgression, even in the westernmost part of the study region where the rise in RSL was as little as 16 m, caused substantial alteration in the coastal geography, opening previously protected basins such as Broughton Channel to more direct marine influence and more energetic currents. Only the submerged deltas have the stratigraphic markers and datable material to be utilized as sea-level index points, but the submerged boulder barricade, sill platform and spits help to constrain RSL and GIA models for the region.

3.6 References

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CHAPTER 4: SUMMARY AND CONCLUSION

4.1 Summary

Previous glacial and sea level research from the 1970s identified eastern Cumberland Peninsula as a potential region of continuous postglacial submergence; unfortunately, neither logistical access nor survey technology was readily available to survey the submerged shorelines until recently. The commissioning of the *MV Nuliajuk* by the Government of Nunavut to operate in the uncharted waters of eastern Baffin Island provided the logistical accessibility for this study, while the onboard installation of a multibeam echosounder for high-resolution mapping of the seafloor provided the survey technology. This study set out to demonstrate that submerged shorelines were preserved on the seabed of eastern Baffin Island and to test the earlier hypothesis of A.S. Dyke (1979) that proposed a fully submerged postglacial RSL record on eastern Cumberland Peninsula. The main objectives were: (1) to locate and map submerged shoreline features at targeted sites within fiords and inlets of the study region; (2) to map the water depths and geomorphology of submerged shoreline features at these sites; (3) to assess the utility of these features as palaeo-sea level position indicators; and (4) to interpret the spatial pattern of submerged sea level features in the context of the regional deglacial history and models of glacial-isostatic adjustment (GIA).

Exploratory surveys of the coastal inlets and fiords of Cumberland Peninsula with high-resolution multibeam bathymetry resulted in the discovery of submerged shoreline features at various depths across northeastern Cumberland Peninsula. These included: one boulder barricade, eight delta terraces, one sill platform and two gravel spits. The features were studied in relation to their RSL position, their comparison with the modern coast, and the deglacial and RSL chronology. Adjacent modern shoreline analogues (or lack thereof) were identified and mapped from aerial photography, and topographic and surficial geology maps. Where none were located in the study area, reference was made to published examples. Qikiqtarjuaq provided small boat accessibility in Broughton Channel for fieldwork along the submerged boulder barricade and adjacent modern coastline. Shoreline classification of other sites, including detailed analysis of parts of Boas and Akpait fiords relied extensively on archival aerial photography and ship-based observations. In summary, this thesis presents new detail on the depth, character and spatial pattern of the submerged early Holocene shoreline on northeastern Cumberland Peninsula.

4.1.1 Research Findings

New data for the seabed morphology in fiords of eastern Baffin Island is presented in this thesis, which documents the discovery of four types of submerged shoreline features. Boulder barricades, deltas, sill platforms and spits are distinctive coastal features that are formed at sea level or within wave base range and provide an indication of past sea level position. Chapter 3 documents for the first time a submerged boulder barricade. The feature, located along eastern Broughton Channel, is indicative of a sea level 16 m below present. This finding also reveals a substantially different coastal setting in which Broughton Channel was a semi-enclosed basin, separated from Baffin Bay by an isthmus connecting Broughton Island to the mainland, across from the Hamlet of Qikiqtarjuaq. The subsequent rise in RSL brought about a major change with the opening of Broughton Channel. The open channel is now a tidal passage with strong currents, a condition that likely accounts for the lack of a boulder barricade along the modern coast. The high currents cause the landfast ice in deeper parts of the channel to break up earlier than it would otherwise, removing the barrier to drifting intertidal ice laden with boulders. By removing a necessary condition for the formation of a boulder barricade, the opening of Broughton Channel prevented the formation of boulder barricades later in the Holocene.

This study presents a geomorphic characterization of a submerged barrier platform found at the mouth of Akpait Fiord. The sill platform (51-52 m bsl) provides a minimum depth range for the lowstand on eastern Cumberland Peninsula. The 50 m bsl gravel spit feature is indicative of coastal erosion and sediment transport. RSL at -50 m or more would bring the surface of the sill within wave base while the spit extended headward into the fiord. The spit feature is interpreted to have formed when the sill platform was breached as Akpait Fiord was opened to Baffin Bay, which renewed erosion of the northeastern coast and longshore drift. The acoustic profile of the sill platform suggests a wedge-like unit (B) interpreted as overwash deposits on the surface of the subaerial barrier platform. Combined, these features indicate a lower RSL between 60 and 50 m bsl.

Submerged deltas provide the best opportunity to constrain the age of the postglacial lowstand. The eight mapped deltas cover a wide spatial distribution across the north and eastern peninsula. A subbottom profile from the submerged fiord-head delta in Boas Fiord reveals imagery of the transgressive surface that marks the contemporary sea level (34 m bsl). The westernmost submerged deltas in Kangert Fiord display evidence of kettle holes indicative of an ice-contact setting, which reveal the presence of valley ice at the fiord-head and side-entry valley during delta formation. Many of the submerged deltas are situated adjacent to coastal moraines correlated to Cockburn-equivalent ice limits (9.5-8.5 ka; Dyke, 1979; Margreth, 2015). The kettle-holed deltas can provide further evidence of ice limits in fiord-heads in the absence of coastal moraines.

Deglaciation was asymmetrical across Cumberland Peninsula. The southern fiords were ice-free by the Younger Dryas re-advance (ca. 11.7 ka), but the northern fiord-heads were not ice-free until after the re-advance of the Cockburn Substage (ca. 9.5-8.5 ka; Margreth, 2015). Recession from one of these ice limits provided the sediment and meltwater pulse for delta deposition; however, the recessional history is not temporally constrained in northeastern Cumberland Peninsula and therefore the age of deposition is still unknown. Margreth (2015) suggests that the submerged deltas may correspond to the Cockburn Substage; however, Cockburn-equivalent moraines are not observed along the adjacent coasts of all the submerged delta locations. With both proximal moraines for age control and a stratigraphic marker of former sea level, the deltas are potentially good sea level index points. The results of this study constrain the lowstand and therefore deposition of the submerged shorelines. However, until absolute ages are determined for the proximal moraines or the deposition of the deltas, they cannot provide index points for the sea-level curves in the region.

The study of submerged shoreline indicators presented in this thesis confirms the preliminary hypothesis of submergence for the outer coast of Cumberland Peninsula (Dyke, 1979; Andrews, 1989). The spatial distribution of the lowstand across the peninsula is revealed by submerged shoreline features (16-52 m bsl) described in this thesis. These plot a shoreline gradient of 0.35 m/km falling towards the east. The shoreline features tightly fit a linear depth vs Longitude plane that suggests synchronicity of the submerged shoreline development.

These results confirm the inference drawn from the eastward tilt of the marine limit gradient in the southwest (Dyke, 1979), which led to the conceptual model of submergence in eastern Cumberland Peninsula. The marine limit and submerged shoreline gradient are offset from each other, attributed to the differential rates of crustal adjustment between the southwest and northeast parts of the peninsula, as the southern peninsula experienced rapid recession at an earlier time (Dyke et al., 2003; Margreth, 2015). Further age constraint on local deglaciation of the northeastern peninsula is required.

4.1.2 Contributions

This study contributes to Arctic coastal and marine sciences by characterizing both the modern shore zone and the early Holocene submerged shoreline. Notably, over the course of this study, many uncharted fiords and passages were mapped for safe transit in high-resolution with multibeam bathymetry (Appendix A & C: Cruise reports). The documentation of high-resolution submerged shorelines within these fiords provides new data to partially fill the knowledge gap in the postglacial sea-level history of Cumberland Peninsula. In addition, the study at Broughton Channel not only reveals bathymetry of the channel surrounding the Hamlet of Qikiqtarjuaq, but also offers the first documentation of a submerged boulder barricade in the literature. In summary, this study presents the first characterization of the modern and early Holocene submerged shore zone of northeastern Cumberland Peninsula.

Though the absolute age of the lowstand is still unknown, it is constrained by fiord-head ice limits, which provided meltwater and sediment for formation of depositional shoreline features. The submerged shoreline gradient, developed in this thesis, will add to the dataset used to model postglacial GIA to provide a better understanding of the crustal response and sea-level history of Cumberland Peninsula.

4.1.3 Research Gaps and Future Work

The age of the postglacial lowstand has been constrained by the deglacial chronology from the literature, but the remaining uncertainty in absolute chronology is a limitation. Future research should strive to date the formation of the submerged shorelines described in this thesis. Of the mapped shoreline features, the submerged deltas are best suited to provide constraints on the timing of the postglacial lowstand. A piston core has been taken in the prodelta sediments of one of the deltas, and it is anticipated that further coring will target the other deltas as well. These cores will provide the depositional sequences associated with delta sedimentation, and if organic material is preserved within the cores, the age of deposition may be measured by radiocarbon dating.

Though dating the marine sediments associated with delta deposition is imperative to temporally constrain the postglacial submergence history, the ages of the adjacent coastal moraines are also important for understanding the relation between deglaciation and RSL. These moraines are thought to be early Holocene from the recession of Cockburn-equivalent ice limits (9.5-8.5 ka), and associated with the deposition of submerged deltas as the glacial recession provided a source of meltwater and sediment. This hypothesis can be constrained using cosmogenic radionuclide (CRN) dating of surface boulders on the moraines. The absolute ages of these moraines will help to constrain the chronology of Holocene glacial events, and provide a basis for crustal adjustment and sea-level interpretations.

St. George's Bay, NL provides an analogue for the interpretation of the submerged sill platform at the mouth of Akpait Fiord (Shaw and Forbes, 1992; Shaw and Courtney, 1997). However, the submerged sill platform does not constrain the depth of the lowstand at this study site. To obtain evidence for the depth of the lowstand in relation to the sill height requires basin core analysis. Two piston cores have been collected aboard the *CCGS Amundsen* (October 2014) from Akpait Fiord, one from the central basin, and one within the mass transport deposits at the base of the sill platform. The basin core records depositional sequences, which could include environmental changes from marine to brackish water or even to freshwater environments if the lowstand reached a depth greater than the sill platform (> 52 m bsl). Radiocarbon dating of organic material within the depositional sequences may constrain the temporal setting of the lowstand. Alternatively, continuous marine sedimentation would suggest that Akpait Fiord was not closed off from Baffin Bay and sea level remained at a depth above 52 m bsl. The analysis of these cores goes beyond the scope of this thesis, and will be carried out by successive students.

In addition to constraining the age of the lowstand, further exploration for submerged shorelines may constrain the spatial distribution of submergence on

Cumberland Peninsula. The survey strategy was revised based on the coastal settings in which submerged shorelines have been located in previous surveys.

For a better understanding of the lowstand and isostatic adjustment processes across Cumberland Peninsula, it is important to continue to explore possible locations of submerged shorelines. To revise the survey strategy used at the start of the multibeam surveys, the recession marked by fiord-head moraines is taken into account. Though the ages of the recessional moraines are mostly unknown, the mapped moraine systems can provide the basis for interpretation of fiord-head glacial coverage (Margreth, 2015).

The regular revision of the survey strategy has proven to be successful, as it allowed for the rediscovery of a submerged delta (Site #3) previously reported in Miller and Dyke (1974). From the literature, it appeared that a submerged delta had been mapped in outer Padle Fiord; however, the precise location could not be determined from the information at hand. It was only from the revision of this strategy with the local surficial geology and topography that the location was rediscovered. The targeted site included a large, prominent glaciofluvial system that crosscuts a side-valley moraine and enters into an embayment in outer Padle Fiord. Based on the eastward lowstand gradient, the delta was presumed to have a delta terrace depth between 20 and 30 m bsl. As a result, the submerged delta presented in this paper at site #3 was relocated and mapped at a depth of 29 m bsl.

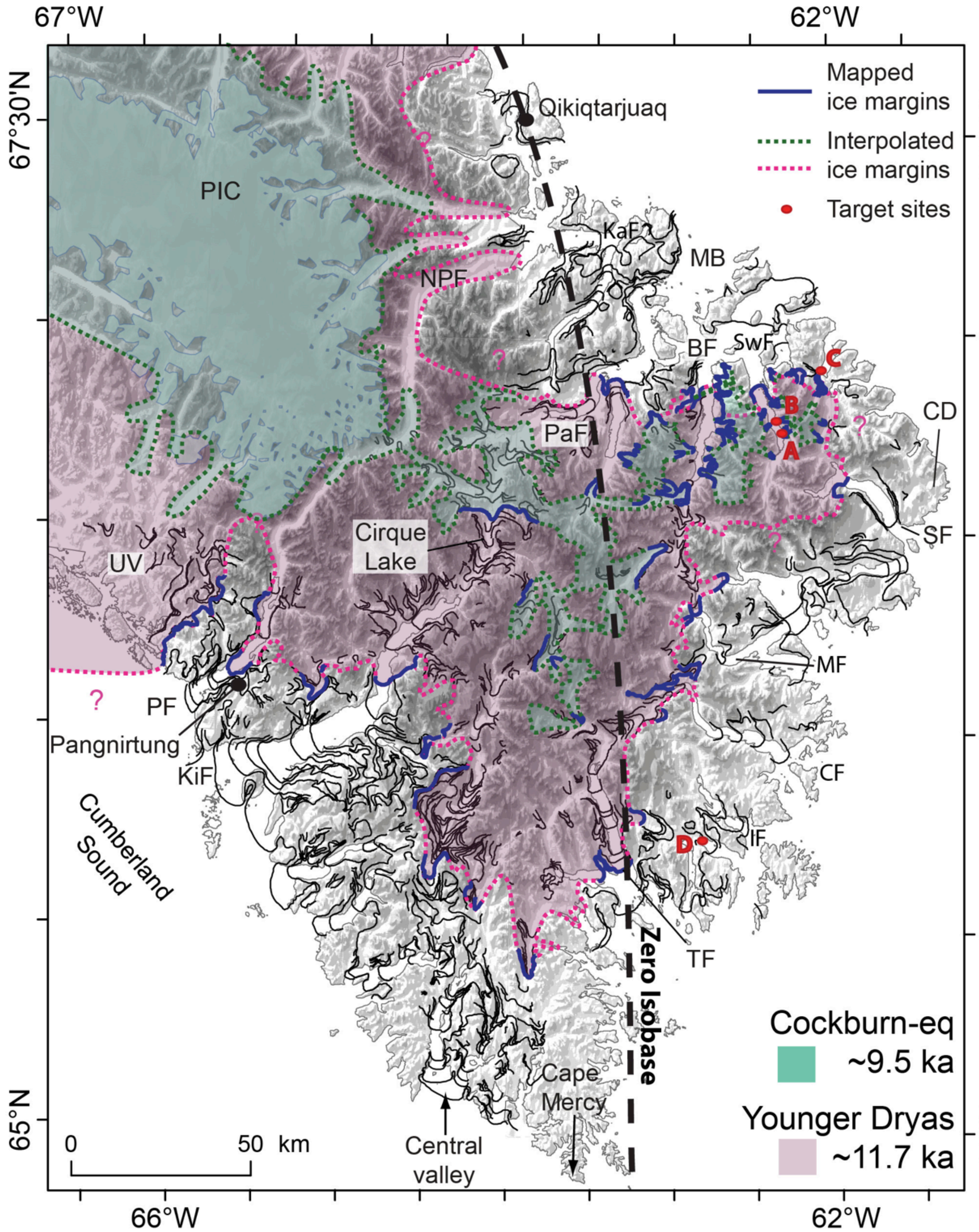

Figure 4.1: Targets for future multibeam surveys are highlighted alongside recessional ice margins on Cumberland Peninsula that highlight the Cockburn-equivalent and Younger Dryas ice limits. Modified from Margreth, 2015. Zero isobase is delimited in accordance with Kaplan and Miller (2003). NPF: North Pangnirtung Fiord, PaF: Padle Fiord, MB: Merchants Bay, BF: Boas Fiord, SwF: Southwind Fiord, CD: Cape Dyer, SF: Sunneshine Fiord, MF: Mermaid Fiord, CF: Clephane Fiord, TF: Touak Fiord, KiF: Kingnait Fiord, PF: Pangnirtung Fiord, UV: Usualuk Valley, PIC: Penny Ice Cap.

Four target locations for future multibeam surveys (Fig. 4.1) have been identified as a result of the refined survey approach (see section 2.5.3). Each site (A, B, C and D) includes a glaciofluvial source cutting through a moraine and till veneer at the apex of a sheltered side-entry valley or fiord-head. The locations situated at side-entry valleys (A and B) would result in triangular-shaped submerged deltas, whereas the two fiord-heads with narrow accommodation space (C and D) would result in long and narrow deltas with straight progradational fronts.

Sites A and B are both situated in Southwind Fiord, which has been mapped (Appendix A.7.6), but not at these side-entry locations. The present extent of multibeam coverage reveals an intriguing fiord, with fiord-head bedforms and seafloor channels, as well as a terrace along the eastern side at the fiord-head. The interesting seafloor geomorphology, as well as the locations of two side-entry valleys crosscut by Cockburn-equivalent moraines, makes this fiord a target for future multibeam surveys. From the tilt of the submerged shoreline gradient (0.35 m/km; presented in Chapter 2 and 3), these deltas are predicted to occur at 38-42 m bsl. Site C is located at the head of an unnamed fiord that opens to the east into Baffin Bay. The fiord-head is draped in a cross-valley moraine that corresponds to ice limits between 11.7 and 8.5 ka (Margreth, 2015). The submerged shoreline gradient predicts that this delta should occur at 45-55 m bsl. Site D, on the southeastern coast, is targeted to better constrain the differential recession chronology and lowstand trend predicted between the southern and the northern coast. If the southeast coastal submergence follows the tilt of the shoreline gradient, a submerged delta is predicted to occur in this location at a depth of 30-35 m bsl.

To the east of Kingnait Fiord, where the marine limit gradient is thought to pass below sea level, the physiography differs from that observed in the north. Along the southern coast of Cumberland Peninsula, there are more extensive drainage systems with many catchments and valleys that lack proximal alpine glaciers. As well, the southern fiords of Cumberland Peninsula were deglaciated before their counterparts in the north. In this revised survey strategy, no locations have been targeted for submerged shorelines on the north coast of Cumberland Sound west of Cape Mercy. This assumes that the lowstand in the south was relatively synchronous with that of northern Cumberland Peninsula, but lacked the proximal glaciers and sediment supply during the shoreline-building episode.

The absence of long-term continuous GPS and tide-gauge measurements results in a knowledge gap between the postglacial submergence and the modern trends in RSL change. At present the instrumental record includes a decade of sea level and uplift data in the Hamlet of Qikiqtarjuaq (James et al., 2014). In order to understand the present trends in uplift that have been observed over the last decade, and how they project into the future, the GPS and tide-gauge recording stations must be maintained to create a long-term sea-level-record.

4.2 Concluding Remarks

The results of this study advance our knowledge of the postglacial sea-level history along Cumberland Peninsula. Specifically, sea-level evidence from ten submerged shoreline sites has constrained the spatial distribution of the lowstand along the northeastern coast. Furthermore, the geomorphology of the submerged shoreline features has been characterized in relation to the coastal setting at the time of formation and to conditions on the modern coast. The relation between the submerged shorelines and contemporary sea level provides further knowledge of the coastal palaeo-geography at the lower sea level, and of the nature of coastal change through the Holocene transgression.

In addition to filling gaps in the scientific literature, understanding the nature of submergence and how it contributes to coastal change has important implications for coastal communities. The future development of Qikiqtarjuaq, NU will have to take into account the present discrepancy between long-term (geological) and short-term (instrumental) records of sea level and crustal trends. In this context, maintenance of the tide gauge and GPS recording stations will provide a more continuous record alongside the geological sea-level dataset, which will provide a firmer basis for sea-level projections.

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A *MV NULIAJUK* CRUISE REPORT: CLYDE RIVER & QIKIQTARJUAQ TO PANGNIRTUNG

October 3- 19, 2012, & October 2-19, 2013

A.1 INTRODUCTION

This report is a combination of two field seasons, both of which involved the seabed mapping of coastal fiords and inlets of Cumberland Peninsula, starting in Qikiqtarjuaq and ending in Pangnirtung, NU. The 2012 cruise was able to map Clyde River before returning to Qikiqtarjuaq, and is therefore also included in this report. These consecutive cruises were made possible through the partnership of the Government of Nunavut (GN), ArcticNet, University of New Brunswick's Ocean Mapping Group, and Memorial University of Newfoundland and through the funding of GN, ArcticNet, and the Canadian Hydrographic Society. GN provided the *MV Nuliajuk*, which is equipped with geoscience/hydrographic survey equipment, including multibeam and subbottom echosounders. This report documents the separate field seasons chronologically, but displays the data in a consistent geographic catalogue starting in Clyde River, jumping to Qikiqtarjuaq and following the coasts around the peninsula (Fig. A.1).

A.2 SCIENTIFIC OBJECTIVES

Over the field seasons, collaborative research was conducted during the time spent mapping the coastal fiords and inlets of Cumberland Peninsula. With a multibeam bathymetry echosounder the seabed was mapped in high resolution for three purposes. The first objective was to test out a hypothesis put forward in the 1970's that suggested a lowstand sea level would be found along the easternmost fiords of Cumberland Peninsula (Pheasant et al., 1973; Dyke, 1974; Miller et al., 1974; Dyke, 1979; Andrews, 1980; Clark, 1980). These surveys were aimed at discovering and documenting submerged shorelines, such as delta terraces, boulder barricades, and beach terraces. These geomorphic features are indicative of a low sea-level stand within the past 8,000 years, and will help to better constrain the submerged sea-level history and crustal response of the region. The second objective was to create baseline bathymetric charts for safe access corridors and anchorages for ship traffic. And the third objective was in support of fisheries habitat mapping, including baseline maps of the locations of T. Siferd's previous research on clam abundance, in order to better understand and map the regional benthic habitat. The purpose of this report is to provide an overview of all the target locations mapped, and to document the geomorphic features that provide insight into the lowstand hypothesis. For the purpose of this report, the subsequent target surveys will only refer to the first of these objectives.

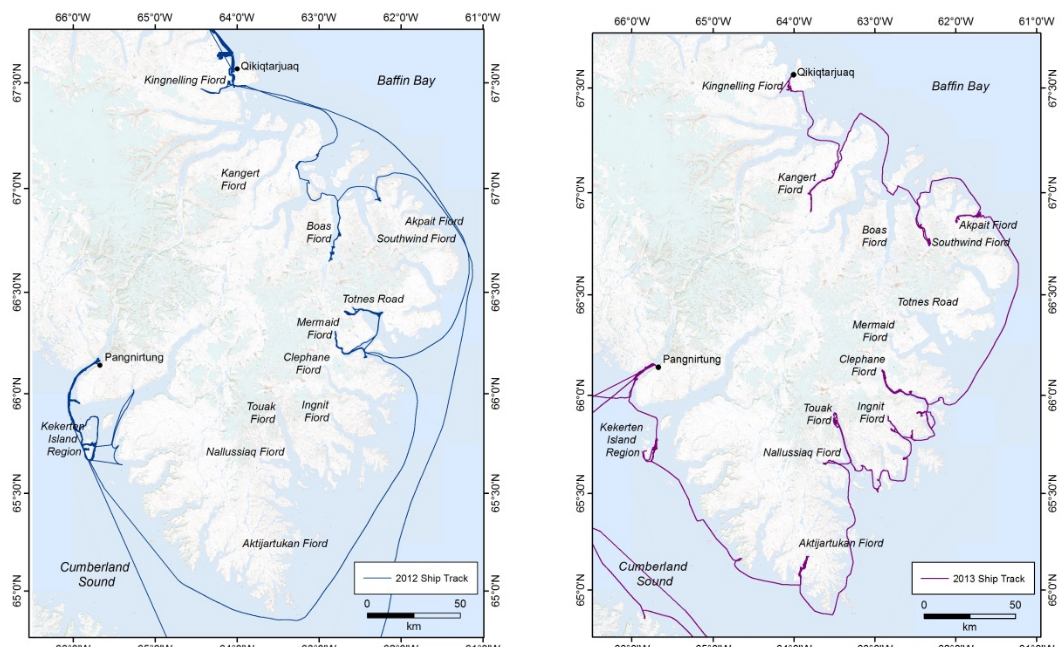


Figure A.1: A) Ship tracks from 2012, B) Ship tracks from 2013.

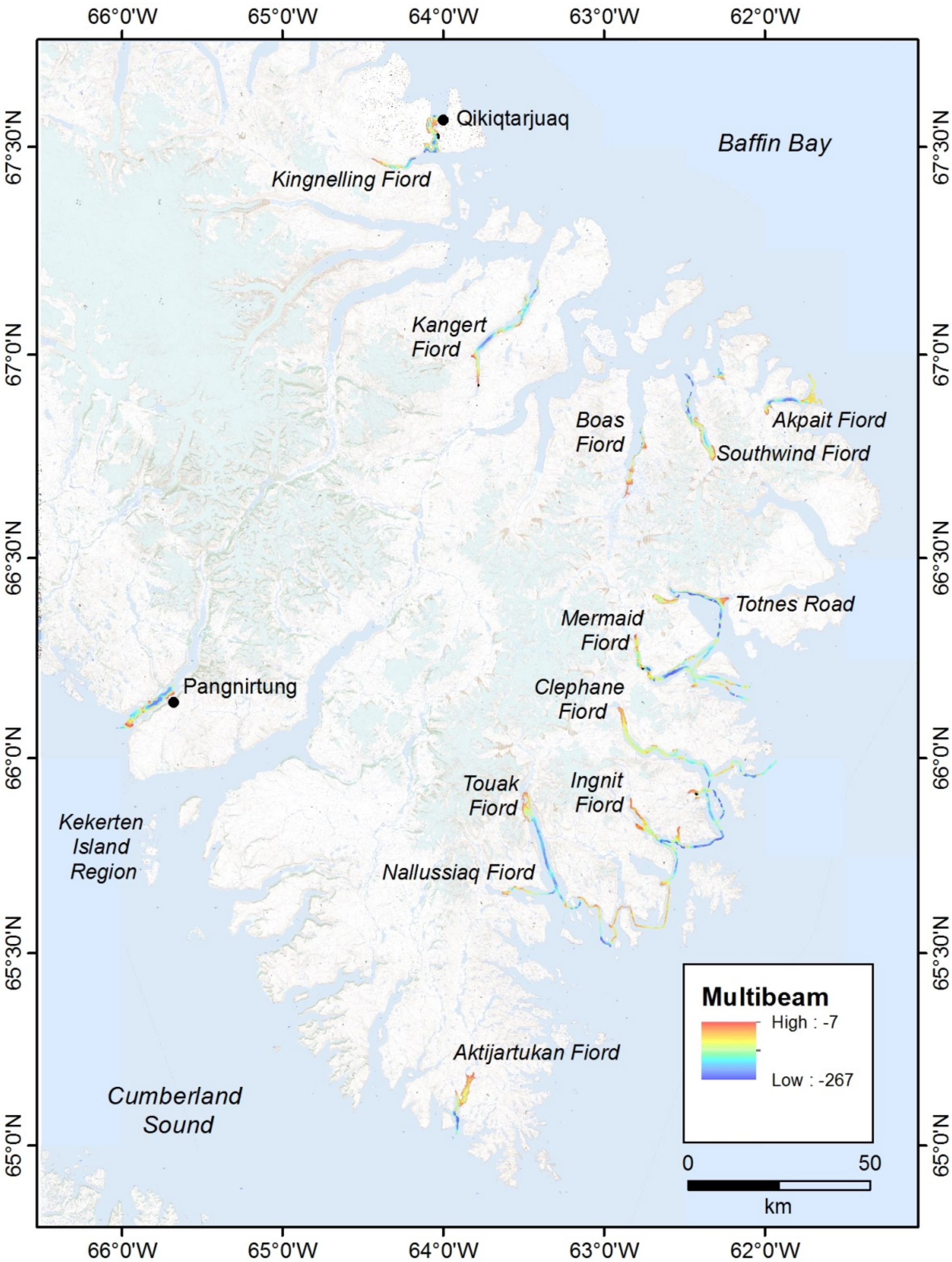


Figure A.2: Location map of Cumberland Peninsula, eastern Baffin Island, including all the multibeam of the sites mapped from both the 2012 & 2013 field season. Only the names of known fiords are included with the locations.

A.3 NULIAJUK OCTOBER 2012

A.3.1 CRUISE PERSONEL

Cecil Bannister	Captain
Robert Noel	First Mate
Kevin Hewitt	Crew member
Levi Ishulugaq	Crew member
Denise Malliki	Crew member
Anton Starby	Crew member
Beth Cowan	Memorial University, Department of Geography
Don Forbes	Memorial University, Department of Geography
James Muggah	University of New Brunswick, Ocean Mapping Group
Anand Hirogi	University of New Brunswick, Ocean Mapping Group

A.3.2 DAILY LOG

(Time in UTC)

Day 1: Saturday October 6, 2012

- Ocean Mapping Group on board from Clyde River
- Anchor up at 1130h
- Pick up Don Forbes and Beth Cowan at 1200h at Qikiqtarjuaq dock, by community member Joshua.
- Anchor up at 12:30h and continue mapping from Qikiqtarjuaq northwest until just past Akuliaqatta Bluff creating a grid for clam habitat
- CTD casts done
- EM3002 multibeam echosounder problems, take 5-10 min to connect again. Not sure of the problem, have emailed the EM3002 makers. Occurs approximately 4 times a day.

- Anchor dropped at 23:30

Day 2: Sunday October 7, 2012

- Anchor up at 11:30
- Began mapping Broughton Channel. Mapped a grid south of the tombolo, on the west side of the channel, and Broughton Harbour. Filled in the previous gaps in Amundsen and earlier Nuliajuk multibeam data, along the possible boulder barricade on the east side of the channel, and in front of the Qikiqtarjuaq harbor.
- Found boulder barricade at 15-16 m depth along east coast, and terrace at 16-17 m on the west coast
- One shut down of the multibeam at ~14:30, but James downloaded new Firmware software and since it has been working fine.
- Anchor dropped at 21:30

Day 3: Monday October 8, 2012

- Anchor up at 11:15
- Mapping to infill Broughton Harbour and southern Broughton Island as we wait to drop Anton off in Qikiqtarjuaq. S Broughton Island is supposed to have a good clam habitat, was very rocky and steep.
- CTD cast (15:00 & 18:30)
- Mapped Kingnelling Fiord and within Broughton Harbour and southern Broughton Island. Perhaps a boulder barricade at the northern tip of mapped grid in Broughton Harbour, though need to see the final map. Looks to be dispersed boulders along the edge, though no terrace.
- Kingnelling Fiord was expected to have a submerged delta at the head, but no evidence of that. Perhaps still has a sediment source that has graded it to present sea level.

- Thought we would be fueling today, but delayed until tomorrow due to holiday.
- Anchor down at 23:20

Day 4: Tuesday October 9, 2012

- Fuelling and grocery run in Qikiqtarjuaq- with the zodiac and local community boats.

Day 5: Wednesday October 10, 2012

- Anchor up at 0828h
- Transit to Merchant's Bay (~5.5 hr), precipitous slopes on mountains to south (Iqitarjuaq Island & Quikiavik Island) and high cliffs on southeast corner of Broughton Island.
- 2000h Mapping west coast entrance of Bay (2 previous GPS locations from clam divers), close to the shore. Appear to be bedrock shoals with steep slopes. Eastern site has a couple of small coves with gravel beaches- one with very small lagoon.
- CTD cast
- Anchor down at 21450h around the Duck islands

Day 6: Thursday October 11, 2012

- Anchor up at 1045h
- Transit around the south of Duck Island
- Transit to Boas Fiord
- 1400h Mapping grid cove, where previously recorded submerged delta therefore nicknamed Giffs Cove. Found the lip to be at ~35 m depth, need to see final data. Appears to be an inner shelf as well, with a lip at ~30 m depth.
- CTD scan (2045h)
- Transit over a terraced drop off at the head of Boas fiord, which then was mapped as a delta terrace ~30-35 m depth.
- CTD (2115h)

- Camera site 1 & 2; Grab site 1, 2 & 3. Didn't take final camera coordinates, only at the start of the transect. The lights were too bright and therefore obscured the surface.
- Anchor down at 2300h

Camera

Transect 2012-1

Start: 0:00:00:00, End: 0:04:50:00

Transect 2012-2

Start: 0:06:09:00, End: 0:11:51:02

Day 7: Friday October 12, 2012

- Camera down at anchor with the light covered in parchment paper, which seemed to work great. Camera site 3.

Camera

Transect 2012-3 (1050h)

Start: 0:00:00:00, End: 0:05:43:21

Medium-coarse grained sand with scattered gravel (subangular) and spotting of algae clusters upon a flat bottom. Scattered benthic organisms- urchins, brittle stars.

- Anchor up at 11:05
- Transit out of Boas, broadening mapped corridor, stopped to fill in the end of Boas.
- Transit to sill, to chart the barrier for other ships to enter the fiord
- Transit to "Giffs Cove." Camera site 4 & 5; Grab site 4 & 5 (coordinates were taken this time, when camera was on bottom and when it was hauled up)
- Within the inner shelf (sample 4) & outer shelf (sample 5)

Camera

Transect 2012-4 (1454h)

Start: 0:00:00:00, End: 0:08:12:50

Transect 2012-5 (1519h)

Start: 0:11:19:13, End: 0:18:05:10

Fine sediment (silt-clay?) covered by a brown algae and shell hash. Uncommon boulders (20-50 cm diameter, subangular-subrounded), some of which are encrusted in calcareous algae. Benthic organisms- brittle stars, urchins.

Interesting unknown features, flat white disc like features (10-50 cm diameter), some are elongate too. Close up, these look like little ice rinks, Don suggested they could be gas hydrates (Fig. A.3).

Figure A.3: Screenshots from Transect 2012-5 of unknown white discs, possible gas hydrates. The scale is marked by a 10 cm distance between laser beams.

- CTD 1615h
- Transit to unnamed cove just east out of Southwind fiord, previous clam exploration done- no mapping. Grid mapped of submerged delta at -45 m. Levi nicknamed cove- Qingakallak cove (Big Nose).
- CTD cast 2136h in the cove.

- Transit to anchor site, but couldn't get there because of bad weather so returned to cove for anchor
- Anchor down at 2145h.

Day 8: Saturday October 13, 2012

- Anchor up at 0830h
- Transit past Cape Dyer into Exeter Sound, large ~15 s swells from the southeast.
- 2000h transit up Mermaid Fiord. Searching for delta terrace, but none. Anchor at the end of Mermaid Fiord.
- Anchor down at 2205h

Day 9: Sunday October 14, 2012

- Anchor up at 1205h
- Rough water, therefore staying close within Mermaid's fiord. High wind, loess over sandur.
- CTD cast 1215h
- Transited to a cove in front of Mount Rayleigh, and continued into Totnes Road. Possible terrace at 44 m, but no subbotto penetration and lower angle front. 1415h, stream entering on left bank draining lake higher up is incised and has some sand on upper beach on the up-fiord side. Small subaerial alluvial fan (coarse gravel) extends out to form submarine fan which we picked up at 20 m depth
- Continued on to the northwest coves, remnant glacial tongue high up in the valley to the right with ouldery alluvial fan extending out into the very steep submarine fan. Valley to left is hanging with small stream outlet on west side of fan. Knudson showed slumping on submarine fan slope giving way to draped stratified glaciomarine deposits in deeper water. Too windy to keep surveying.

- CTD cast 1900h
- Anchored in southern cove of Totnes Road "bear cove"
- Anchor down at 2300h

Day 10: Monday October 15, 2012

- Awoke to find us lying very close to shore off outwash fan at head of the fiord beside a small iceberg that grounded during the night.
- Anchor up at 1030h
- Anchor down at 1040h
- The winch broke down. Had to rebuild the key for the sprocket wheel, spent all day with maintenance. Nicknamed the cove "bear cove," observed 7 polar bears here, and continued counting the next day.
- After dinner: Camera site 6; Grab site 6

Camera

Transect 2012-6 (2120h)

Start: 0:00:00:00, End: 0:07:27:11

Fine sediment (silt-clay) drape, with many benthic organisms (brittle stars and many unknown to us). Difficult vision, lots of suspended sediment. Uncommon boulder (20 cm diameter). Small bumps and divots in surface (10 cm wide) within an overall flat surface, all draped in fine sediment.

Day 11: Tuesday October 16, 2012

- Anchor up at 1030h
- CTD 1210h
- Mapped inner basin "bear cove". Showed active prodelta slope on fan at head of fiord.

- Mapped just south of Mount Raleigh ("bad weather cove")- possible terrace, not very distinct, picked up high winds again.
- Camera site 7 & 8; Grab site 7 & 8

Camera

Transect 2012-7 (1529h)

Start: 0:00:00:00, End: 0:05:35:23

Starts out in large kelp on top of boulders (average 70 cm diameter) encrusted with calcareous algae with cobbles, within medium sand and shell hash. Patches of algae covered fine sediment (silt-clay?), similar to the surface of transect 2012-5.

Transect 2012-8 (1615h)

Start: 0:05:35:24, End: 0:10:40:02

Many benthic organisms- sea spider, brittle stars, crinoid, and unknown corals (<10 cm). Fine grained sediment (silt-clay) upon a smooth flat surface. As move inshore, scattered kelp fans and boulder (15 cm diameter).

- Mapped cove with barrier within southern Exeter- possible erosional terrace? Didn't get enough coverage of it though to get a good profile of the feature.
- CTD 2030h
- Anchor down at 20:30 pm at the head of Mermaid's Fjord

Day 12: Wednesday October 17, 2012

- 1115h Camera site 9, poor light on first drop, replaced batteries for second; Grab site 9 in Mermaid's fjord.

Camera

Transect 2012-9

Attempted twice, first the lights were too dim. Batteries were replaced.

Start: 0:03:02:03. End: 0:11:44:11

Fine sediment (silt-clay) with lots of suspended sediments, therefore low visibility. See the slight definition of wave crests with benthic track marks. Upon some wave fronts are small gully-like features.

- Anchor up at 1205h, did a short leg across fiord to look for deeper channel opposite moraine, but delta front appears to go all way across.
- Transit to Cape Mercy, through the night transit to Kekerten Island, substantial swells off Cape Walsingham

Day 13: Thursday October 18, 2012

- Reach Kekerten Island at 1230h , began survey line around islands.
- CTD cast at 12h30h
- Mapping around the islands, went into the old whaling station harbor at 1715h, looking for ship wreck, though not found.
- Set course for Pangnirtung.
- Anchor at Pangnirtung at 2400h, saw aurora overhead throughout evening

Day 14: Friday October 19, 2012

- Water glassy with grease and pancake ice developing.
- Anchor up at 1100h (high tide)
- Mapping the entrance of the Pangnirtung river to the harbor for coastal hazard research, ran several lines showing large numer of channels and chutes on the delta and elsewhere.
- Docked at the new wharf at 1400h
- Refueling and grocery trip at Pangnirtung. Johnny Mike of the HTO came on board and talked about how supportive he is of the Nuliajuk and seabed mapping.

- High tidal range, by the time Don Forbes and Beth Cowan left the ship at Pangnirtung 2100h, they had to climb to the top of the ship and then use a ladder to get onto the wharf.

A.3.3 ISSUES

There were some issues at the start from Clyde to Broughton Channel with the Multibeam software. James Muggah emailed the company and by October 7th was able to download the updated Firmware software. No other software issues since then.

Some changes of course were made due to oncoming bad weather. This occurred in Merchant's Bay and Exeter Sound. The transit around Cape Dyer occurred on October 13th due to strong winds forecasted for October 14th.

Within "Bear Cove" at the end of Totnes Road the anchor winch broke down, the key for the sprocket wheel had split in two. Therefore a day was devoted to repairs, and no mapping or transit took place. The winch is repaired though it will need maintenance upon return.

A.4 NULIAJUK OCTOBER 2013

A.4.1 CRUISE PERSONEL

Cecil Bannister	Captain
Anton Starby	First Mate
Levi Ishulugaq	Crew member
Kevin Hewitt	Crew member
Robert Bennett	Crew member
Dr. Trevor Bell	Memorial University of Newfoundland

John Hughes Clarke Ocean Mapping Group, University of New Brunswick

James Muggah Ocean Mapping Group, University of New Brunswick

A.4.2 DAILY LOG

(Time in UTC)

Wednesday, October 2, 2013

- John Hughes Clarke, James Muggah, Trevor Bell & Cecil Bannister arrive in Qikiqtarjuaq.
- The Nuliajuk was refueling in Qikiqtarjuaq.

Day 01: Thursday, October 3, 2013

- Arrive at wharf for pickup with equipment, 1200h.
- Nuliajuk stuck on a shoal in the harbour, waited until high tide to board, in the mid afternoon.
- 1900h Nuliajuk was free of the shoal and we headed south to the clam habitat mapping sites (Broughton Harbour and Southern Broughton Island).
- 2030h Issues with one of the multibeam's sensors (heave) and so trying to rectify that before doing a system test.
- 1730h Started mapping Broughton Harbour, running up along the main coast and down around the small island.
- 2250h Qik Line 004 – appearance of terrace at about 20 m water depth that may be of shoreline or bedrock origin. We are tracking as shallow as we can go to pick up the shallow Siferd samples.
- 0230h – finished for the night – completed Broughton Island side, reaching to the 10 m contour in places.

Day 02: Friday, October 4, 2013

- Anchor up at 1000h. John ran some tests in the middle of the channel and then we started to fill in the coastal gap along the southwest corner of Broughton Island (1015h).
- 1130h finishing last north-south line and then moving around corner to do some east-west lines and one final line along the inner edge of existing coverage on southern end of island. Finished first line at 1150h. Steep coast here with alternating bedrock outcrops/ridges normal to the shore and shallow troughs, possibly sediment filled. Very steep nearshore
- Finished at 1300h and then headed due south to Kangert Fiord. Deepwater here up to 400 m water depth.
- Travelled through Canso Channel and entered Kangert Fiord at 1600h.
- Kangert Fiord is deep in the middle as we enter it along the western side. Steep bedrock walls give way to steep seabed – 270 m deep at 100 m from shore. There was a sill at the mouth – about 100 m deep along our track – and had obvious bedrock affinities above water.
- About 1730h we crossed the fiord as it became shallow enough and we mapped a small tributary valley mouth that enters the fiord from the east.
- There is a noticeable break in slope in a fan-shaped feature at the mouth of the valley. The break of slope is around 20 or so metres and it slopes up to at least 13 m.
- There is a large moraine in the valley that swings northwards along the main fiord wall. There is also a bedrock sill that has some dramatic topography before dipping below sea level. A large iceberg was hung up on it.
- 1800h – arrived at large tributary valley two-thirds down fiord on western side where there should be significant input of sediment now and in the past. The

tributary valley consists of a hanging valley that forms a waterfall that ends on the lower valley bottom close to the modern shoreline. There is a nice breached end moraine loop at the bottom of the waterfall, a large alluvial fan at the base of a rock canyon to the south and a protalus rampart on the north side below some bedrock cliffs. Took a CTD cast before running lines perpendicular to shoreline in the cove.

- The cove has a remarkably flat surface at 16 m towards outer half, rising gently shoreward to our limit at 10 m. The delta slope descends to at least 60 m water depth and the basin bottoms out around 130 m. We are starting to see a 1-3 m depression behind the flat edge.
- 2100h – finished mapping at site by running along the lip. We could see the closed depression and a slide ridge right off the front of the protalus rampart. Now heading to fiord head to see what is there and to anchor for evening.

Day 03: Saturday, October 5, 2013

- 1000h – started mapping the head of Kangert Fiord.

Camera

Baffin October 2013-01

Transect 13-01: At about 1225h we deployed the camera on the shallowest terrace at about 10-11 m water depth and then drifted down fiord across and into one of the depressions. The terrace had a surface lag of cobble to boulder sub-rounded gravel with a thin silt cap on the gravel clasts [first appeared at 00.03.15 and then again at 00.07.00; still in gravel when the video came back up]. Frequent to occasional sub angular boulders with kelp attached. Once you drop down into the depression (around 00.13.00) the suspended material increases dramatically and you loose the gravel veneer.

Start time: 00.00.00; End time 20.34.08; Duration: 20.5 mins

We lost some of the recording when the camera lost its camera signal (blue screen; 00.07.34 to 00.08.42).

Transect 13-02

John's logging of transect began when the camera was on the bottom (this was a better way to synchronize his logging and the camera transect). We logged for about 22 minutes. We observed overall finer gravel than transect nearer the fiord head, with frequent subangular boulders. Easy to see gravel as less draping of finer mud – more current flow towards edge of terrace. Material becomes more washed the closer to the lip (0:18:20). Once we dropped over lip at 0:20:30, some very coarse deposits and more relief than I would have expected – perhaps related to iceberg ploughing and grounding.

Start: 00:00:00; Bottom: 02:09; Stopped: 24:04

Transect 13-03

We transited down the fiord to the 16-m terrace below the tributary valley on the western side of the fiord. I wanted to image the terrace surface and we drifted across the terrace for about 13 minutes. The surface was thickly covered with an algal mat and hence could not see surface – we tried twice with the break point at 07:14. Occasional large subangular and angular boulders, and lots of brittle stars, sea urchins, etc. Water was fairly turbid with suspended sediment.

Start: 00:00; Bottom: 00:25. Stopped: 13:16.

Finished Tape: Baffin October 2013-01

- 1700h at Recce Site #1 to survey one line on the inside of fan that we quickly mapped yesterday, as we transit out of the fiord.
- 1830h leaving Kangert Fiord and heading north to go around headland into Merchant's Bay.

- Arrived and dropped anchor in Delight Anchorage by 2430h. Weather forecast is for 40 knot northerly winds by Tuesday so that gives us 2 days to map Southwind Fiord and Unnamed Fiord, and be around Cape Dyer by Monday night.

Day 04: Sunday, October 6, 2013

- 0830h – depart Delight Anchorage for Southwind Fiord.
- We are tracking up the west side of the fiord – there are no clear tributary valleys that might have deltas developed along the coast so we will make a transect up to the fiord head and back out again hugging the coast at the 50 m isobath.
- A beautiful clear sunny day again at -6.6 degr Celsius. Ice starting to form in the freshwater layer at the head of the fiord.
- We reached the upper part of the fiord around 1030h. Almost immediately we lost the subbottom profiler.
- Our mapping consisted of mostly deglacial and proglacial subaqueous features at the head of the fiord. Lots of former tidewater and near-tidewater glacier termini that may have occupied the fiord head in the early Holocene.
- Subaqueous channel system recorded on the multibeam, with in-channel bedforms recording a dense undercurrent. We also see some nice sediment failures both from overloading of the seabed slope and sub-aerial mass wasting. No sign of any marked delta terraces.
- On the way out we encountered some uncharted islands and shallow shoals – charted some of these.

1355h

Locations of side valley moraines on east side of Southwind near head:

(1) Start: 66°46.500   62°19.408

Outflow: 66°46.343   62°19. 285

End: 66°46.245   62°19.189

(2) Start: 66°45.939   62°18.960

Outflow: 66°45.794   62°18.916

End: 66°45.360   62°18.650

- 1600h –leaving fiord, en route to Akpait fiord.
- 1900h passing Durban Island and the Fox E radar site cleanup.
- 2215h – dropped anchor for evening at head of Akpait Fiord. From what we have seen so far, it is a typical fiord with multiple basins and sills, the latter not too shallow. The basins look featureless and flat – probably full of mud. Did not get a chance to map any of the shallow head areas – looking at the main head and a tributary arm too.

Day 05: Monday, October 7, 2013

- 1000h –CTD drop. Started mapping Akpait Fiord
- 1130h – finished mapping of main fiord head – nothing to report with regards to submerged sea level indicators; only some minor channel and bedforms near main stream inflows.
- 1200h – finished second inlet.
- When we entered the fiord we ran across what we thought were two sills at about 50 m water depth. The inside edge of both of those sills had a rounded semi-circular form that reminded John of the shape of some submerged spits on the BC coast. On the way out we expanded on the coverage and indeed did reveal two shore-parallel elongate features with high backscatter on their upfiord ends and small channels on their landward side. The depth of these features proved to be about 50 and 30 m.

We dropped the camera to try to groundtruth the backscatter. We ran from deep to shallow as we drifted eastward across the lowest feature. The low backscatter proved to be a fine sediment drape with shells and shell hash and occasional boulders. Over the high backscatter we saw a coarse rounded to subrounded gravel with some angular boulders and only a thin discontinuous fine matrix. On top of the feature we went back into a fine sediment drape. I think it is good evidence for a gravel spit that built upfiord from a sediment source along the northern shoreline of the outer fiord and with the incredible energy of the open ocean of Baffin Bay.

Camera

Transect 13-04

Start 0:00:12 on bottom at 64 m

Drifting ENE from deep to shallow.

High backscatter starts at 0:10:45 and ends at 0:16:49

Transect ends on top of feature at 0:23:43

- Mapped an incredibly flat smooth sill area at about 50 to 51 m. This would be called a sill plain but why is it accordant with the palaeo-sea level? It would imply either pure coincidence or a truncated unconsolidated sill feature that was trimmed by the low sea level. We did not have time to run a camera over it but I suspect it would have been fine sediment. It suggests that the 50 m spit is only a minimum estimate of the lowstand depth.
- 1600h Left Akpait.
- En route to Cape Dyer, large valley side talus slopes were observed to have eroded at the coast. Suggests that they built out at a lower sea level and are now being eroded back as sea level has risen.

- 2330h Arrived at Clephane Bay. Snow had picked up by then. We anchored behind an island at the mouth of the bay.

Day 06: Tuesday, October 8, 2013

- 1200h – Anchor up, at mouth of Clephane Bay and headed upfiord to first target. Arrived and completed CTD at 1330h. Captain wants to anchor in here tonight because of winds (40 knt) and seas (6m) outside. Quite the change from the clear sunny conditions of the last 5 days. -1.5 degr C
- Mapping the 20 m contour in small cove to get some sense of the bathymetry and morphology. The fiord is deep in the middle here, around 150 m. There is a steep slope up to the coastline and a break of slope at about 20 m but no distinctive depositional feature associated with the local delta. Note that the fluvial systems here reach the fiord from high relief terrain down steep slopes and sometimes through local lake systems. I am not sure that this topographic context combined with deepwater close to the shore facilitates the development or accommodation of delta systems that would be preserved on the seafloor.
- Second target upfiord on same northern side. Going from about 100 m water depth in main fiord channel that extends close to shore. The delta feature is really a fan delta that has quite a slope on it as it emerges from a narrow bedrock canyon or channel and descends abruptly to the shoreline. As the offshore slope is equally steep, there is not enough space for the development of a classic delta at lower sea level. The sediments just spill into deeper water. There is a feature on the steep slope at about 33 m water depth that is shore parallel – is it some sort of erosional notch? It does not have a positive profile.

- As we transited up the fiord in very strong winds and low visibility and snow, the seafloor shallowed and we realized that the modern delta edge is much farther out the fiord than the nautical charts or topographic maps suggested. We looked out the window to see boulders sitting on a sandy beach or shorebirds feeding on a sand spit! Found a possible esker, mass wastage features from sidewalls, possible terrace features but nothing too convincing.

Day 07: Wednesday, October 9, 2013

- 1100h Anchor up. Filled in along the edges of the coverage and tucking closer to side valleys where there may be terrace features.
- 1400h Leaving Clephane. Unfortunately we had to turn back because of big seas and wrong wind direction for entering Ingnit Fiord. Instead we entered small bay on outside of Celphane – informally known as "Pause Bay" at 1645h and mapped the head until 2000h. We found a possible incised fiord head deposit down to around 30 m or so, but no well defined terrace.
- 2130h Anchor down.

Day 08: Thursday, October 10, 2013

- 1100h A nice sunrise this morning and clear sunny conditions. Seas are much more subdued – 2 m or so. Attempt at Ingnit Fiord.
- 1330h Arrived at Ingnit Fiord, and turned into Inglis Bay around 1400h
- Mapped Inglis Bay - and were able to transit the whole way to the head but there did not appear to be anything obvious in there related to past sea levels.
- Transited across fiord to an embayment halfway up main fiord on south side. A narrow long inlet that has various depressions and flat terraces within it. Need to see full seabed bathymetry for full picture.

- Mapped lines in and out at the head of Ingnit Fiord, but not much related to sea level. Some shallow sills along entrances.
- 2200h Arrived at Sakiak Fiord to anchor in a small cove near the mouth.

Day 09: Friday, October 11, 2013

- 1100h Anchor up– a bright and sunny and calm morning. -4.1 degr C
- 1500h had some difficulty getting through islands close to shore so detoured around them farther offshore.
- GPS and heading issues which delayed for several hours.
- 1730h approach first unnamed target to north of mouth of Touak Fiord
- Local shoreline here has some well-developed beaches because of open fetch – could there be some submerged features preserved here? It was the same at the next adjacent inlet too.
- 2330h Anchor down, in Touak Fiord on southern side. Position at 65°52.448N 63°30.185'W

Day 10: Saturday, October 12, 2013

- 1230h-Started mapping in Touak Fiord. Looking at channels that carry meltwater and sediment out of these coves into the main fiord. Finished at 1600h.
- Heading upfiord to map the suspected edge of the trough fill not far from this cove. Nothing as obvious as at Kangert for a lowstand delta, although we did run up on the fiord-head delta. Mostly an iceberg impacted slope and a defined bottom channel from the fiord head.
- Went to Nallussiaq Fiord. Mapped a small side valley cove halfway along and then went to the head, which looks mostly sediment starved. Finished at 2330h.

Day 11: Sunday, October 13, 2013

- 1000h Departed Nallussiaq Fiord. Mapping inside route to Aktijartukan Fiord around Cape Mercy. Slightly above zero Celsius outside.
- 2100h Arrived at Aktijartukan Fiord head after mapping en route. The transit was pretty good, although there was a swell for much of the way. This fiord is one of those identified by GN's Fisheries for seabed mapping because of the potential/actual char fishery.

Day 12: Monday, October 14, 2013

- 1200h Anchor up. Levi and Trevor worked on the zodiac with my Lowrance depth sounder. The goal was to infill some single beam tracks in shallow areas inside the 20 m contour. The sounder worked well but we needed to remember to start each sounder log with a waypoint because the sonar log file contains time offsets from the start, not actual time. The waypoint gives you either local or Zulu time. John and James were able to read the *SL2* files produced by the Lowrance sounder and produced tracks and then depths. The time offset allowed a tidal correction.
- Trevor used OMG's YSI CDT at a couple of sites near the river mouth.
- Attempted camera to record some seabed but didn't work (blue screen issue, which might be related to a bad connection in the cable near the camera itself). Saw a herd of about 22 walrus at the mouth of the innermost basin. This makes me think that there must be lots of clams about and considering that we are mapping a fair chunk of these two innermost basins, there is a potential dataset here for clam habitat mapping. The highest backscatter appears to be at the narrow, constricted channel between the two basins.
- 2200h Finished.

Day 13: Tuesday, October 15, 2013

- 1200h Anchor up. Continued mapping in Aktijartukan Fiord, to show Janelle what full mapping of an area can produce. Levi and Trevor used the zodiac to map shoals and the littoral gap. Tried the camera again but the issue appears to be with the cable near the camera.
- 1800h transit to location next to Queen Cape for an overnight anchorage (65°09.926'N 64°39.821'W). Sill at anchor cove below Queen Cape has a very flat broad sill with little relief at ~28 m asl.

Day14: Wednesday, October 16, 2013

- Transit to Kekerten Island Region

Day 15: Thursday, October 17, 2013

- Set off at 1100h in the zodiac to run some camera transects over the small ketch wreck in Kekerten Harbour.

Day 16: Friday, October 18, 2013

- Transit to Pangnirtung
- Mapping of Pangnirtung outer sill

Day 17: Saturday, October 19, 2013

- Trevor Bell departed the Nuliajuk and flew out of Pangnirtung, NU.

A.5 ISSUES

Due to the location of this fieldwork, weather is always an issue. This cruise experienced some pressure from the weather to make it around Cape Dyer, as well as during some transects out of the bays.

There were some issues with the underwater camera, since it would result in a blue screen. This is thought to be related to a bad connection in the cable near the camera itself, and will be shipped back to the manufacturer for further maintenance.

On October 6th, the KNUDSEN chirp 3200 echosounder 3.5 kHz stopped working. This is believed to be due to a power failure, but was unable to be fixed in the field. Therefore there is no subbottom data for the rest of the cruise.

A.6 EQUIPMENT

The geoscience/hydrographic equipment was installed upon the *MV Nuliajuk* in 2012. For the two field seasons the equipment that was used:

- F-185 IMU (SN: F0505026) from Coda – inertial measurement unit for the motion
- correction (pitch, roll and heave) of sonar data
- C&C Technologies CNav 3050 DGPS
- C&C Technologies CNav 2000 DGPS
- Seatex MRU-6 (SN: 1532) – inertial measurement unit for the motion correction (pitch, roll and heave) of sonar data
- CTD: AML Oceanographic SVP&T (surface velocity profiler and temperature) sensor: SN7210 (up to 500m depth)
- Deep Blue Sea Pro Underwater Video System
- WILDCO Ponar grab sampler
- Sub-bottom Echosounder: KNUDSEN chirp 3200 echosounder 3.5 kHz
    - Frequency: 3.5 kHz
    - Software: SoungerSuite:EchoControlClient-2.64
    - Ship speed: average 4 knots, range 1-8 knots

- Multibeam Echosounder: Kongsberg EM3002 multibeam transducer (SN: 426) and transceiver (SN 1582)
    - Frequency: 300 kHz
    - Number of beams: 254
    - Width of beams: 1.5 °
    - Angle: 65 °
    - Software: SIS
    - Software for processing: OMG/UNB swath editor
    - Ship speed: average 4 knots, range 1-8 knots
- Single Beam Echosounder: Furuno FCV-30 & Furuno CH300 searchlight sonar
    - Frequency: 38 kHz
    - Bottom tracking: up to 1500 m depth

A.7 MAPPING LOCATIONS & PRELIMINARY INTERPRETATION

The following includes all the mapped locations from 2012-2013, catalogued geographically starting with Clyde River and then jumping to Broughton Channel and following the coast around Cumberland Peninsula to Pangnirtung Fiord (Fig. A.1). The processed and gridded multibeam data (1 m resolution) are obtained from UNB's Ocean Mapping Group, while the background topographic map are Toporama map sheets from the Centre for Topographic Information, Natural Resources Canada (Geogratis.gc.ca). Each mapped location includes an overview of the geographic location, an image of the multibeam data (with underlying hillshade effect), an image of the corresponding backscatter and a preliminary interpretation of the geomorphology. The subbottom echosounder did not penetrate into the subbottom sediments at many of the locations, and lost power for most of the 2013 cruise. Therefore the profiles are only included where they penetrated into the subbottom and where they add to the interpretation.

A.7.1 Clyde River

Clyde River is a Hamlet at the head of Patricia Bay, a side-entry fiord on the northern coast of outer Clyde Inlet. The river mouth has a submerged delta terrace, which was previously mapped to a depth of 2 m below sea level. The mouth of the river opens into the head of Patricia Bay, which was mapped during the first leg of the 2012 multibeam survey. The head of the valley has low relief, while down-fiord exhibits steep sidewalls, most strikingly on the eastern shores and at the mouth, which include many hanging valleys. The head of the fiord does not continue into a U-shaped valley, like most fiords, it becomes a low-lying plain covered in kettle lakes. This low-lying region meets up with the coastline adjacent to Baffin Bay. The river mouth has been inundated and includes many upstream ponded and kettle lakes in the low-lying region.

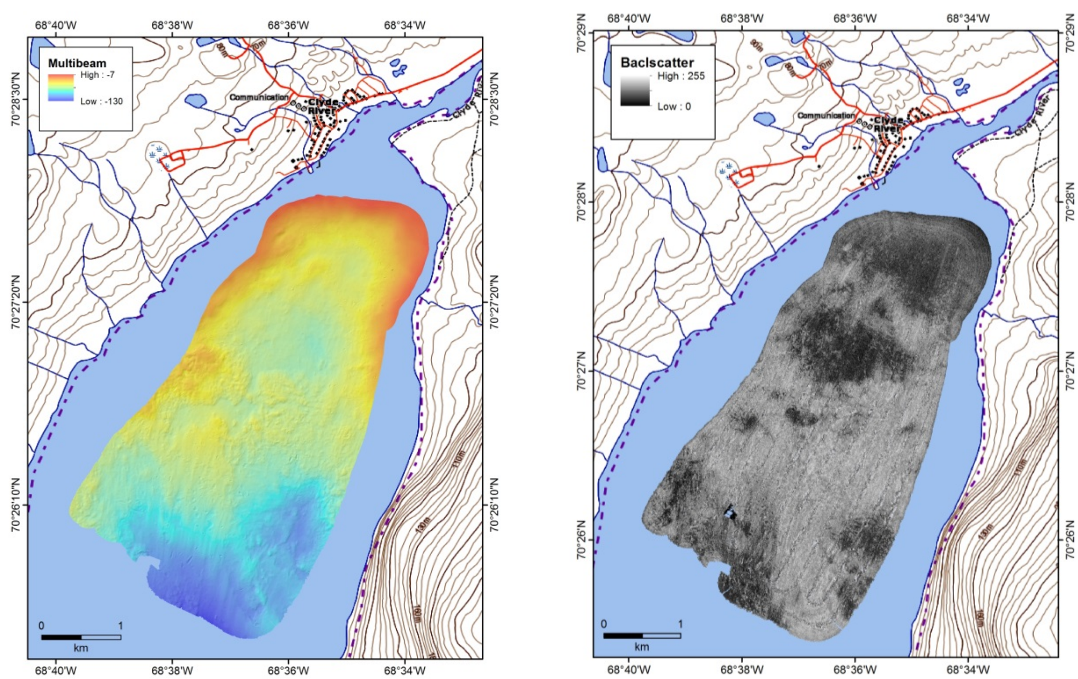


Figure A.4: Clyde River survey coverage.

Patricia Bay is made up of a basin that reaches a depth of -126 m at the southern extent of the surveyed region. From previous multibeam surveys a submerged delta terrace gives evidence of high sedimentation levels at the river mouth. Further south appears to be remnants of glacial material and scour lags on the seafloor. The head has an intermediate slope with evidence of slope failure upon the prodelta front. The sidewalls of the fiord seabed were not mapped, but likely the steep sidewalls continue below sea level at the mouth and up-fiord.

A.7.2 Broughton Channel

Broughton Channel is a marine water body that lies between Baffin Island and Broughton Island. Broughton Channel is open to Baffin Bay to the north, slightly enclosed by a tombolo, and opens to the south of Broughton Island to include Broughton Harbour, adjacent to the entrance basin of Kingnelling Fiord. The mapping focus for this channel was along the east and west coasts, within the vicinity of the Hamlet of Qikiqtarjuaq, and Broughton Harbour (Fig. A.5).

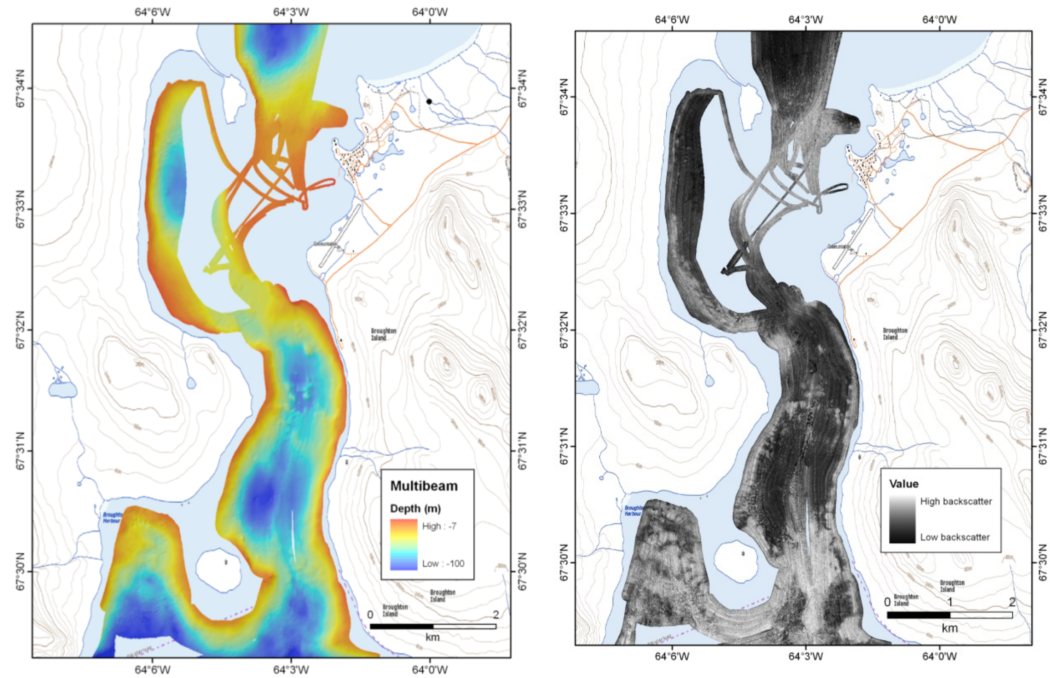


Figure A.5**:** Overview location map of Broughton Channel and Broughton Harbour.

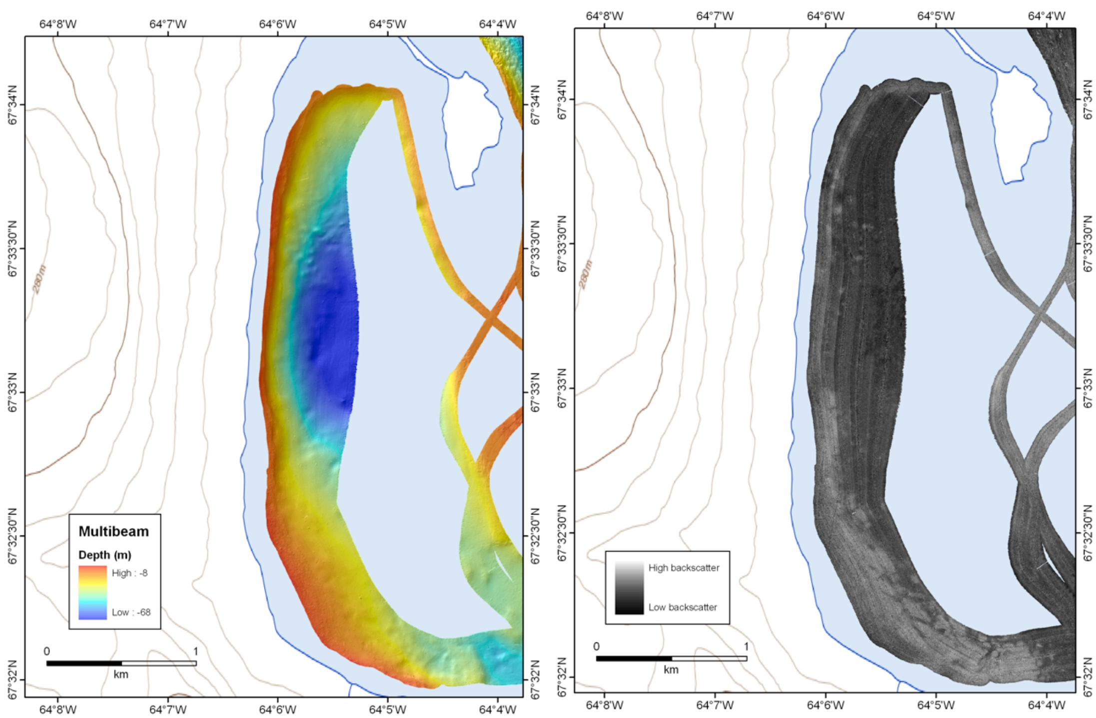


Figure A.6: Western coast of Broughton Channel.

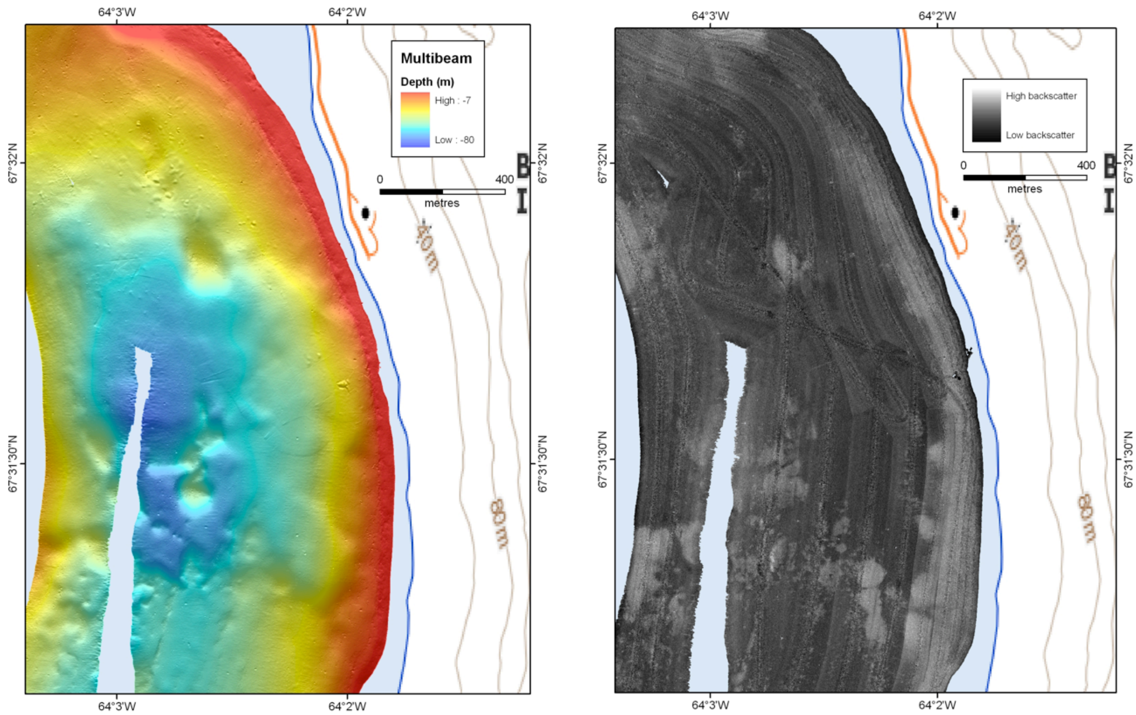


Figure A.7: Eastern coast of Broughton Channel. Location of boulder barricade at 16-18 m below sea level, parallel to the east shore.

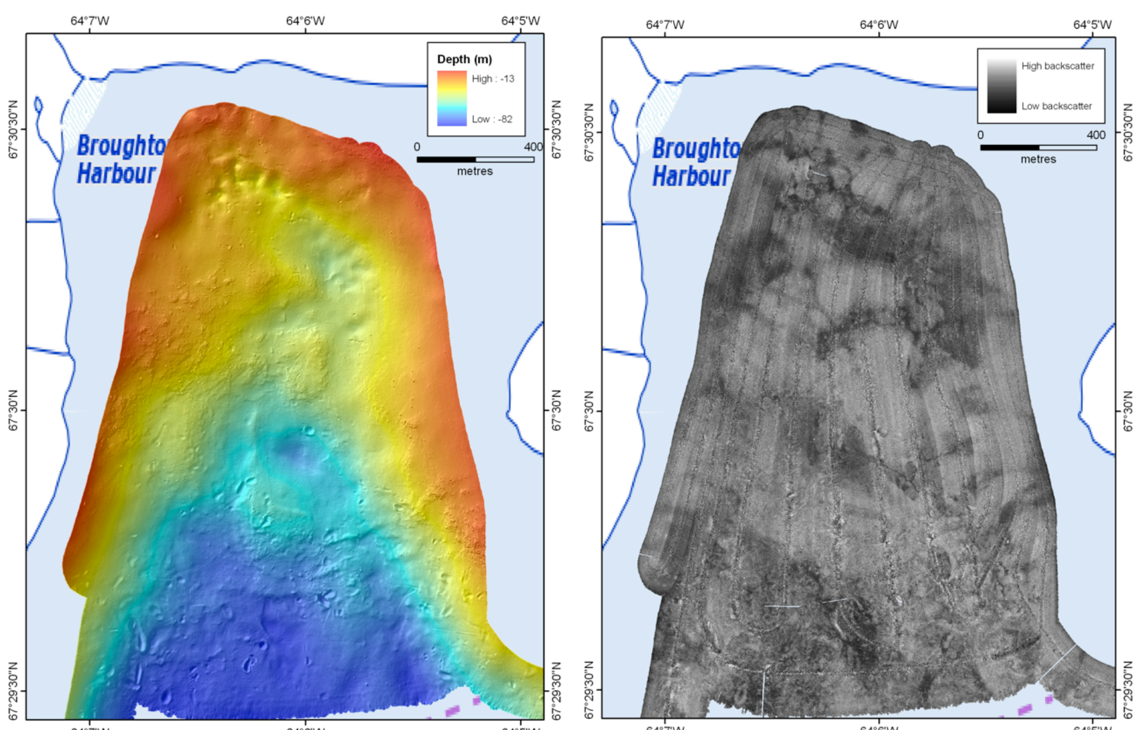


Figure A.8: Broughton Harbour.

The channel is approximately 2 km wide at it's midpoint, with it's deepest at 80 m below sea level within the inner basins, before dropping off into more open waters. The primary area of interest for this region was the discovery of a ridge running parallel to the eastern coast, which was interpreted as a boulder barricade (Fig. A.7). This feature is approximately 1.8 km long, is located at a depth of 16-17 m, and on average is 120 m from the coast. This is the only local that a submerged boulder barricade was discovered throughout this region. Along the western coast of Broughton Channel, on average 150 m from the shore, there is a break in slope at 16-17 m below sea level (Fig. A.6), though without a boulder barricade. As the coast wraps around and into the tombolo, this terrace feature progressively becomes a gradual slope from the nearshore to the basin. To the north, in between the tombolo island and the community is a shallow platform, with it's shallowest point at 12 m below sea level, but on average it remains at 14 m below sea level (Fig. A.5). This platform drops off into basins to the north and south at a depth of 17 m. Due to the presence of a tombolo, it is clear there is a source of sediment and longshore drift towards the east, it is unsure whether this platform may have been glacially deposited material that has since been a sediment catchment, or whether there is an alternative source of material.

Broughton Harbour has a maximum depth of 80 m below sea level, with no apparent terrace, or break in slope (Fig. A.8). Broughton Harbour is delimited to the east by an island, which is interpreted to have been a tombolo at a lower sea level. The waters were too shallow for further investigation, and were mapped up to a minimum depth of 14 m, which gives further evidence that this could have been a barrier during a sea level lowstand.

A.7.3 Kingnelling Fiord

Kingnelling Fiord is 16.5 km long and on average 1.3 km wide along an east-west strike, with steep bedrock cliffs at the mouth and more gently sloping bedrock and alluvium closer to the head. Along the sidewalls, remnants of cirques are observed as well as hanging valleys.

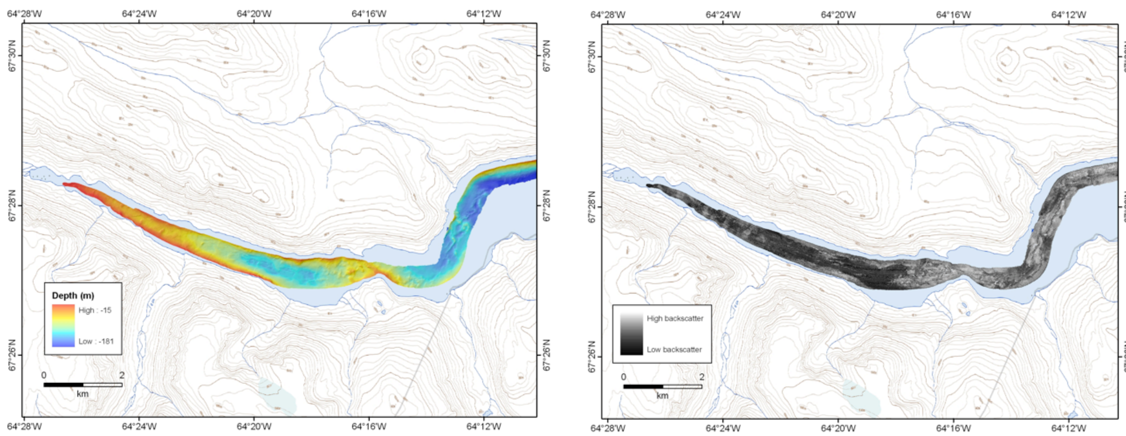


Figure A.9: Overview of Kingnelling Fiord.

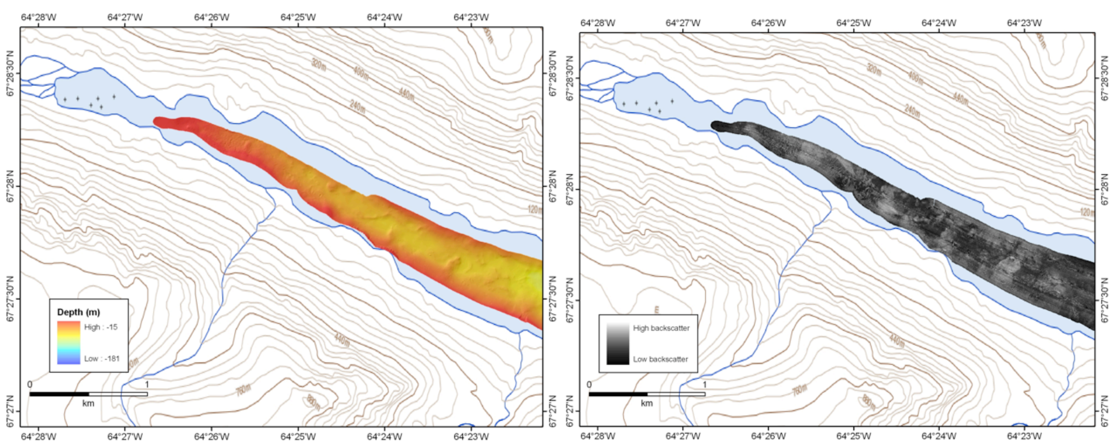


Figure A.10: Kingnelling Fiord head.

The steep walls of the fiord continue below sea level, with the deepest seafloor at 130 m within the inner fiord. Halfway along the fiord, there is an inner basin before a sill, which is likely a remnant of a recessional or terminal moraine (Fig. A.9). The outer fiord continues into deeper waters, up to 160 m, and includes a remnant of a seafloor (possibly a meltwater) channel that has not been sufficiently infilled. From the inner fiord up to the fiord head is a gradual slope, with occasional iceberg pit and wallow marks (Fig. A.10).

A.7.4 Kangert Fiord

Kangert Fiord is located to the east of North Pangnirtung Fiord, striking northeast-southwest approximately 45 km long, with an average width of 2 km. It includes some tributary valleys to the west and south, but is mostly contained by steep sidewalls, if not hanging valleys. The head of the valley joins with that of Padle Fiord to the south.

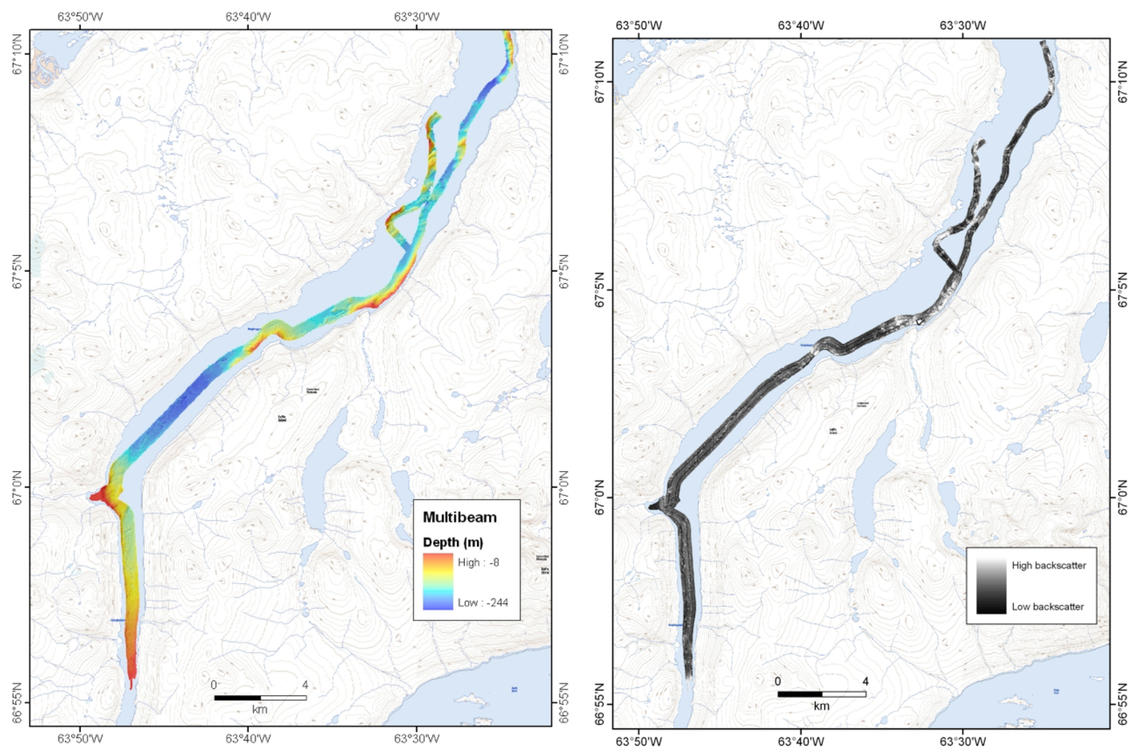


Figure A.11: Overview of Kangert Fiord.

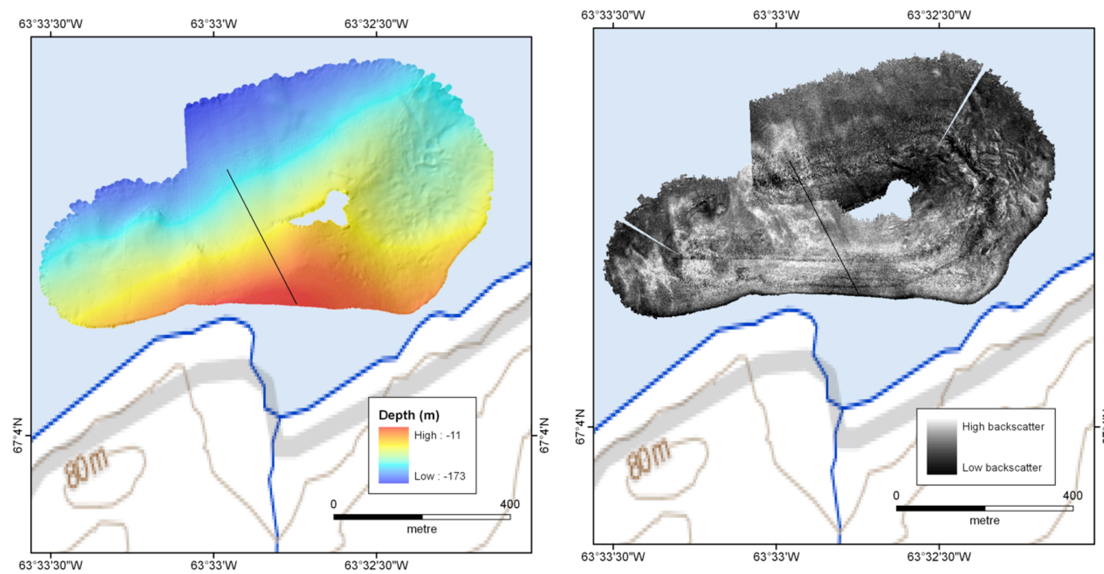


Figure A.12: First recce entering Kangert Fiord.

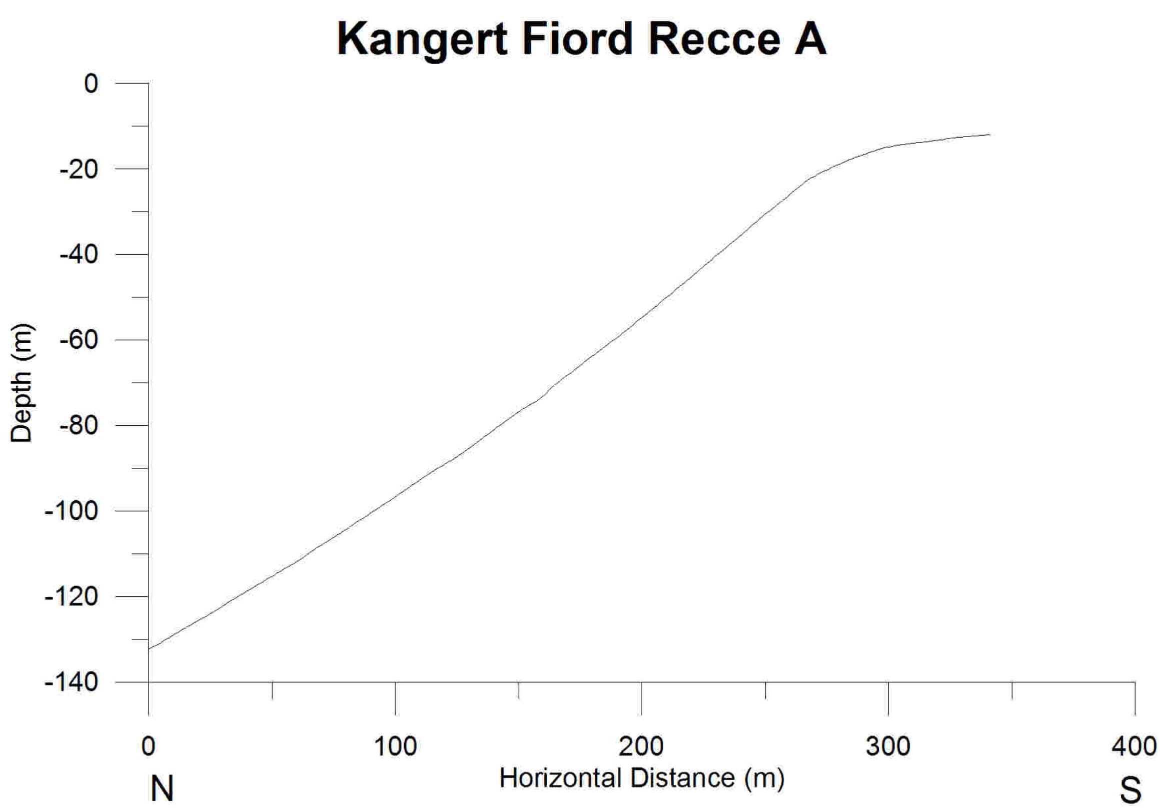


Figure A.13: Profile of Kangert Fiord recce, from Figure A.12.

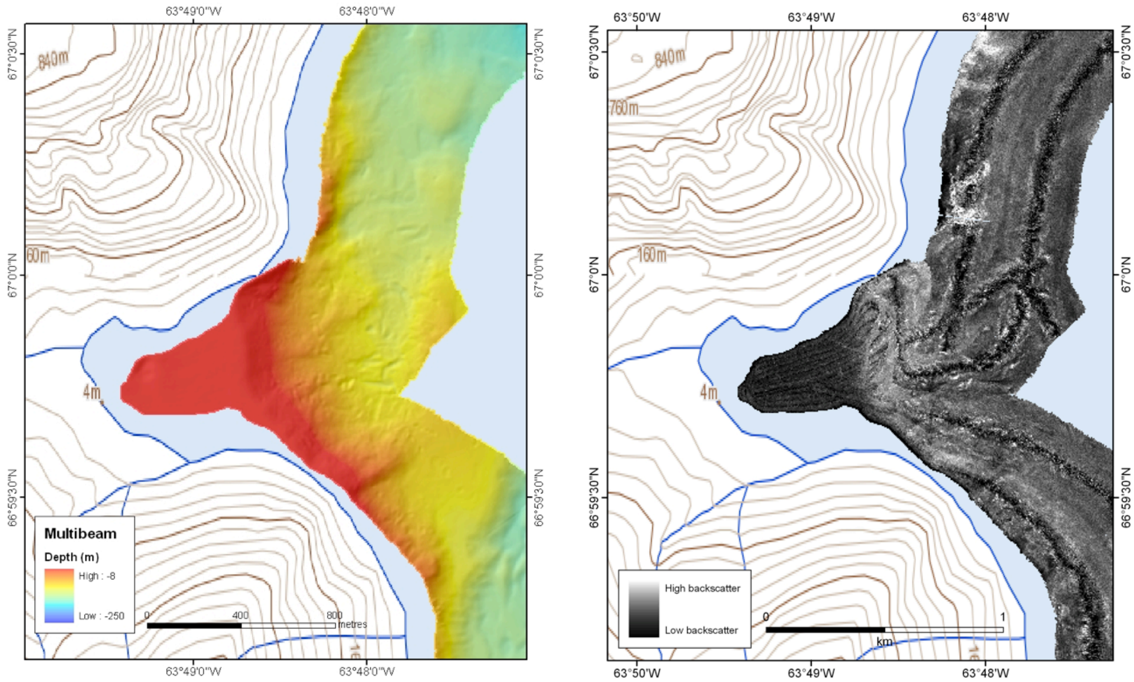


Figure A.14: Side entrance along western coast of Kangert Fiord.

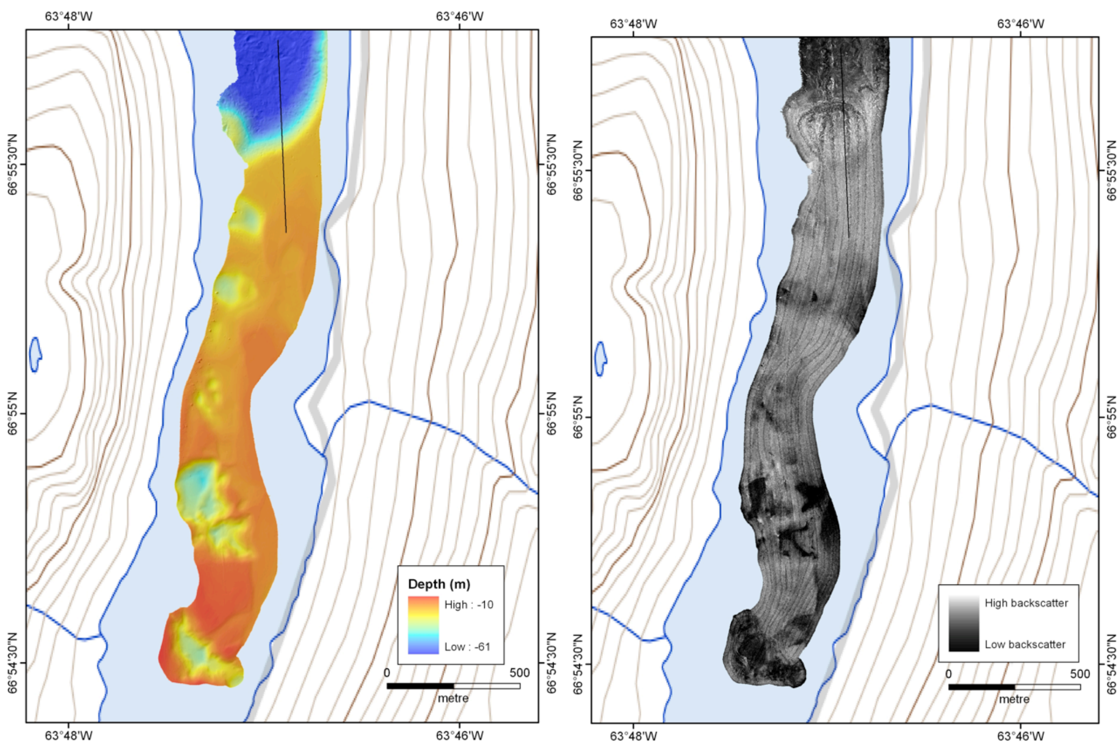


Figure A.15: Kangert Fiord head

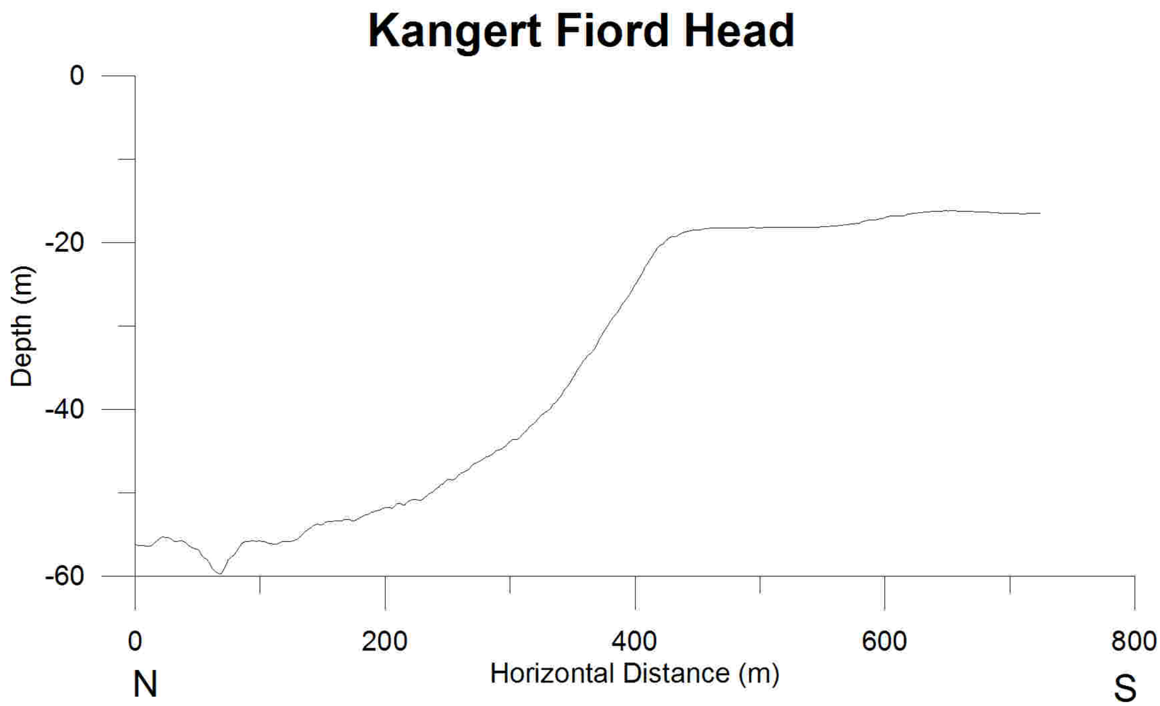


Figure A.16: Profile of Kangert Fiord head, from Figure A.15.

Entering Kangert Fiord, at it's mouth, is a sill about 100 m deep. The sill contains a 270 m deep basin with steep bedrock sidewalls. The data shows three terraced features. The first of which is fan-shaped, entering the fiord from the mouth of a side valley with a break in slope at 19 m (Fig. A.12; Fig. A.13). Along the western wall, a side entrance delta is mapped (Fig. A.14) with the lip of the terrace 18 m below sea level. This feature is located in the mouth of a tributary valley that consists of a hanging valley, with a waterfall entering close to the modern sea level. This delta terrace extends 700 m seawards, and is approximately 700 m wide. It descends at a slope of 3.4° to 60 m water depth, and then into the 200 m deep basin. Some pit and wallowing marks are observed upon the lip and upper terrace, as well as a large, 6 m deep and 70 m wide depression at its head. This depression is similar though not as extensive as those found upon the Kangert head delta terrace. Up to the head of the fiord, at depths of 40-110 m, there are many pit and wallow marks and gouged features observed. The Kangert head delta terrace's break in slope is at 19 m below sea level, descending along a 5° slope to the base of the side entry delta and into the basin (Fig. A.15; Fig. A.16). Similar to the side entry delta, the head delta has a series of large depressions, the deepest of which has a relief of 20 m and is 250 m wide. The smaller depressions are bowl shaped, with gentle sidewall gradients, whereas the largest is steep sided. The subbottom does not show any penetration, and therefore has no evidence as to whether or not these depressions have draping sediments. The preliminary interpretation is that these are formed by ice stuck in the sediments as the delta was prograding, and thereby left a kettle depression as melting ensued.

From the video footage, the terrace was found to contain a surface lag of cobble to boulder sub-rounded gravel, with a thin silt cap on the gravel. The video that was taken within the fiord head delta terrace depression showed an increase in suspended materials and a decrease in the gravel veneer. The closer to the lip of the terrace, the sediments become more washed and therefore coarser due to the faster current flow towards the edge.
The terrace and delta terraces appear to be of similar depth, and therefore give strong evidence to the depth of the lowstand in Kangert Fiord, within the range of 18-20 m.

A.7.5 Boas Fiord

Boas Fiord is located along the southern coast of Merchants Bay, striking north-south for a length of 34 km, with an average width of 2.7 km. To the south, remnant valley and cirque glaciers surround Boas Fiord head. Along the sidewalls of Boas Fiord are tributary valleys and hanging valleys, and the head of the fiord is made up of a braided river plain that is sourced from the junction of three main tributary valleys.

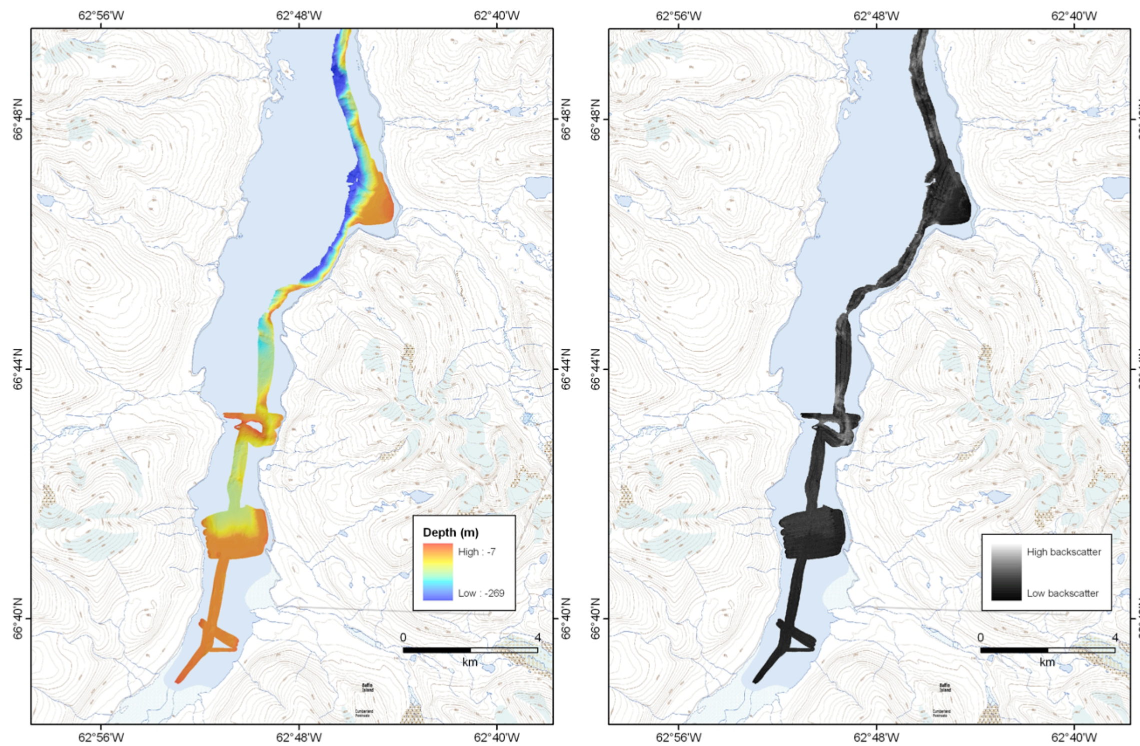


Figure A.17: Overview of Boas Fiord.

Boas is a deep fiord with basin depths greater than 300 m below sea level. The majority of the fiord is one main basin, with sidewalls reflecting the slope of the subaerial sidewalls. Along the fiord is a side entry valley with a submerged delta terrace (Fig. A.18), which has a break in slope at 37 m below sea level. This site was a target due to personal communications from Dr. G.H. Miller, who previously ran a continuous trace echosounder along this submerged delta (1975). The terrace is remarkably flat and smooth, with no remnant channels upon the delta plain, therefore post-deposition likely infilled thechannels. Video footage supports the low backscatter return on the terrace, due to the deposition of fine-grained sediments covered by brown algae. The rare calcareous encrusted boulder (20 cm diameter, subangular-subrounded) can be found upon this surface along with shell hash, as well as the curious white disc-like features that are speculated to be gas hydrates (Fig.

A.3). Upon the delta terrace is a second lip, with a break in slope at 27 m below sea level. This is likely due to a resurgence of sedimentation upon the delta terrace from the side entry valley. Along the edge of the delta terrace are many pit and wallow marks from icebergs. As well, the delta front has channels and gullies along its slope (3.7°), reaching the fiord floor at a depth of 230 m.

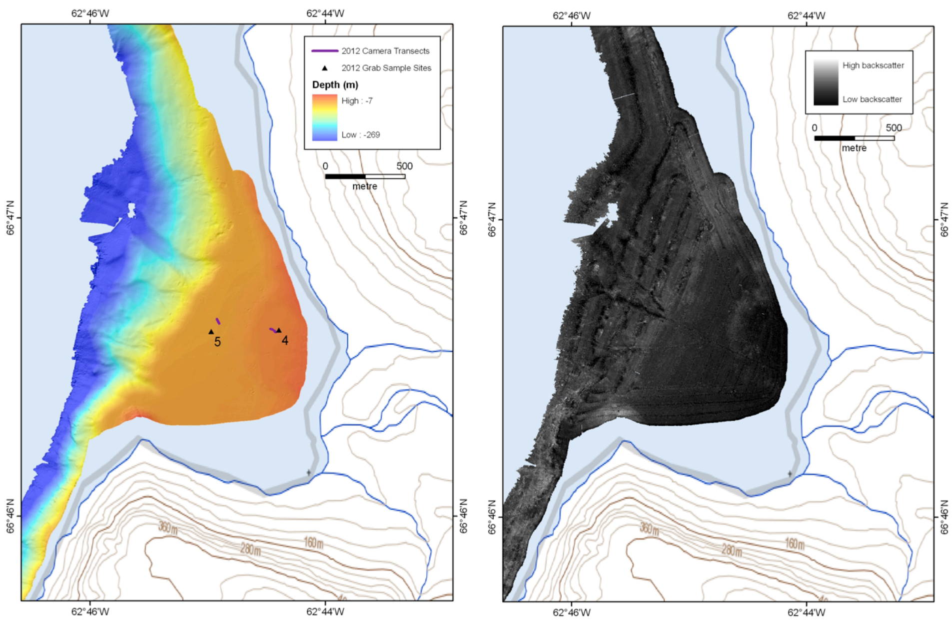


Figure A.18: East side entrance to Boas Fiord. With camera and grab sample locations.

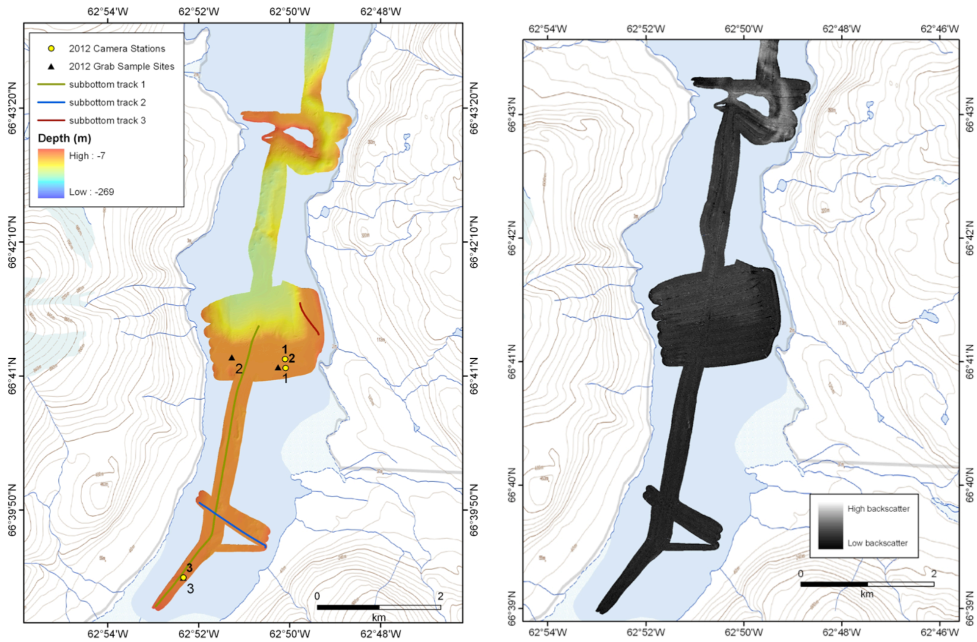


Figure A.19: Boas Fiord head, with camera and grab sample locations.

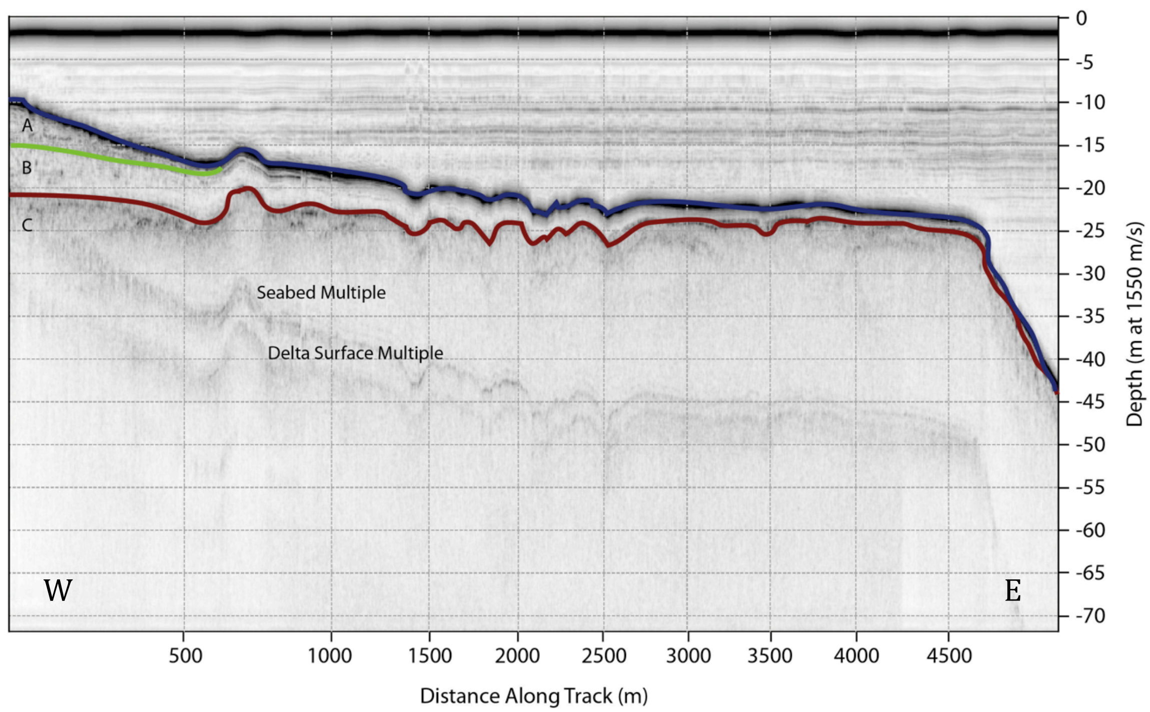


Figure A.20: Subbottom profile of Boas Fiord, track 1 in Figure A.19. A) prograding front of modern delta, B) glaciomarine draped sediment, C) submerged delta.

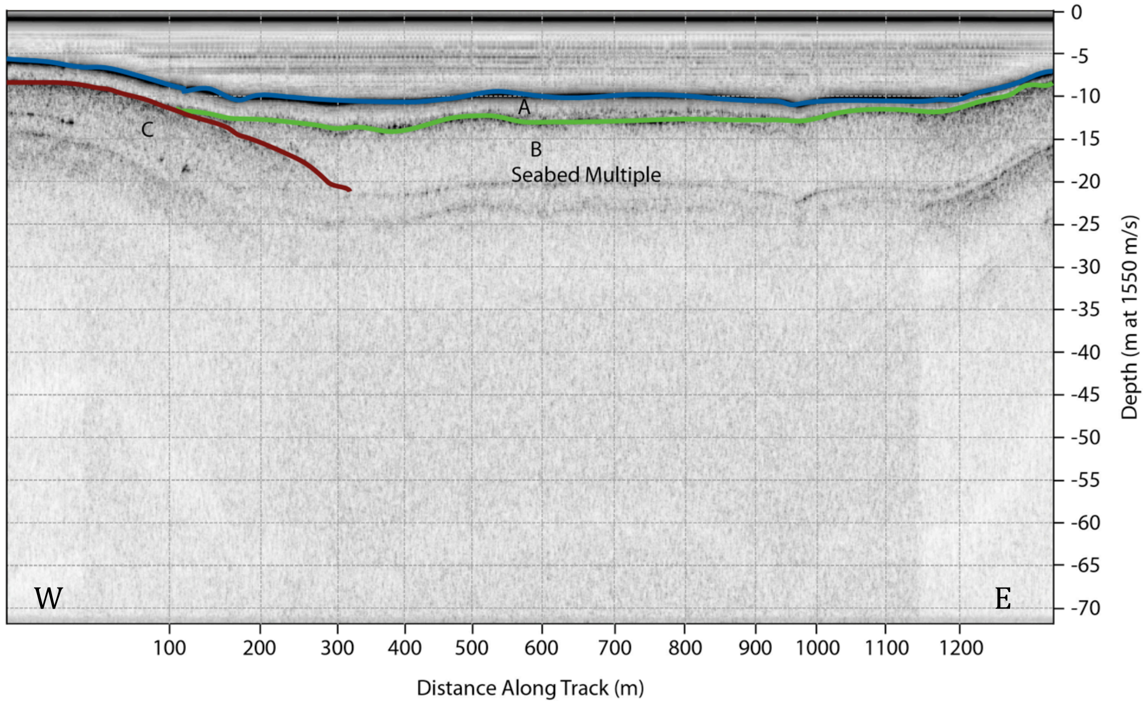


Figure A.21: Subbottom profile of Boas Fiord head delta, track 2 in Figure A.19. A) glaciomarine draped sediments, B) Holocene delta top, C) lateral progradation along the fiord margins.

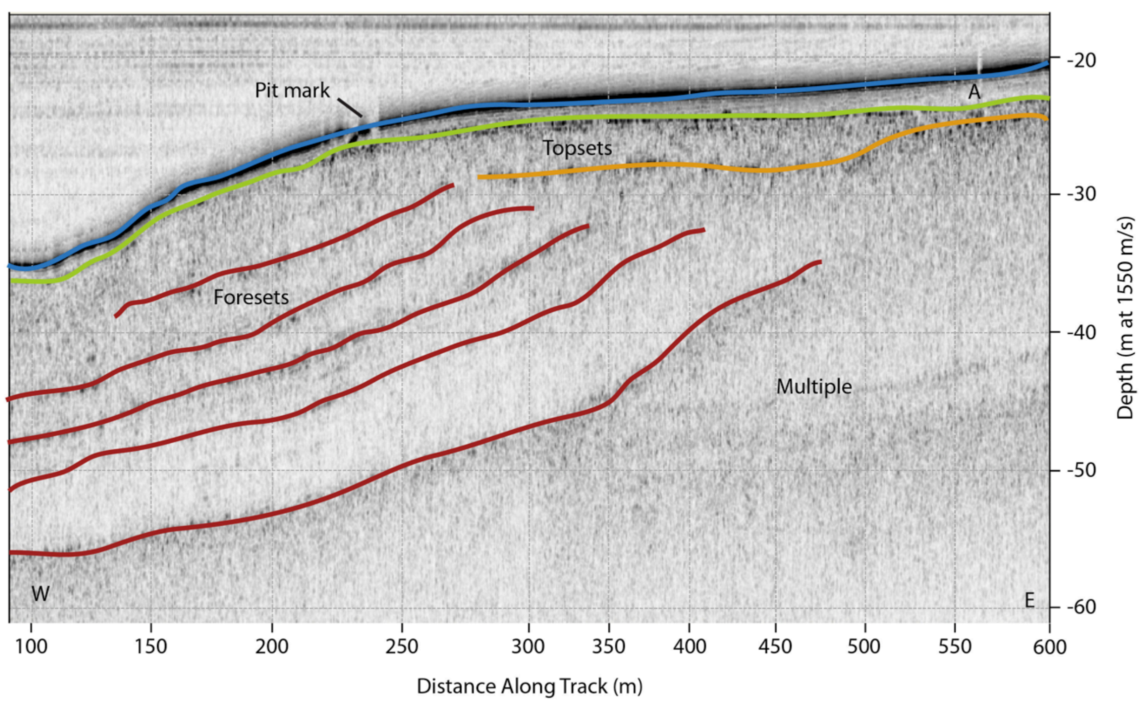


Figure A.22**:** Subbottom profile of Boas Fiord head delta, track 3 in Figure A.19. A) glaciomarine sediment drape.

Almost at the fiord head is a sill, likely a terminal moraine, which is shallower than 10 m below sea level, but a safe transit was mapped to the east within 45 m depth range (Fig. A.19). This sill creates another basin in front of the fiord head, which reaches 90 m below sea level, but rises steeply to a submerged fiord head delta with a terrace at 33 m below sea level. The delta terrace is flat and similar to the one found further down fiord with a gentle gradient up to the fiord head braided river plain. The delta front shows some gullies and delta front channels, as it slopes (5.8°) down to the 90 m deep basin floor. Along the lip of the terrace and the delta front are many pit and wallow marks from icebergs (Fig. A.22). Video footage of this terrace shows that it is made up of medium to coarse sand with scattered gravel (subangular) and is dotted by algal clusters upon the flat surface. The subbottom profiles of Boas Fiord head show good penetration, distinguishing the glaciomarine sediment draped ontop of the submerged Holocene delta terrace (Fig. A.20, A.21 & A.22). Delta foreset and topset beds are distinguished along the lateral extensions of the submerged fiord head delta (Fig. A.22), which establish the limit of palaeo-sea level at the intersection between topset and foreset.

A.7.6 Southwind Fiord

Southwind Fiord strikes northwest-southeast, and is 27 km long with an average width of 3.2 km. Southwind Fiord's mouth opens into Merchants Bay, to the east of Boas Fiord. The head of Southwind is surrounded by many remnant valley glaciers, as well as Southwind Glacier, with it's terminus 6 km up the valley. The mouth of the fiord has steeper sidewalls, compared to a shallower gradient on the sidewalls at the head of the fiord.

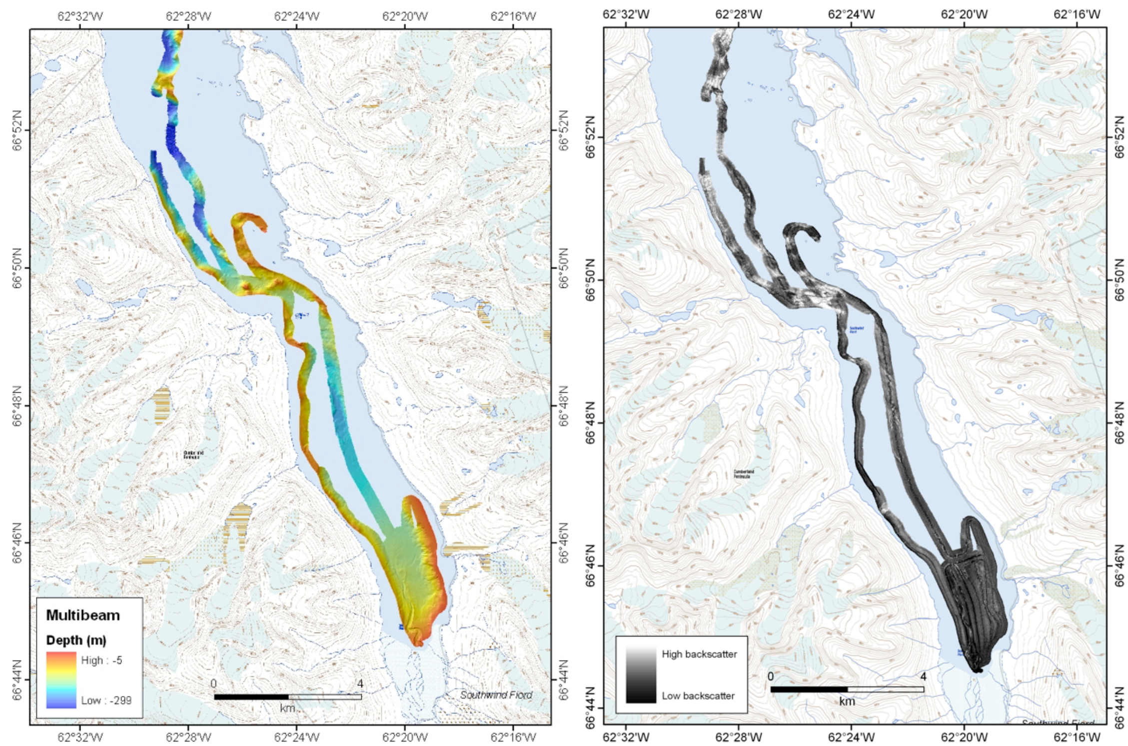


Figure A.23: Overview of Southwind Fiord.

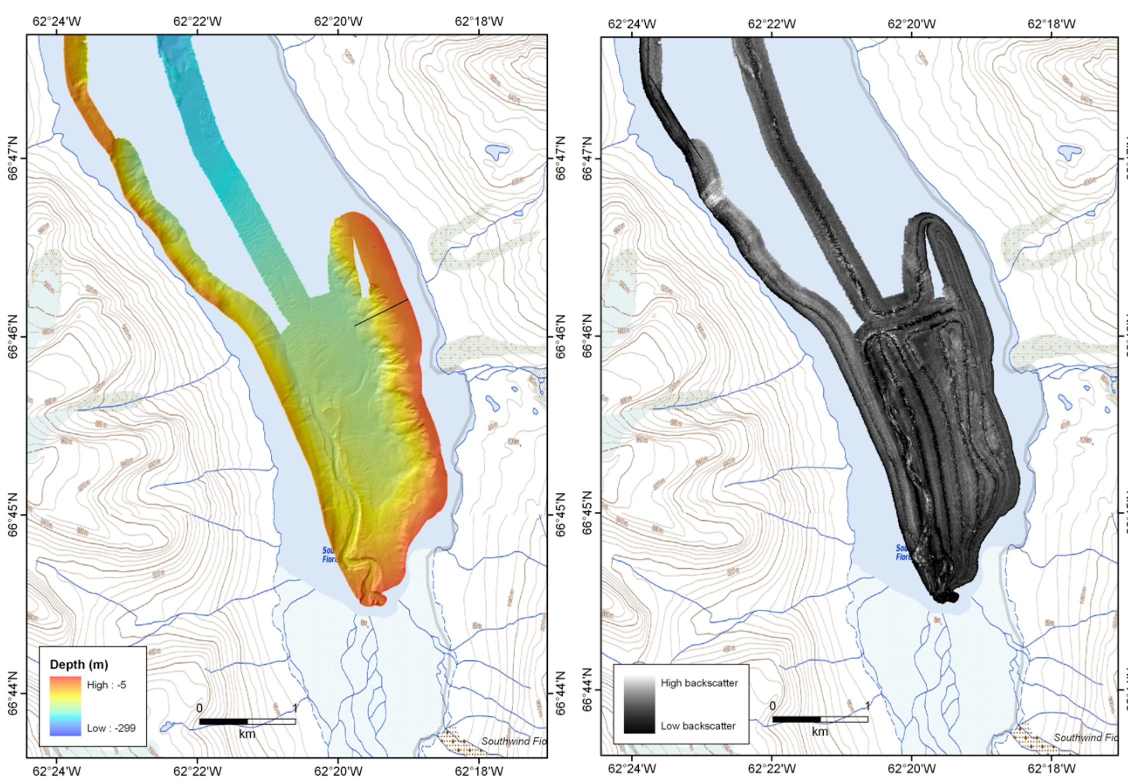


Figure A.24: Head of Southwind Fiord.

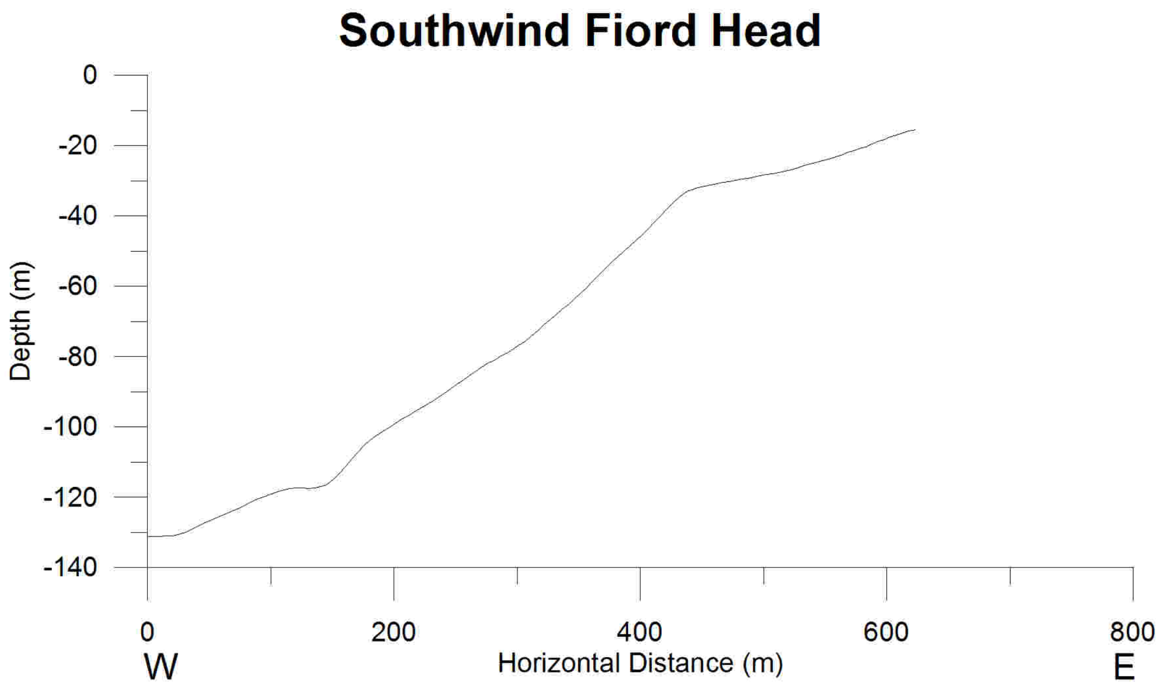


Figure A.25: Profile of east side of Southwind Fiord, from Figure A.24.

The mouth of Southwind fiord is a basin of 280 m depth, with steep bedrock sidewalls. Entering the fiord, the basin steeply rises to a headland. Overall, Southwind has steep sidewalls to the west, and shallower slopes to the east with more sedimentation. Halfway through the fiord is a shoal 35 m below sea level, which could be remnant of a recessional moraine (Fig. A.23). Within the upper fiord is a 190 m basin, which gradually slopes up to the fiord head. The fiord head has a distinctive channel, with up to 20 m high levees, and in-channel bedforms (Fig. A.24). These bedforms extend out into the fiord as it slopes down to the basin. Along much of the sidewalls are slope failure scars. Along the eastern side of Southwind Fiord head is a break in slope at 30 m below sea level (Fig. A.24 & Fig. A.25), which is accentuated by arcuate scarps. This terrace could have formed by subaqueous discharge from tidewater or near-tidewater glacier termini. Likely, this fiord head contained tidewater glaciers during the lowstand, and therefore this terrace formed at a later time. There is also evidence of subaerial mass wasting, which along with the subaqueous slope failures might suggest a trigger.

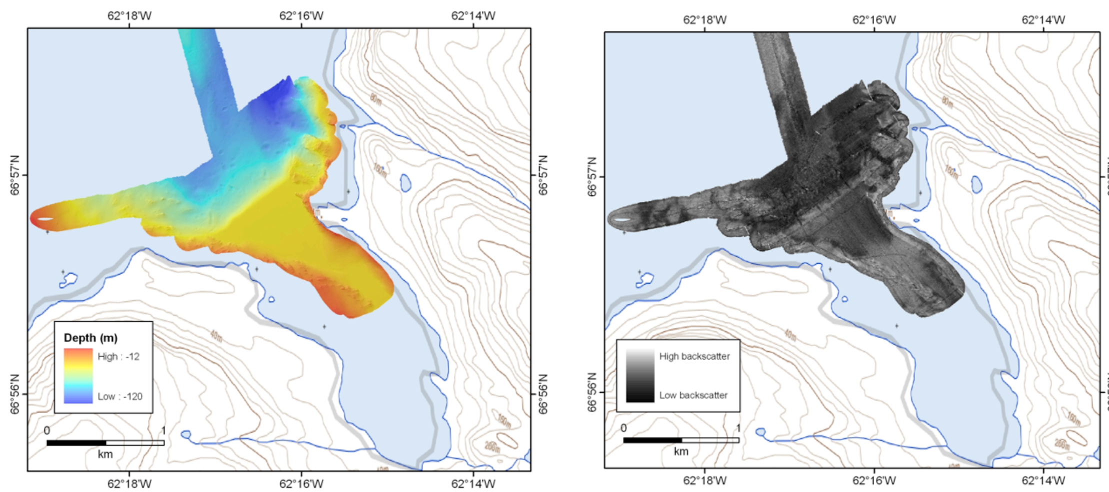


Figure A.26: Embayment east of Southwind Fiord.

The embayment to the east of Southwind Fiord opens to Merchants Bay, though is sheltered by Amittuarjuk Island to the north. It is located at the mouth of several drainage rivers, which are sourced by higher elevation lakes and in some cases meltwater from small remnant cirque and valley glaciers. At present there is no delta, and is not fed by a low-lying valley. However, a submerged delta terrace is mapped with a lip at 43 m below sea level (Fig. A.26). The terrace is remarkably flat; any channels upon the delta surface have since been infilled. The edge of the delta is 880 m wide, and slopes (4.7°) down to a depth of 110 m. There are small bedrock outcrops along the sidewalls at its mouth, as well as some pit and wallow marks from icebergs along the delta front and edge.

A.7.7 Akpait Fiord

Akpait Fiord is located almost at Cumberland Peninsula's easternmost point. The fiord strikes east-west for a length of 16 km, where it's mouth opens into Baffin Bay (Fig. A.27). The head of the fiord is positioned at a complex set of junctions between multiple valleys and low-lying outlets, with remnant cirque and valley glaciers within the valleys to the west and south.

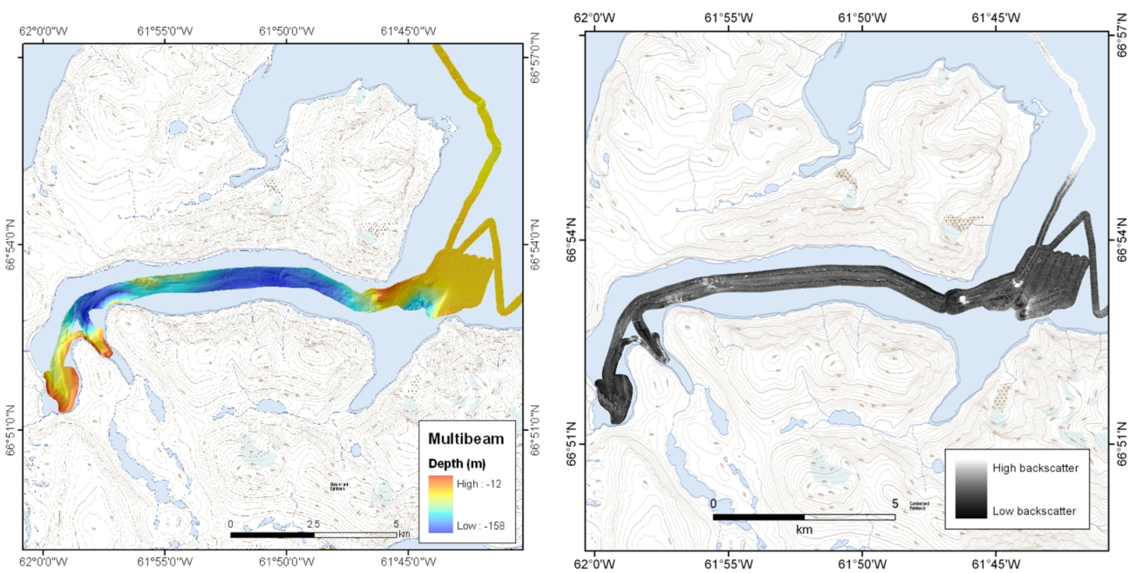


Figure A.27: Overview of Akpait Fiord.

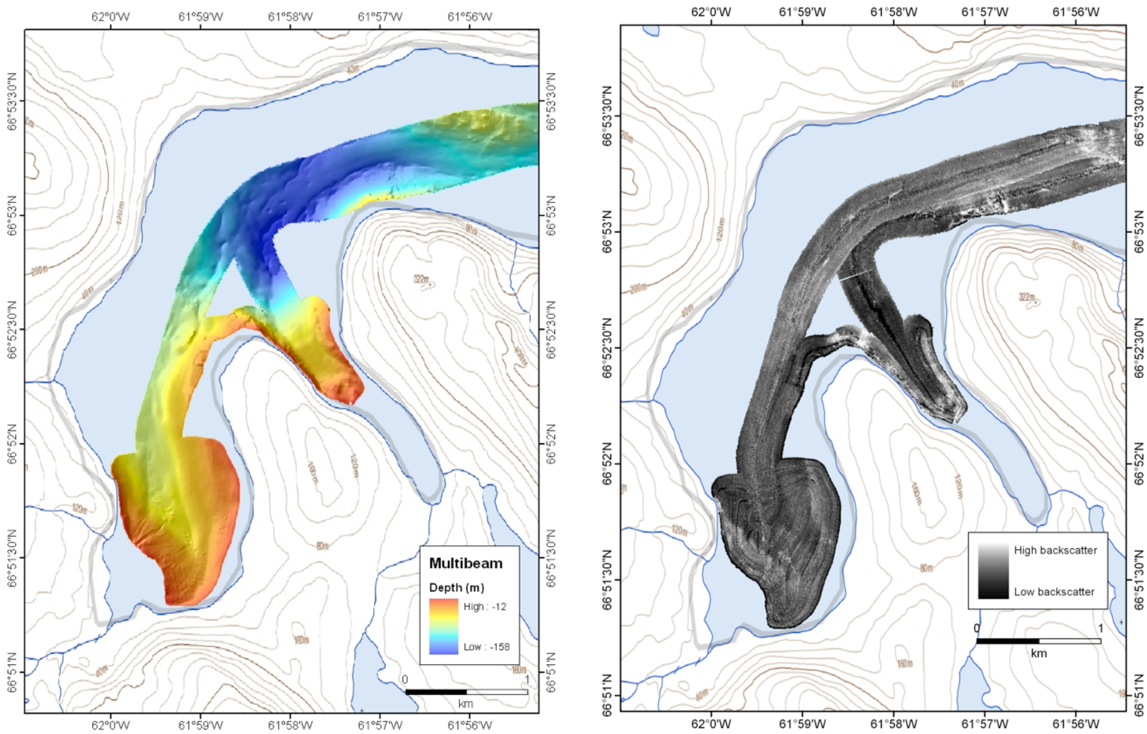


Figure A.28: Akpait Fiord head.

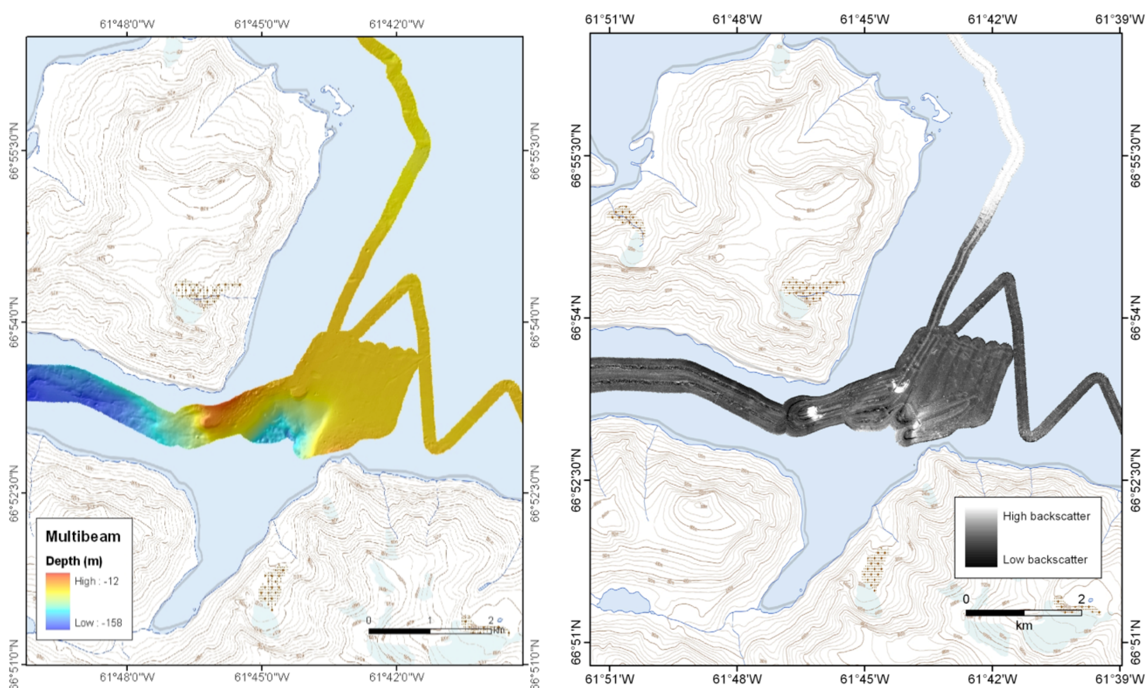


Figure A.29: Akpait Fiord mouth.

The Akpait Fiord contains a single basin, with a sill plain at the fiord mouth (Fig. A.27). At the eastern edge of the sill are two slightly elongate, high backscatter features that strike northeast-southwest (Fig. A.29). From video footage the high backscatter was observed to be coarse rounded to subrounded gravel with some angular boulders and a thin discontinuous matrix. Moving along the feature, it is draped by a fine sediment. These might be gravel spits that built upfiord from the currents of Baffin Bay redistributing sediments along the northern shoreline of the outer fiord. The easternmost is at a depth of 50 m, and the western at 30 m below sea level. This shows evidence to the amount of potential entrainment from the northern shoreline, as well as the currents in the outer fiord from Baffin Bay. The sill plain is at 50-52 m below sea level, which slopes into the 125 m deep basin with a convex profile, but extends outwards into Baffin Bay. This feature is similar to a barrier platform and spillover, as described by Shaw and Forbes (1992) in St. George's Bay, NL. This feature is interpreted to have been made up of glacial material deposited as a moraine, and as sea level lowered to a lowstand the morainal bank may have been subaerially exposed. Once sea level began to transgress, the morainal bank came in contact with wave action, redistributed the material into a planed off surface, and prograding landwards into a spillover. This interpretation would require the surface to be within range of the wave base, in order for wave and current action to entrain and redistribute sediment. From the spit formation at 50 m depth, there is a potential non-glacial sediment source from the northern shorelines that has migrated southwards and into the fiord mouth, thereby adding to the platform. From this interpretation, this platform would suggest a sea level of approximately 50 m below present sea level. If the lowstand were any lower Akpait Fiord would have become a freshwater lake, in which case cores of the basin sediments could tell the history of the sea level further. Unfortunately, the subbottom echosounder was not working and therefore there is no subbottom data to help with the interpretation of this feature.

The fiord basin reaches a maximum depth of 155 m in the upper fiord, which rises steeply to the fiord head (Fig. A.28). The fiord head was mapped to a depth of 15 m, which displays an active slope with subaqueous channels and bedforms, adjacent to the main inflow. At the fiord head is a tributary arm, which was also mapped to 15 m depth. This arm shows steep sidewalls of bedrock, and perhaps a moraine remnant at the extent of the multibeam. The tributary head slopes down from a short platform at 51 m and into the basin floor at 155 m.

A.7.8 Totnes Road

To the south, Totnes Road opens to Baffin Bay, with Mount Rayleigh to the north and many valley glaciers. Totnes Road strikes approximately east-west for a length of 19 km, and for the most part is a 9 km wide bay, with tributary coves to the east and west. These coves are at the mouths of tributary valleys, and along the northern mountainous shorelines are many hanging valleys including glacial termini.

Totnes Road is made up of a deep basin, 260 m below sea level, with steep sidewalls continuing up to the adjacent mountains to the north (Fig. A.30). The cove at the eastern extent of Totnes Road was mapped. This cove is made up of a break in slope at 80 m below sea level, along its western edge, but is built up by sediment fans from the northern and eastern inflow, with a remnant subaqueous channel running through the centre (Fig. A.31). This could be a remnant of an older lowstand at 80 m depth that has since been covered by recent sedimentation. However we would need cores of the sediment to determine the depositional history further.

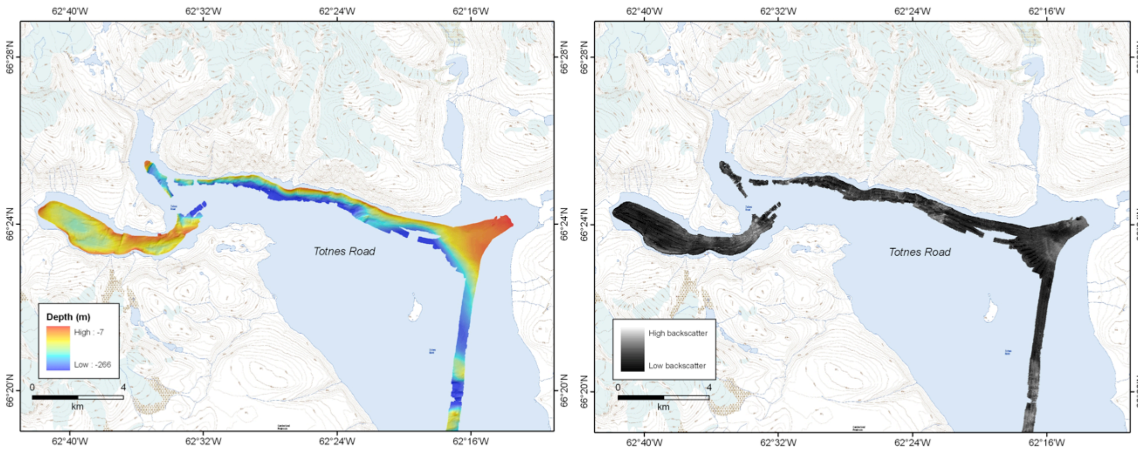


Figure A.30: Overview of Totnes Road.

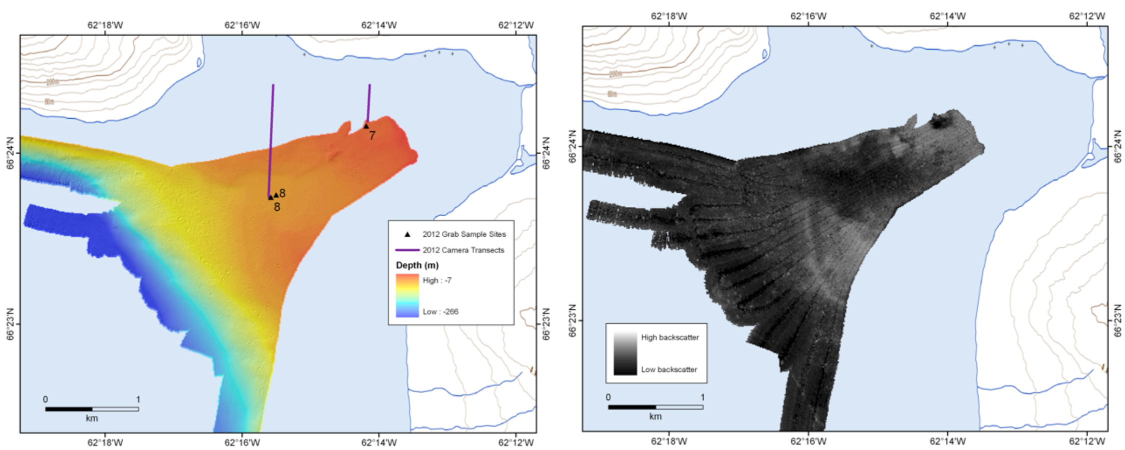


Figure A.31: Totnes Cove, with camera and grab sample locations.

Underwater video footage displays large calcareous encrusted boulders (on average 30 cm diameter, maximum 70 cm diameter) within fine-grained sediment and shell hash. In between are patches of algae covered heterogeneous sediment, similar to that observed at the side entrance delta in Boas Fiord. The second video footage, further offshore, shows many benthic organisms upon a smooth surface of fine-grained sediment and the rare boulder (15 cm diameter) becoming more common landwards, which act as anchors for large kelp fans.

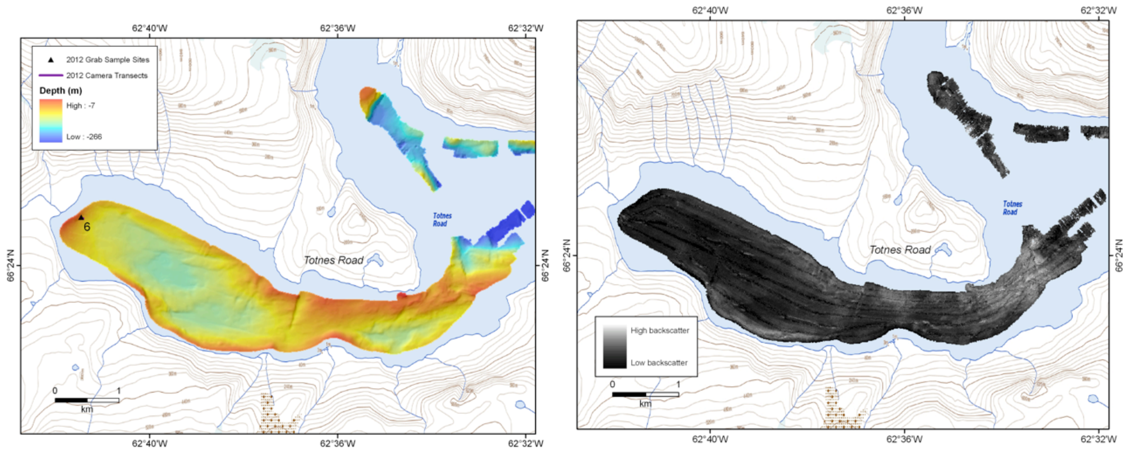


Figure A,32: Western tributary of Totnes Road.

The cove at the end of Totnes Road (Fig. A.32) lies within an overdeepened valley with many hanging valleys sourced by remnant valley glaciers. The cove is a 135 m deep basin with steep sidewalls and enclosed by a moraine sill, 40 m below sea level, at its mouth, which opens into the 260 m deep basin of Totnes Road. Video footage adds to the low backscatter of the western basin showing a draping of fine silty sediment along with the rare boulder (20 cm diameter). The video had low visibility due to the concentration of fine suspended sediments.

A.7.9 Mermaid Fiord

Mermaid Fiord is 23.5 km long, and on average 2.2 km wide. Halfway along mermaid fiord is a western side entrance U-shaped valley, and the head of the fiord is a junction point and sourced by three U-shaped valleys and one hanging valley. The main river follows a long catchment system before it reaches the fiord head, which contains a sandur/ delta plain.

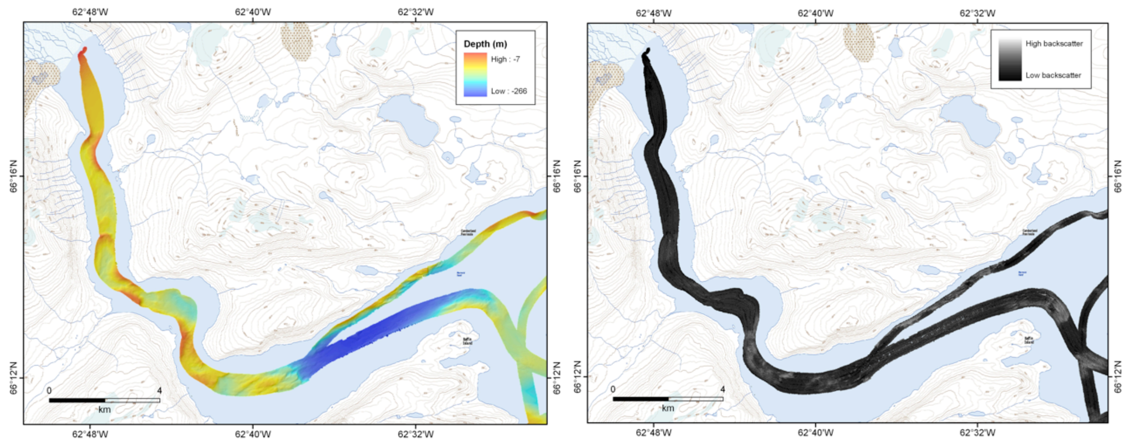


Figure A.33: Overview of Mermaid Fiord.

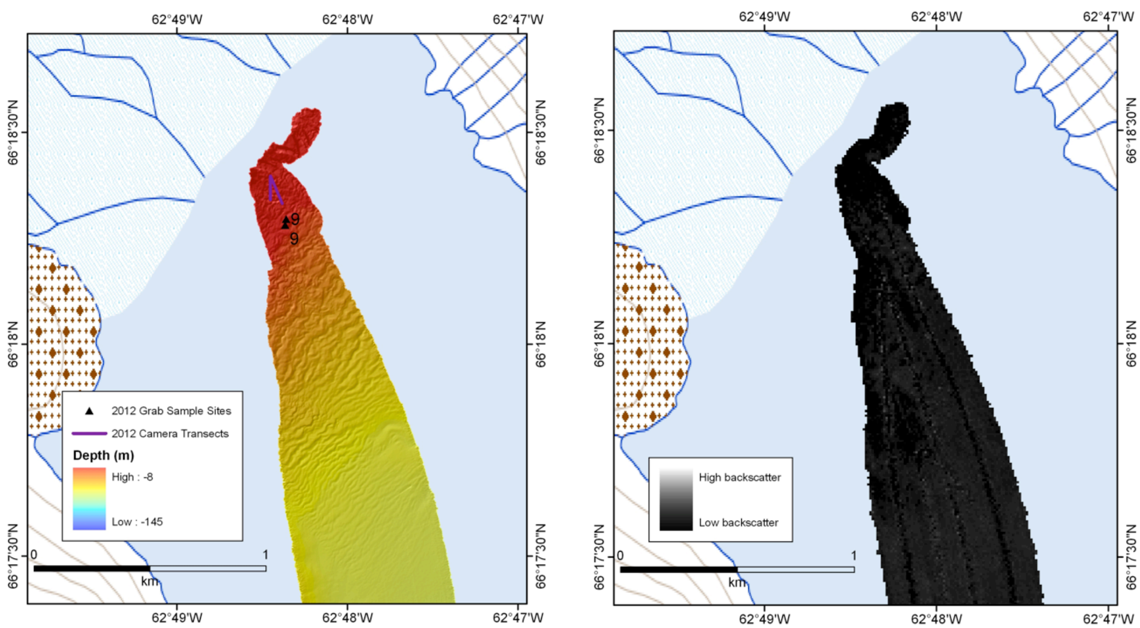


Figure A.34: Mermaid Fiord head.

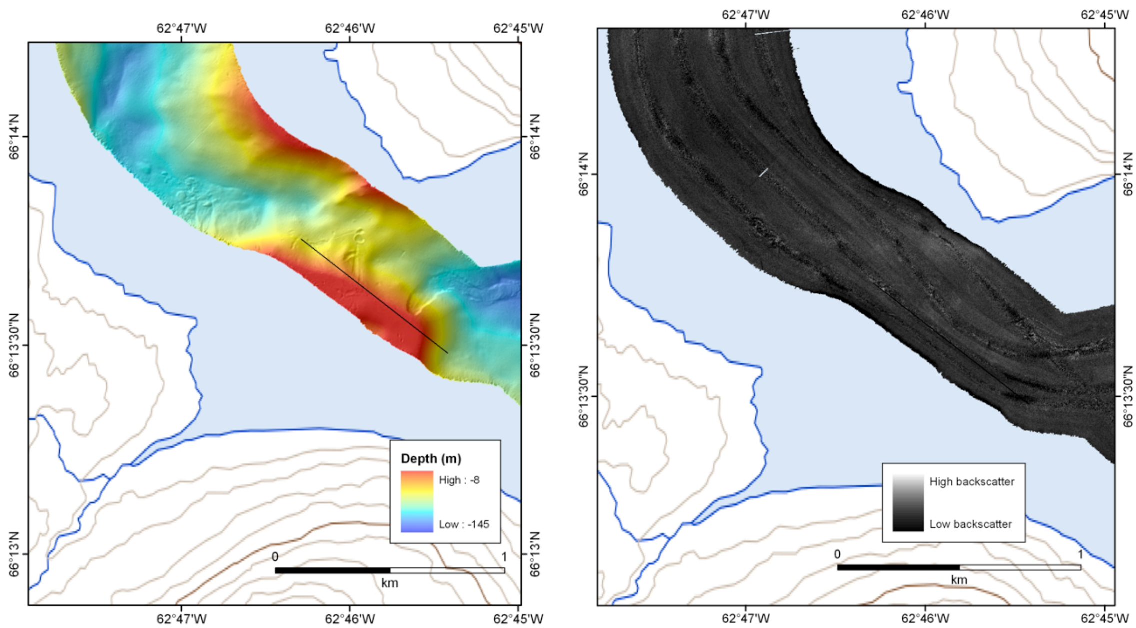


Figure A.35: Southwest entrance into Mermaid Fiord.

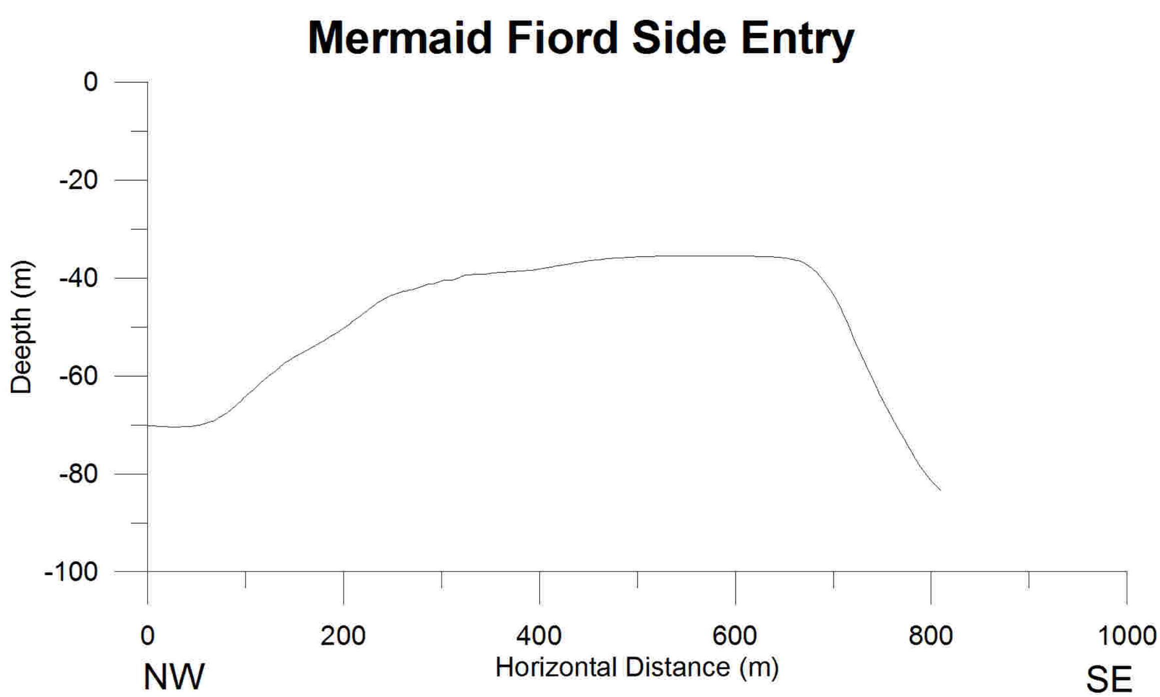


Figure A.36: Profile of Mermaid Fiord side entrance delta, from Figure A.35.

At the mouth of Mermaid fiord is a 230 m deep basin with steep sidewalls (Fig. A.33). Glacial material, perhaps the extent of a moraine, marks the interior edge of this basin, where the fiord turns towards the northwest. The fiord's interior basin has a maximum depth of 140 m. Halfway up the fiord is a side entry U-shaped valley that joins to the southwest with the head of Clephane Fiord. At the side entry valley mouth is a delta terrace, of which only the lip was mapped (Fig. A.35; Fig. A.36). The lip of this delta terrace is at 35 m below sea level, is approximately 950 m wide, and slopes (2.5°) down to a depth of 100 m. The delta front has some slope failure scars.

The head of Mermaid Fiord is comprised of a continuous slope down from the fiord head delta front to the fiord basin at 90 m below sea level (Fig. A.34). Along this slope is a set of ridges and troughs propagating from the fiord head. These features are not continuous across the fiord, and provide 1-3 m relief. These could be attributed to arcuate banding of pressure ridges, or creep folding, which are produced by continued sediment supply upslope but reduced motion along the slide margin (Syvitski et al., 1987). An alternative interpretation would be that these are large-scale bedforms. The subbottom does not penetrate, and therefore it is unknown whether these features have faulted planes or continuous sediment layers. The overall slope has a concave-upward shape, which might help to explain a slide surface more so than a bedform formation. The video footage has low visibility due to high levels of suspended sediments, however the crests of some of these features can be observed under or within a silt-clay sediment drape. Along these features are also benthic track marks, and occasionally a gullying effect can be seen on the edge of ridge.

A.7.10 Clephane Fiord

Clephane Fiord strikes northwest-southeast for 40 km, and is on average 3 km wide (Fig. A.37). The head of Clephane Fiord is surrounded by remnant cirque and valley glaciers, which provide the water source for the fiord head and tributaries. The fiord head is at a junction of multiple tributary valleys, one of which is a side entry valley into Mermaid Fiord, the same one that deposited a side entry submerged delta. Clephane Fiord opens into Baffin Bay, sheltered by islands.

Clephane Fiord is similar to many of the other fiords; it has a basin in the outer fiord at a depth of 180 m below sea level, with steep side walls (Fig. A.37). The first recce was mapped to get a sense of the bathymetry and morphology, showing the fiord to be deep in the middle with steep slopes up to the coastline and a slight break in slope at 20 m below sea level (Fig. A.38). The break in slope does not appear to be from any distinct depositional feature related to a lowstand. The fiord head has a modern delta that has prograded much further than the present topographic maps, therefore the multibeam bathymetry could not reach further. Clephane Fiord head is made up of slope failures off of the sidewalls and delta fans. The head of the fiord shows no terrace, and rather a rough slope (Fig. A.39). Along the front of this slope is perhaps the remnants of a subglacial channel, further down the slope the channel continues, however it is infilled in the centre by a mound that runs through the channel up to the height of the levees. This is interpreted as a small subglacial channel that was infilled by an esker. The head of this embayment, southwest of the entrance to Clephane fiord, is at the end of U-shaped valley, whose water source comes from the drainage of many elevated lakes into a central river channel. Within this vicinity are scarce glaciers, the only remnant valley glaciers are to the northwest.

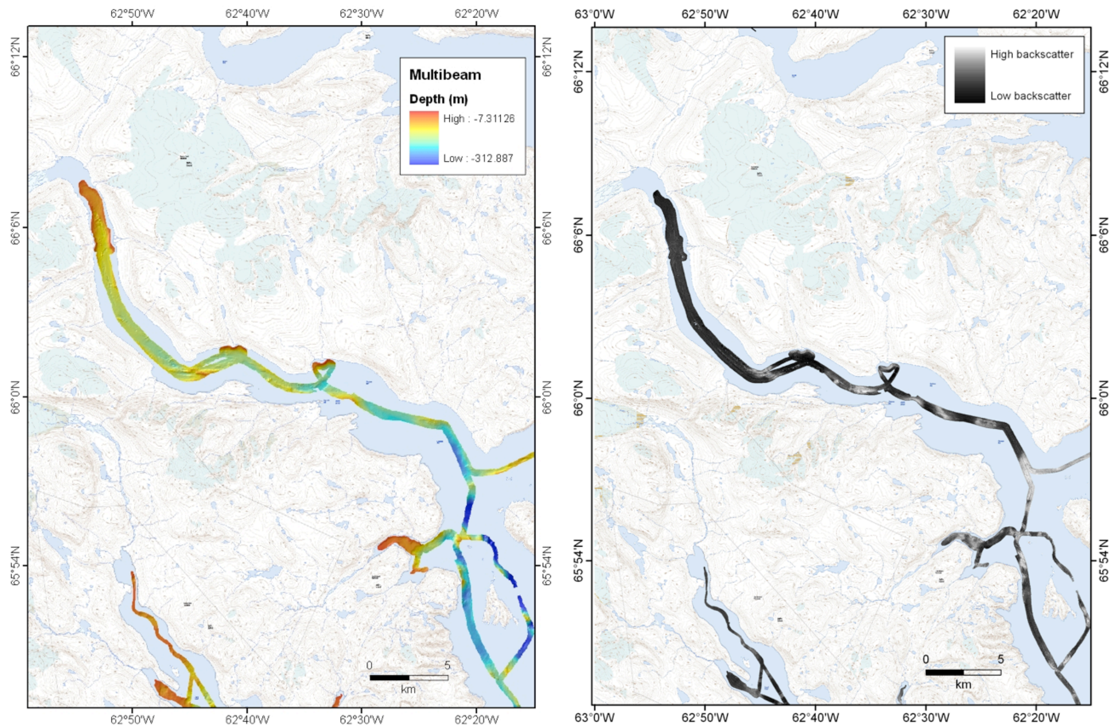


Figure A.37: Overview of Clephane Fiord, and outside embayment.

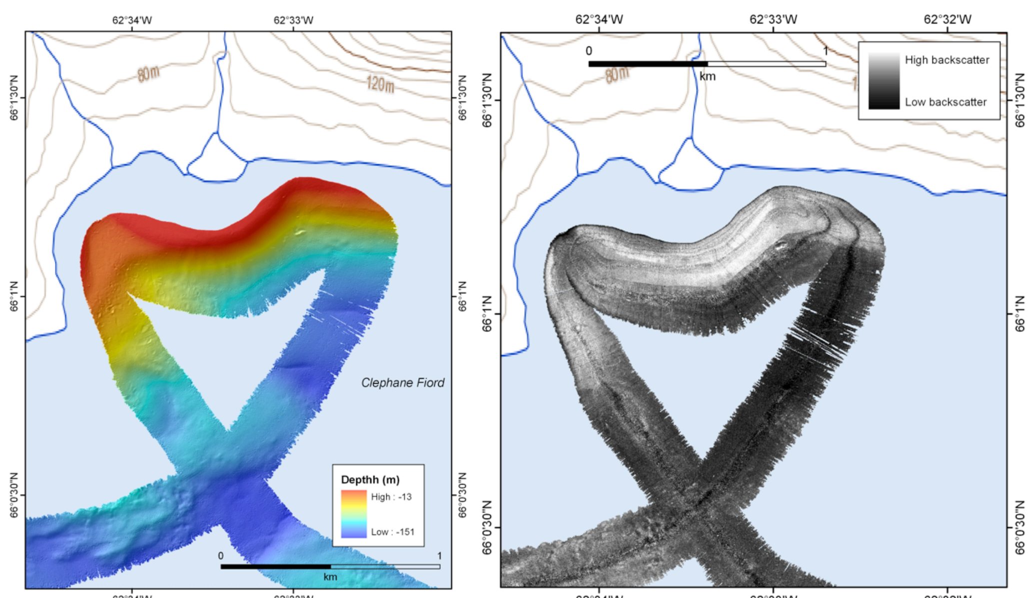


Figure A.38: First recce entering Clephane Fiord.

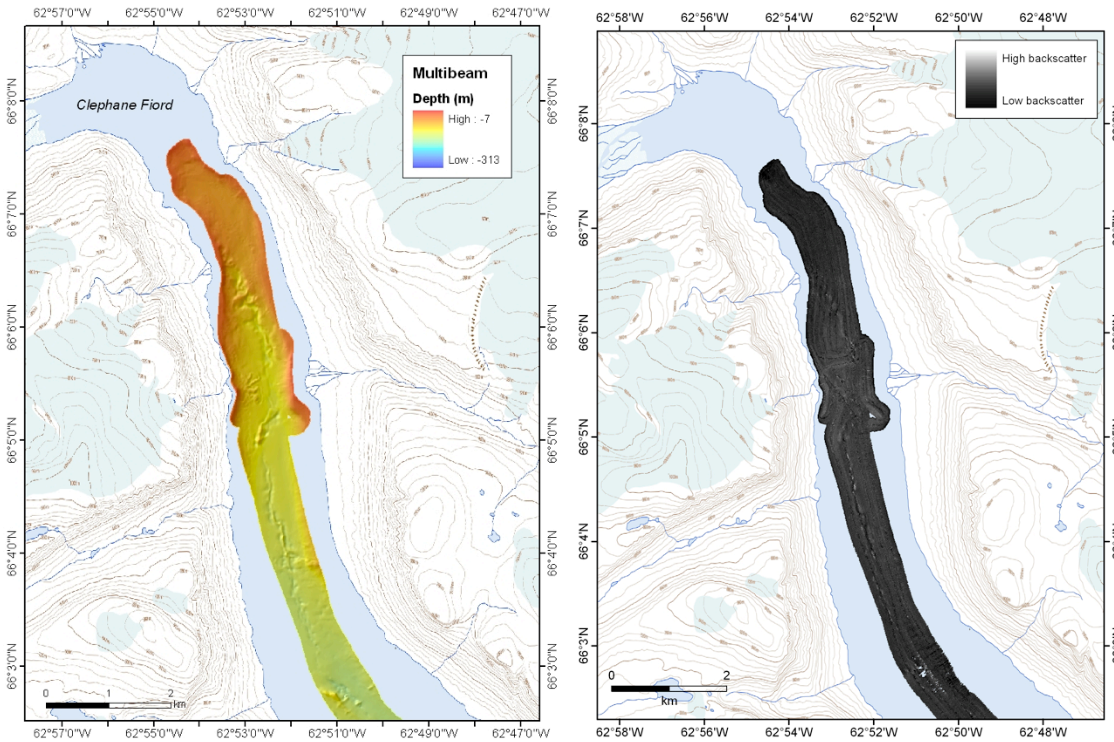


Figure A.39: Clephane Fiord head.

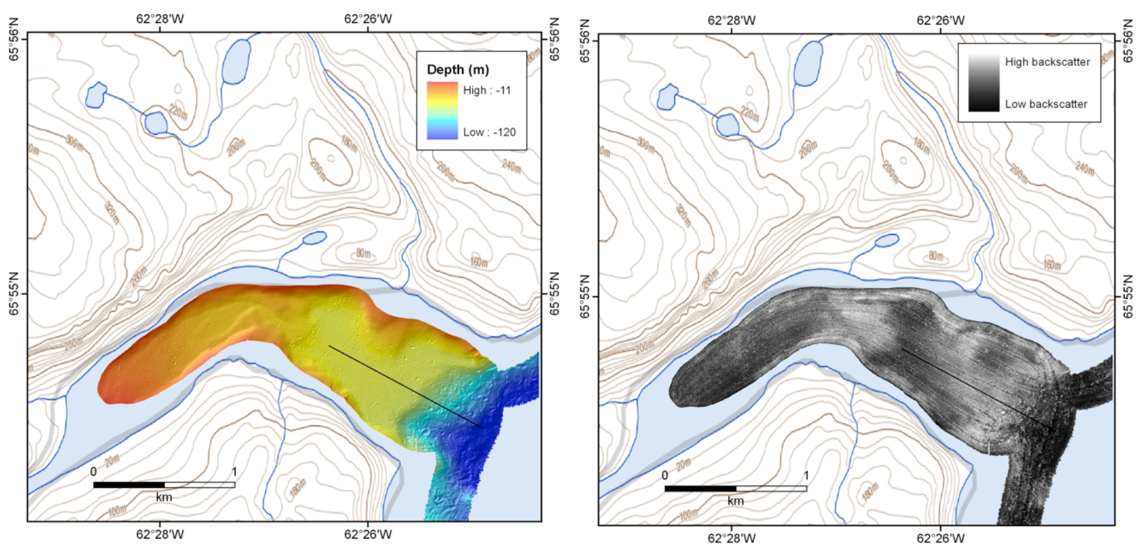


Figure A.40: Embayment southwest of Clephane Fiord mouth.

The embayment was where the ship took protection from the wind and waves, during which time the head of the bay was mapped (Fig. A.40). This was a lucky encounter, since this is the site of a submerged delta terrace, with a lip at 45 m below sea level (Fig. A.41) that slopes (11.7°) down to 180 m in the bay. Upon the terrace and delta front are many pit and wallow marks from grounded icebergs. At the head of the delta is a remnant channel that ends upon the main terrace, and has been infilled. The terrace is remarkably flat, and therefore any channels that were present upon the delta have since been infilled by post-depositional sediment. Since the delta's deposition, there has been more recent sedimentation from the tributary rivers' outflow upon the delta terrace. This submerged delta is evidence of a lowstand for this region, and adds to the previously described sea level indicators mapped during these surveys.

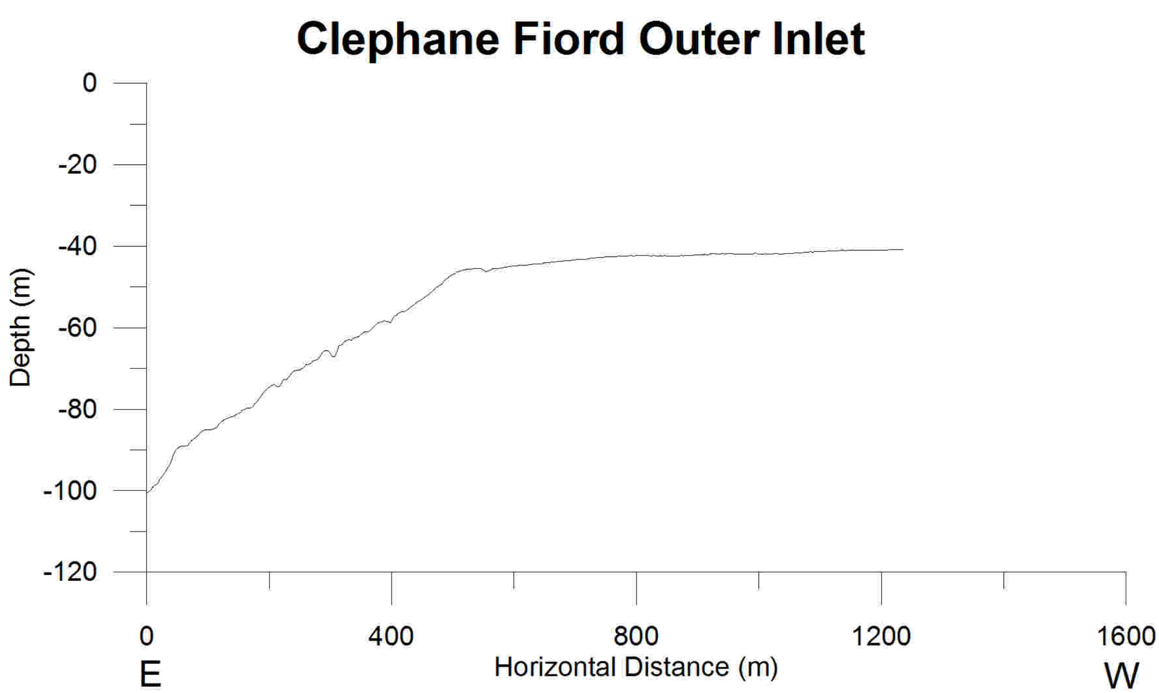


Figure A.41: Profile of embayment delta, from Figure A.40.

A.7.11 Ingnit Fiord

Ingnit Fiord strikes northwest-southeast and opens into Baffin Bay, along Cumberland Peninsula's eastern coast. The fiord is 21 km long, and on average 2.1 km wide. Ingnit Fiord head is within close proximity to valley glaciers and remnant cirque glaciers to the northeast. Ingnit Fiord includes a tributary arm to the south as well as many tributary valleys, and Inglis Bay is located to the north of the fiord's mouth.

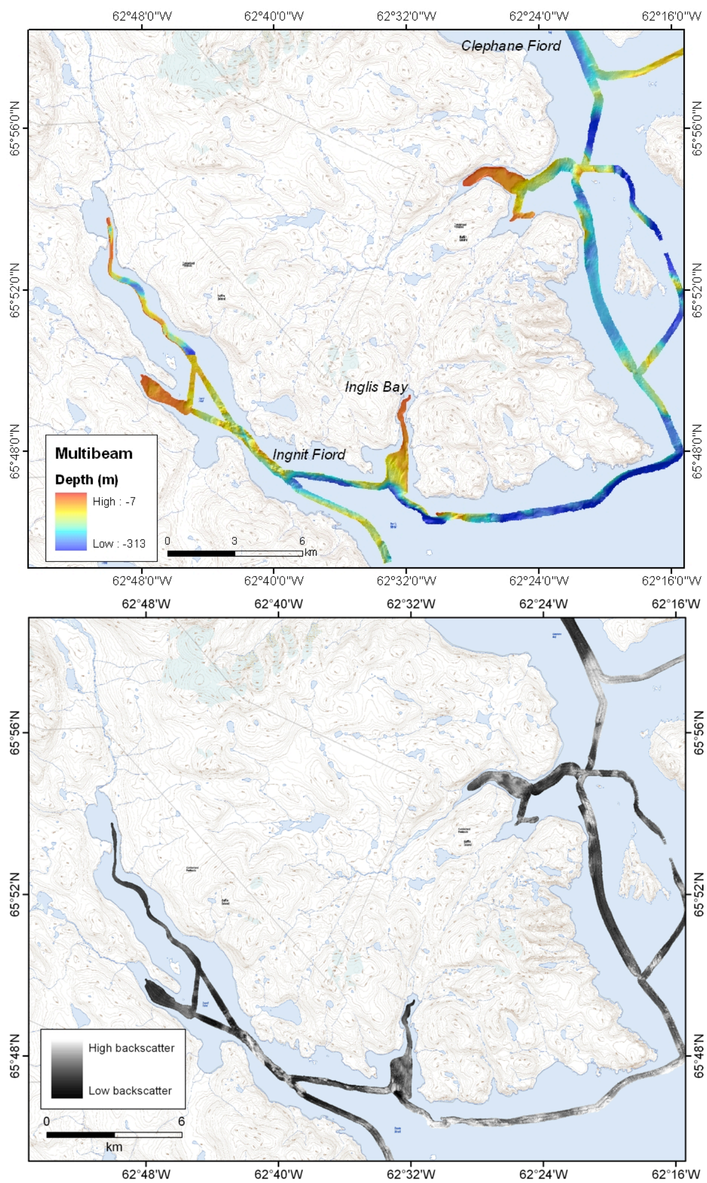


Figure A.42: Overview of Ingnit Fiord and Inglis Bay.

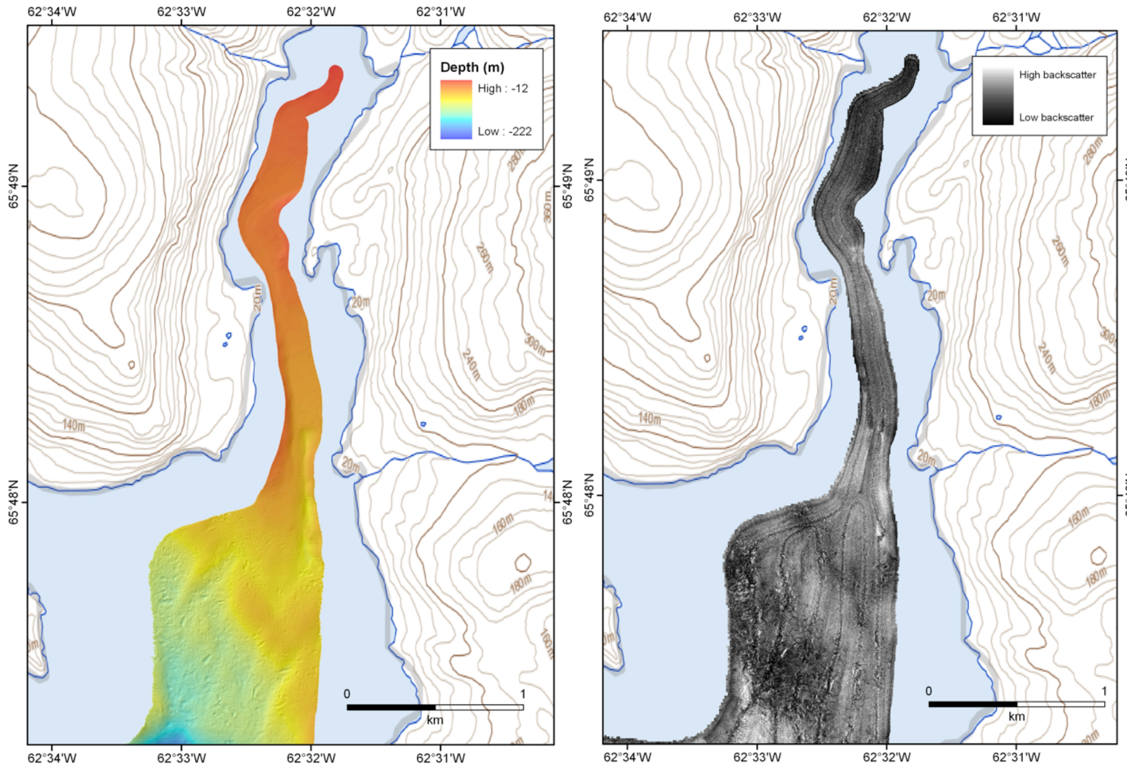


Figure A.43: Inglis Bay.

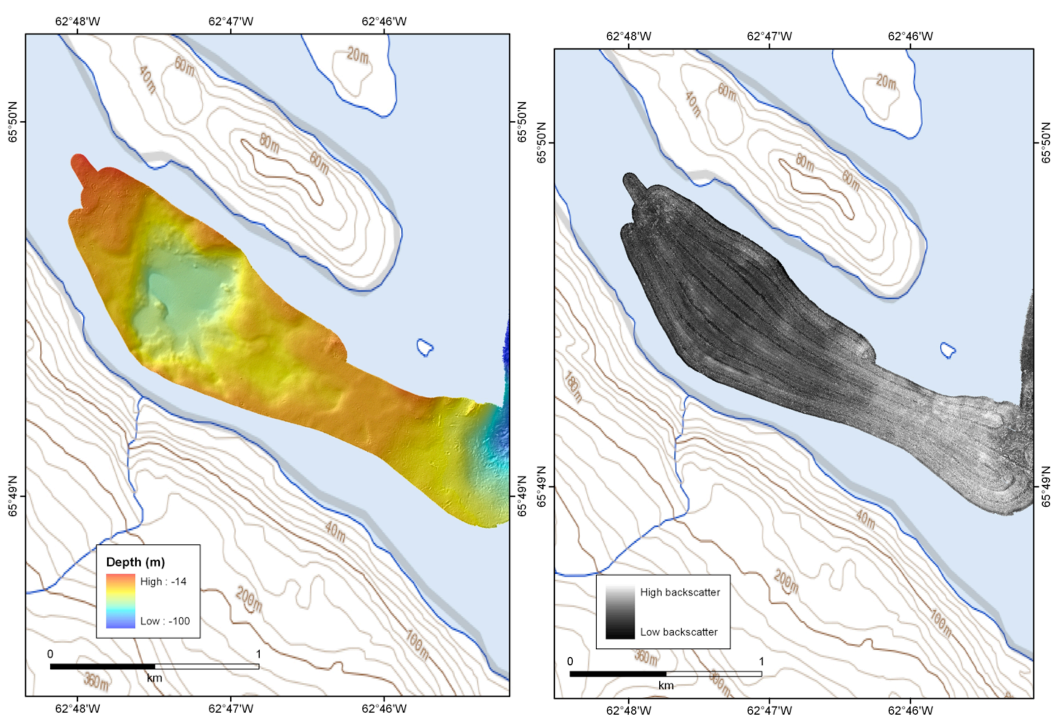


Figure A.44: First recce entering Ingnit Fiord.

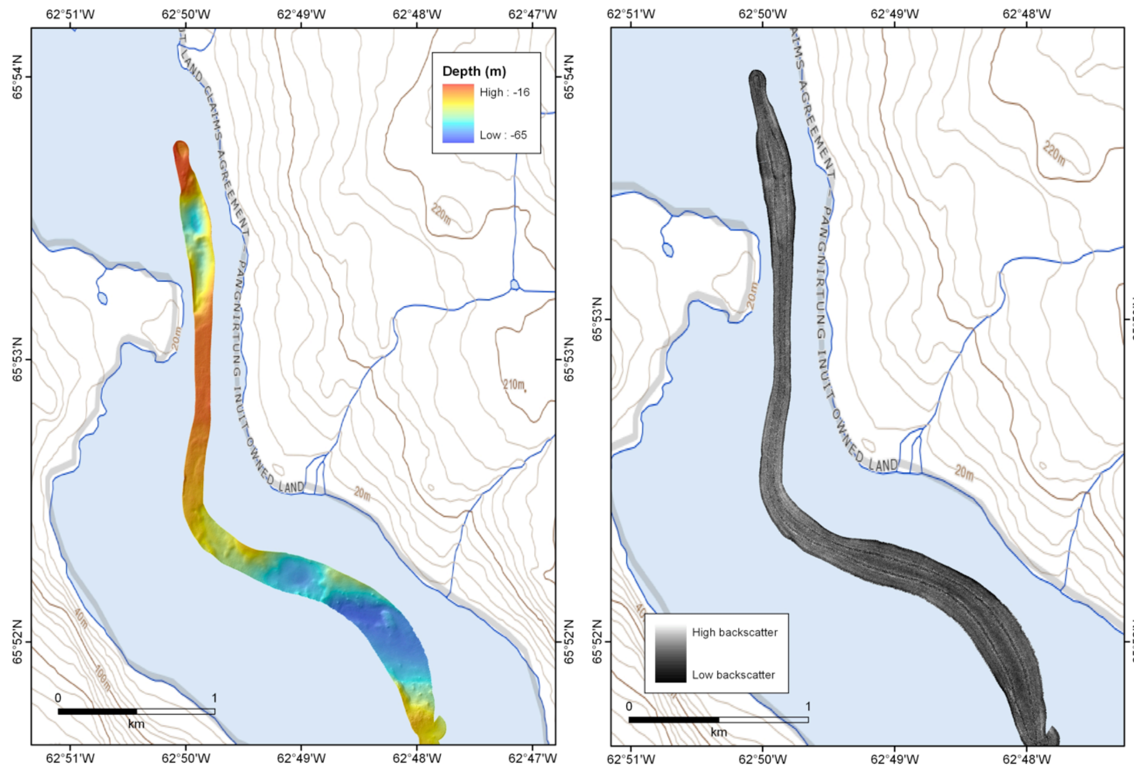


Figure A.45: Ingnit Fiord head.

Ingnit Fiord opens up into Baffin Bay with a 190 m deep basin at its mouth (Fig. A.42). Inglis Bay is made up of continuous subaqueous sediment fan, which displays gullies along it's slope as it opens into the mouth basin (Fig. A.43). The main fiord is pinched at its midpoint by steep bedrock sidewalls. The tributary arm is a steep sided depression at 48 m below sea level, infilled with fine sediment (Fig. A.44). The mouth of this tributary is marked by a sill 26 m below sea level, with many pit and wallow marks, which slopes down to the main fiord's basin floor at 90 m below sea level.

Moving further into the fiord is another sill and basin, at a minimum depth of 24 m, and a maximum depth of 52 m below sea level (Fig. A.45). At the fiord head is a 15-20 m depression in the seabed. This could be another basin in between two sills, but there is not enough coverage to characterize these features further.

A.7.12 Touak Fiord

Touak Fiord strikes northwest-southeast for a distance of 33 km, and is on average 3 km wide. The head of Touak Fiord is in close proximity to valley glaciers and remnant cirque glaciers, and has a braided river valley without a delta plain, that extends up valley almost to the termini of the main valley galcier. Touak is a classic fiord with steep sidewalls and side entry tributary valleys, including some hanging valleys. The mouth of Touak Fiord adjoins the mouth of Nallussiaq Fiord to the southwest. These two open into an embayment along Cumberland Peninsula's eastern coast that feeds into Baffin Bay.

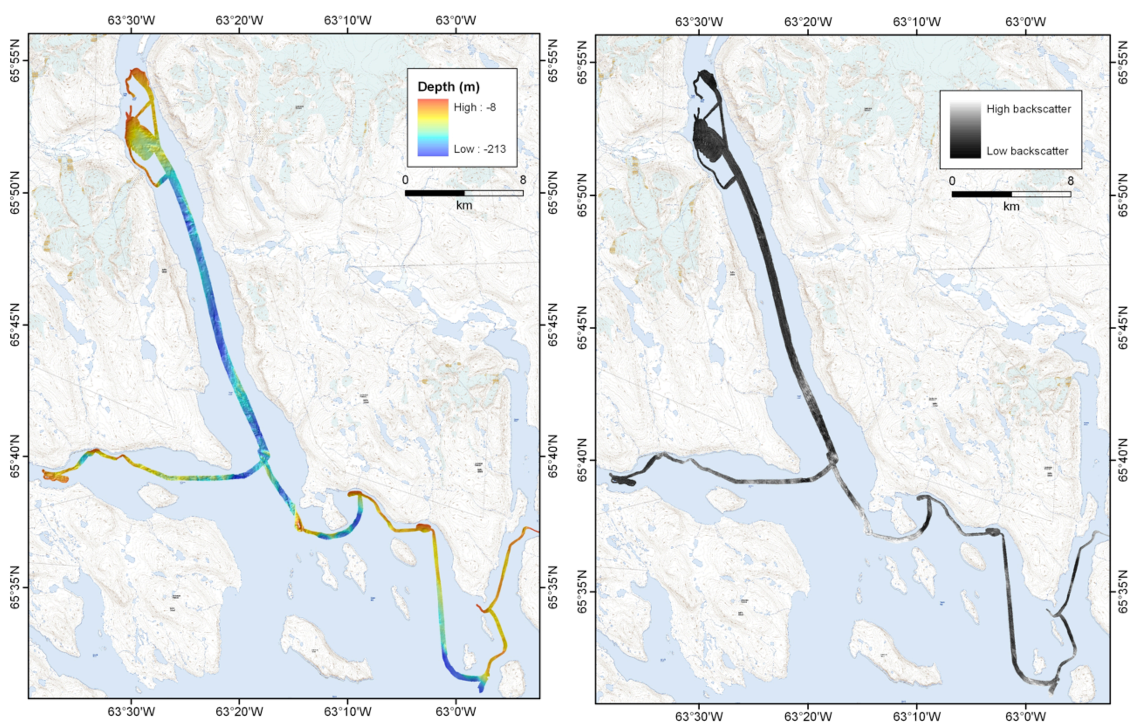


Figure A.46: Overview of Touak Fiord, and outside embayments.

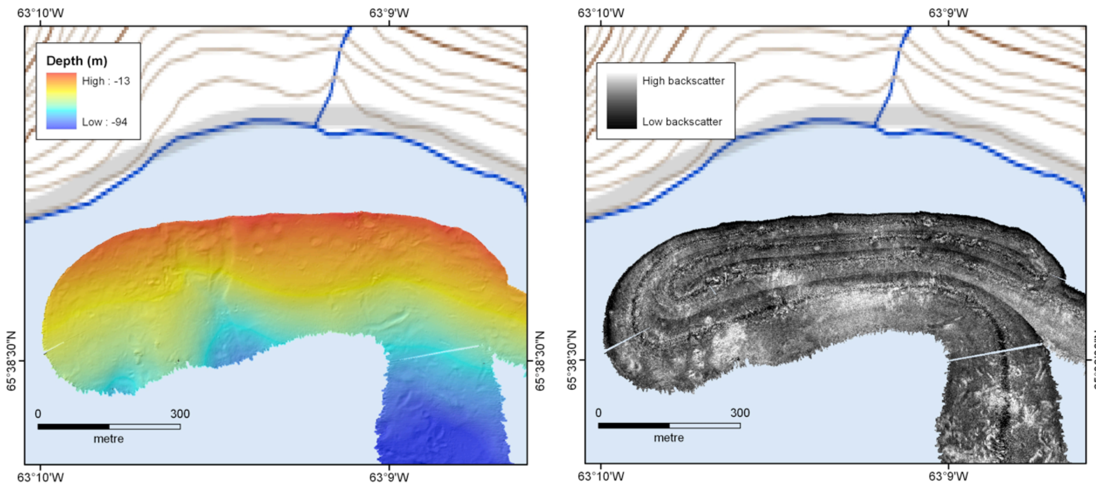


Figure A.47: Falls Bay, first embayment east of Touak Fiord mouth.

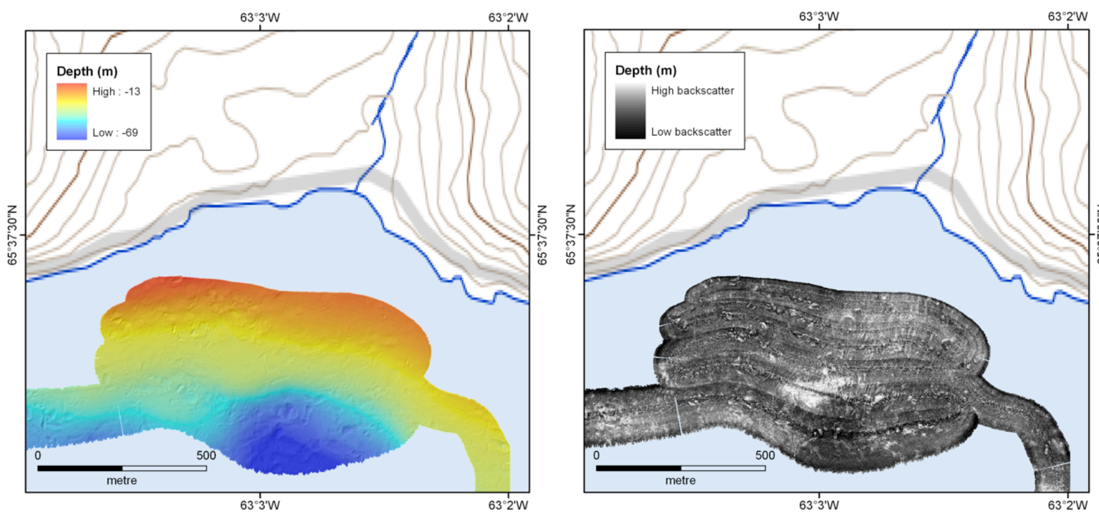


Figure A.48: Embayment east of Falls Bay.

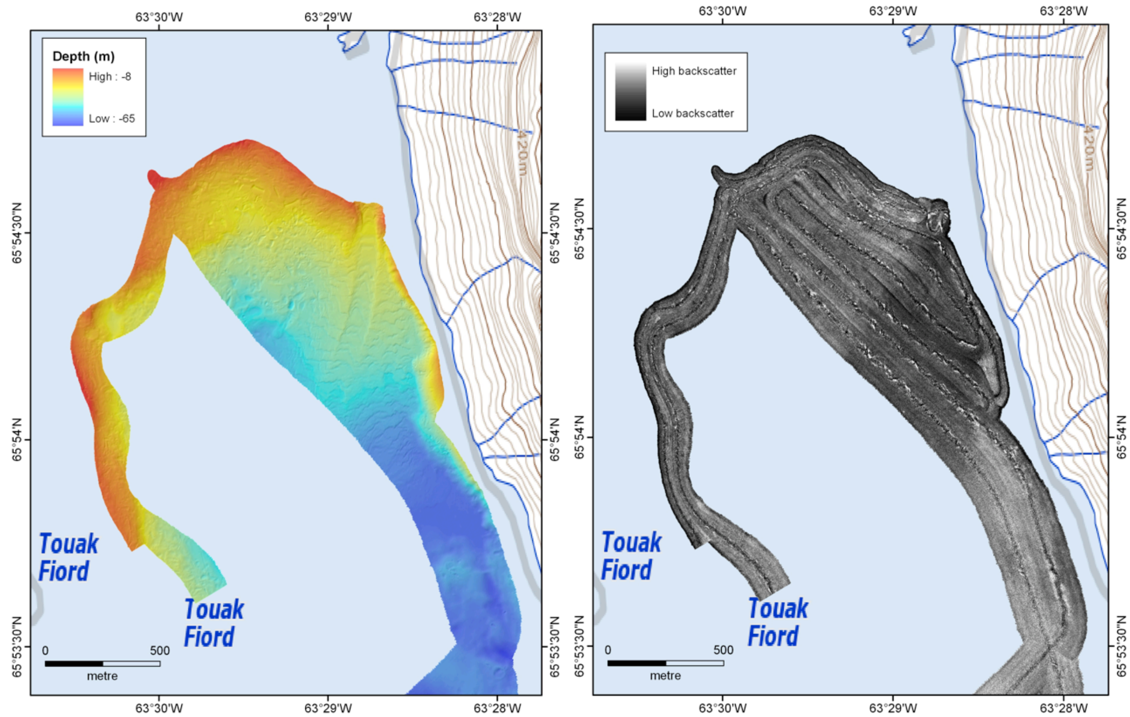


Figure A.49: Touak Fiord head.

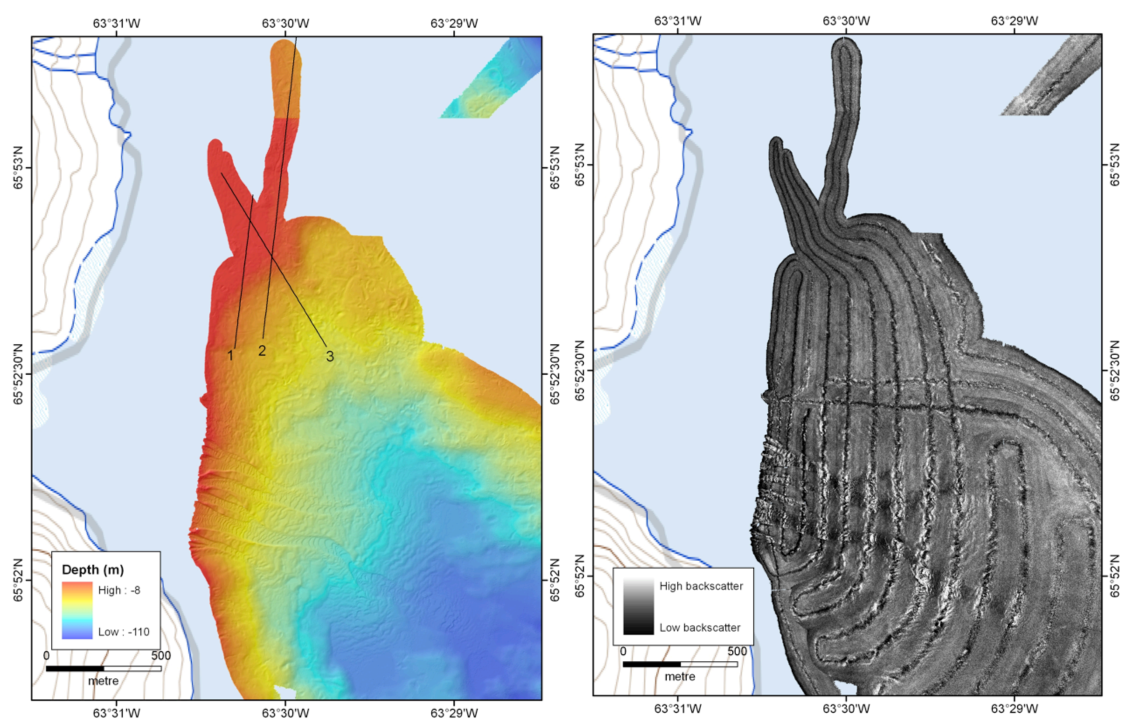
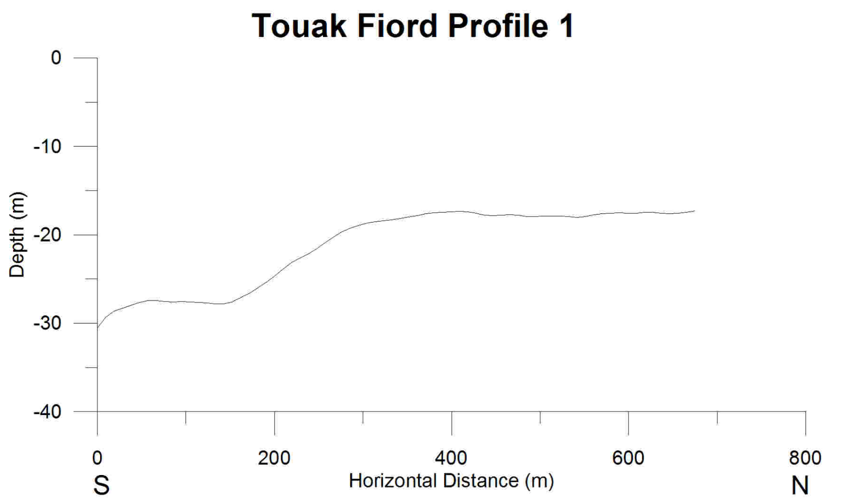
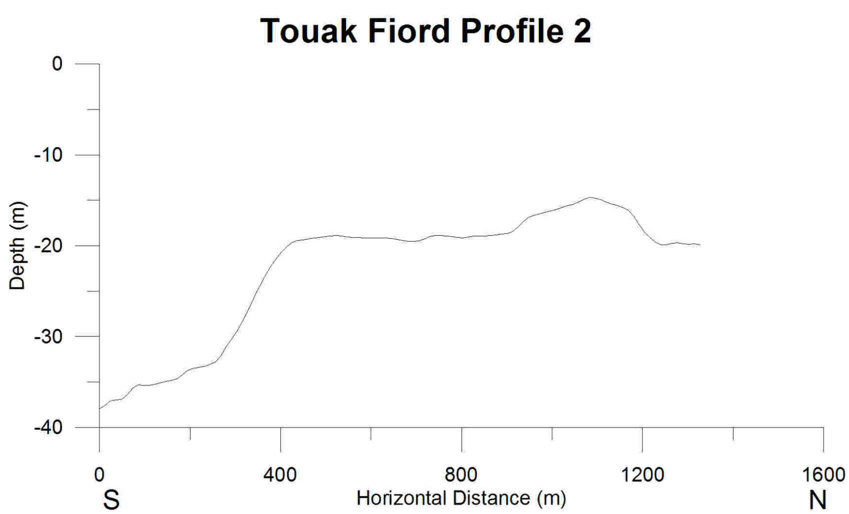


Figure A.50: Recce south of Touak Fiord head.

Along the transit into Touak Fiord, two coastlines were mapped in search of lowstand indicators. Falls Bay and the embayment to the east (Fig. A.47 & Fig. A.48) have well developed beaches at their modern shoreline due to the open fetch, however the submerged region does not show any terrace or significant depositional feature. A moderately steep slope into the adjacent basin characterizes both of these sites.

At the mouth of Touak Fiord are shoals with reliefs of 70 m off the seafloor, which is at a depth of 166 m. Most of the outer fiord is glacially scoured, with minimal evidence of sediment deposition, perhaps due to strong currents. Touak Fiord has steep sidewalls, and it is only at the head of the fiord that sedimentary deposition is mapped along the edges of the fiord from inflowing tributaries. In the centre of the fiord are remnants of glacial material. The fiord head exhibits a gentle slope with a channel along the eastern edge that includes in-channel bedforms (Fig. A.49). Adjacent to the mapped fiord head, but down-fiord to the west appears to be a terraced fan delta (Fig. A.50). Profiles along the tracts are shown in Figure A.49, showing a terrace lip at approximately 20 m below sea level. This feature perhaps extends from the delta fan to the south that exhibits gullies along its slope. Unfortunately this feature was not mapped and therefore has many unknowns, in particular its point source and extent. Perhaps it is something that could be looked into in future multibeam surveys.





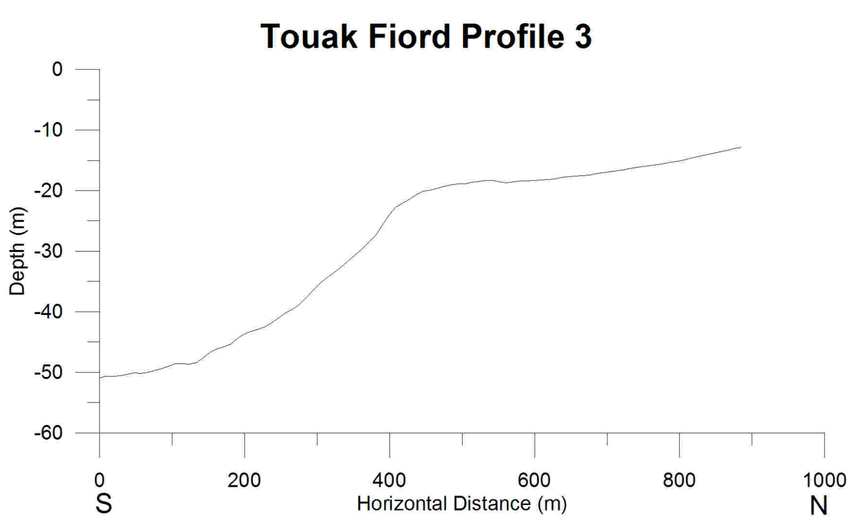


Figure A.51:Profiles of Touak Fiord eastern side, from Figure A.50.

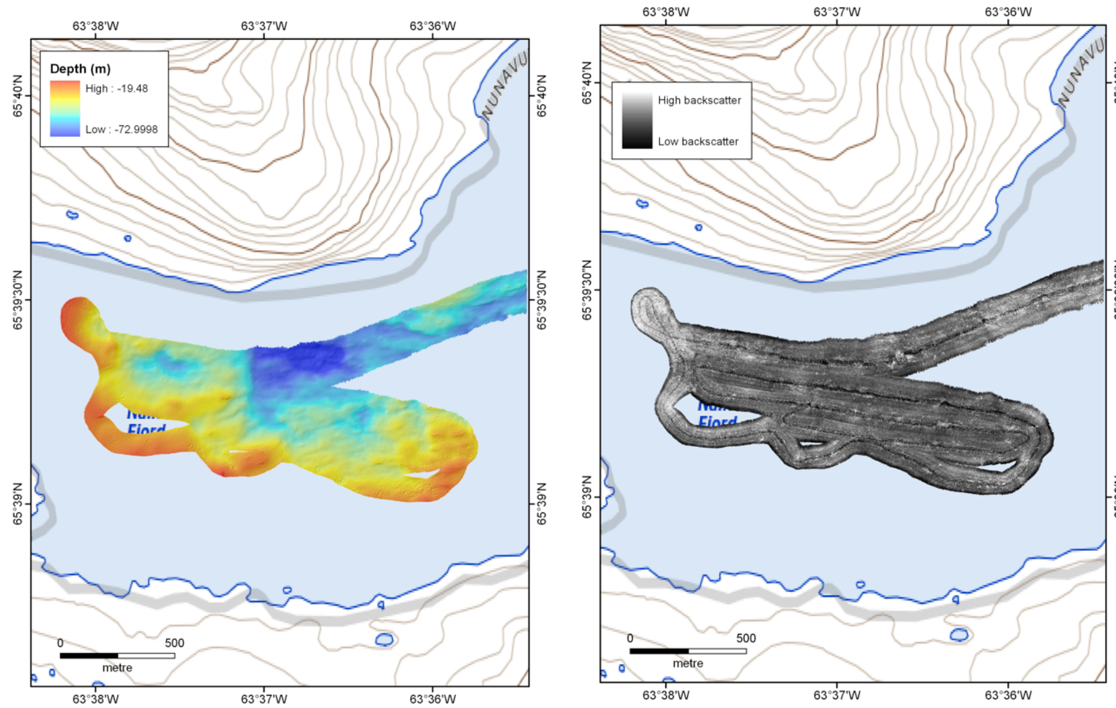


Figure A.52: Nallussiaq Fiord, west of Touak Fiord mouth.

Nallussiaq Fiord strikes east-west for a length of 18 km, with an average width of 2.9 km. The head of this fiord is a junction between multiple tributary valleys with the source water coming from a series of upstream lakes. The multibeam mapped a basin and slope that is sediment starved (Fig. A.52). The basin has a depth of 190 m with steep sidewalls.

A.7.13 Aktijartukan Fiord

Aktijartukan Fiord is a north-south striking fiord that is a tributary of a much smaller fiord, which opens up into Cumberland Sound to the south. It is not a characteristic fiord with a fiord head delta, but rather has a series of embayments at it's head and actually continues inland with a series of attached lakes. The main fiord system is 12 km long and on average has a width of 1.3 km. Within the immediate vicinity of the fiord, there are no remnant glaciers.

The single-beam echosounder was used on the Nuliajuk RHIB to map shoals and the littoral gap in the multibeam data, and is the only site that this technique was used on this cruise.

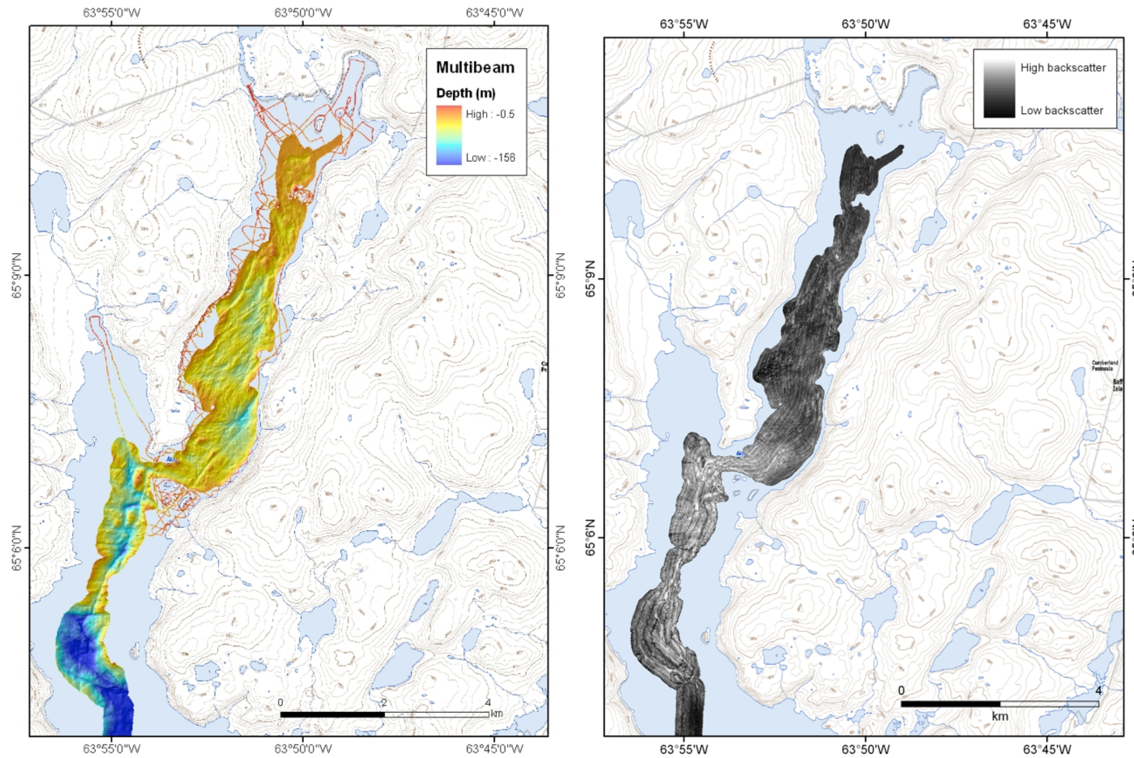


Figure A.53: Overview of Aktijartukan Fiord, including single beam echosounder transects with the Nuliajuk RHIB.

Aktijartukan Fiord is remarkably starved of sediment deposition, in comparison to the other fiords we have observed. There is deposition at the head of the fiord, but the basins look to have recently been glacially scoured since they have not been infilled by sediment (Fig. A.53). There are not the typical steep sidewalls, as in the majority of the fiords, but rather jutting bedrock across the seabed. In the outer fiord the bedrock looks to be scoured by a single stream or fracture running through it. The inner basin reaches 87 m, at its lowest point, and the outer fiord reaches a depth of 140 m.

A.7.14 Pangnirtung Fiord

Pangnirtung Fiord is the location of the community of Pangnirtung. The fiord strikes northeast-southwest and is approximately 42 km long, and on average 2.3 km wide, opening into Cumberland Sound. Along the head of the fiord, and along the eastern side of the fiord are many remnant cirque and valley glaciers. The head of the fiord incorporates a thin but elongate braided river valley situated at the base of the U-shaped valley. Along the fiord are steep sidewalls with glacially sourced drainage, resulting in alluvial fans, and multiple hanging valleys and tributary valleys.

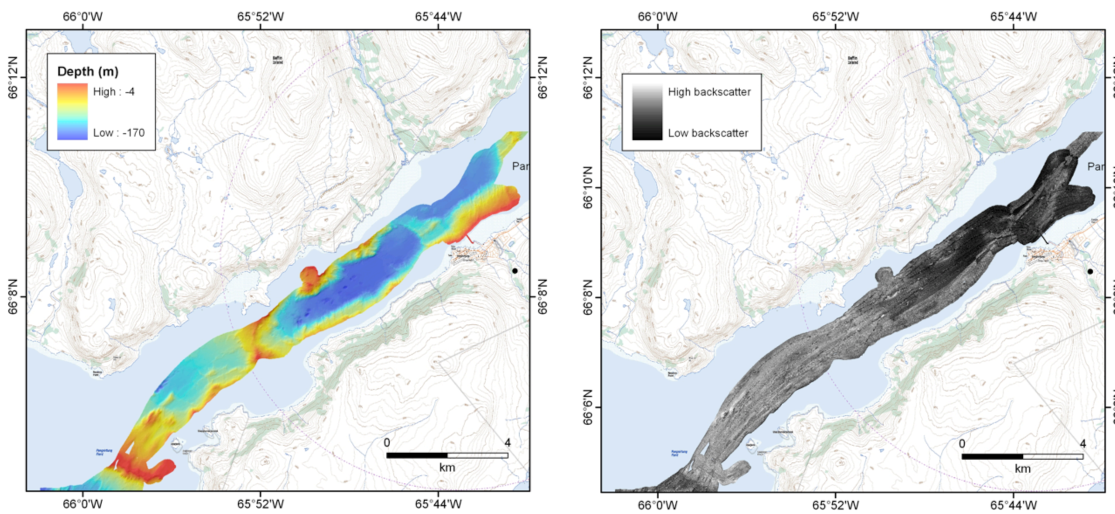


Figure A.54: Overview of Pangnirtung Fiord.

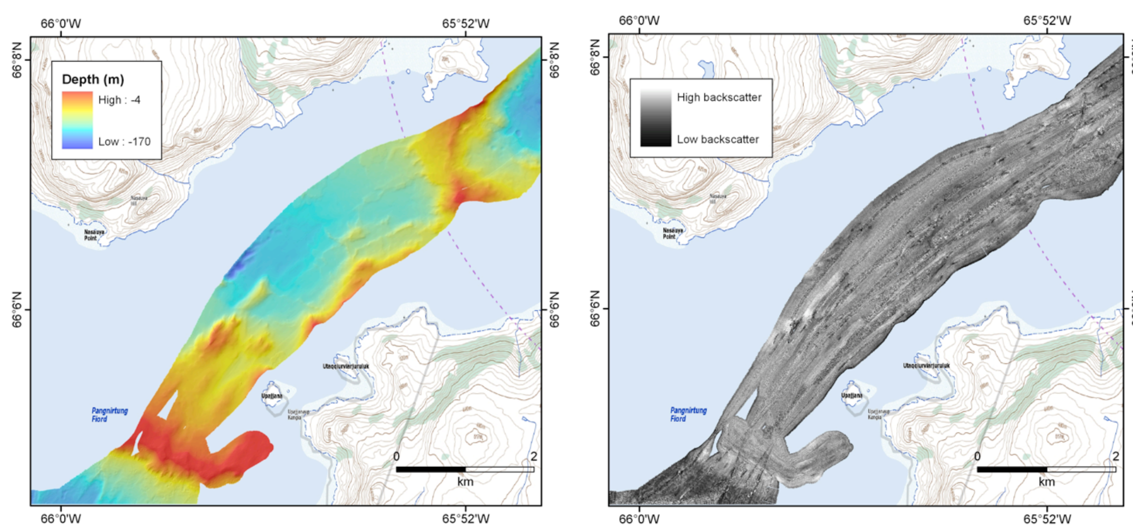


Figure A.55: Pangnirtung Fiord mouth.

Pangnirtung Fiord is a characteristic fiord with a series of basins and sills (Fig. A.54). Two sills are observed from the multibeam map and interpreted as moraines, one at the mouth is 25 m below sea level and likely the terminal moraine and another just inside the fiord, is a recessional moraine at 45 m below sea level (Fig. A.55). In between is a basin with a depth of 155 m, further up the fiord is another basin with a depth of 158 m. Along the sidewalls of the fiord are many talus and alluvial fans, and just in front of the community is an extensive tidal flat dropping off into the basin. Adjacent to the Hamlet of Pangnirtung is a tidal flat at a depth of 7 m, which drops off into the second basin within the fiord to a depth of 158 m. The slope shows active channeling and failures due to continued river sedimentation.

A.8 SIGNIFICANT FINDINGS

These two cruise seasons resulted in the baseline high-resolution bathymetry charts for safe anchorage and corridors, as well as to add to benthic habitat datasets for specific fisheries locations. In addition, these two cruises resulted in the discovery and documentation of nine submerged shorelines, mainly delta terraces but also a barrier platform with spillover and a boulder barricade upon a beach terrace. These depositional and erosional features are all formed at, or in close proximity to sea level and therefore limit the elevation range of sea level.

Deltas prograde through continued sedimentation and deposition at sea-level. Gilbert-style deltas are steep-faces deltas, whose delta plain (horizontal topsets) prograded on to a steeply dipping delta front (foresets), which continue on top of horizontal prodelta sediments (bottomsets) (Masselink et al., 2003), which can be distinguished in subbottom profiles (Boas Fiord, Fig. A.20). Alluvial-fan deltas are generally built up of coarse gravel and sand along fiord sidewalls and from side entrance valleys (Prior et al., 1990), which are present at various water depths in Kangert Fiord, Boas Fiord & Mermaid Fiord. Fiord-head deltas are usually built of finer-grained gravel, sand and silt, of extensive volume from large supply catchments. Due to the confining valley walls, the fiord-head deltas are rarely fan shaped, and usually have across-fiord, relatively straight progradational fronts (Prior et al., 1990). Kangert and Boas Fiords both have fiord-head deltas (Fig. A.12 & A.19). The delta within a cove to the east of Southwind Fiord (Fig. A.26) shows similar characteristics to a fiord head delta, due to confining valley walls, however it is not found at the head of a fiord. The formation of a fiord-head delta within a cove is likely due to similar large supply catchments depositing into the cove, as are present at fiord-heads. The submerged deltas are interpreted to have been ice-contact deltas (Miller, 1975), which indicates that these evolved from grounding-line fans or other subaqueous depositional features and was further built out directly from glacial margins (Benn et al., 2010). From long-term development of the deltas, downslope aggradation and slope instability, combined with fiord bottom sedimentation, progressively decreases the delta front gradient (Prior & Bornhold, 1990), resulting in the low slope inclinations of these submerged deltas.

At the mouth of Akpait Fiord is a platform at a depth of 50-52 m below sea level, which is remarkably flat, and has a convex slope along its landward edge (Fig. A.29). This feature has been interpreted as glaciogenic sediments that have been remobilized and deposited by littoral processes prograding from a barrier beach spit into a barrier platform with a landward spillover. A similar feature was described by Shaw et al. (1992) in St. George's Bay, Newfoundland. The primary deposit may have been an ice-contact deposit, from when the glacier reached the fiord mouth, which explains a glacially over-deepened basin. The glaciogenic material has since been reworked by wave action and entrapped drifting sediment from the northern shoreline, adding finer-grained sediments to the heterogeneous deposit. The spillover forms from the mobilization of sand and gravel by wave action, across the shallow feature into the deeper basin on its landward side (Shaw et al., 1992). The spillover therefore must have been at a water depth within the range of the active wave height. The feature is currently at approximately 51 m below sea level, which represents a maximum depth of the sea level lowstand.

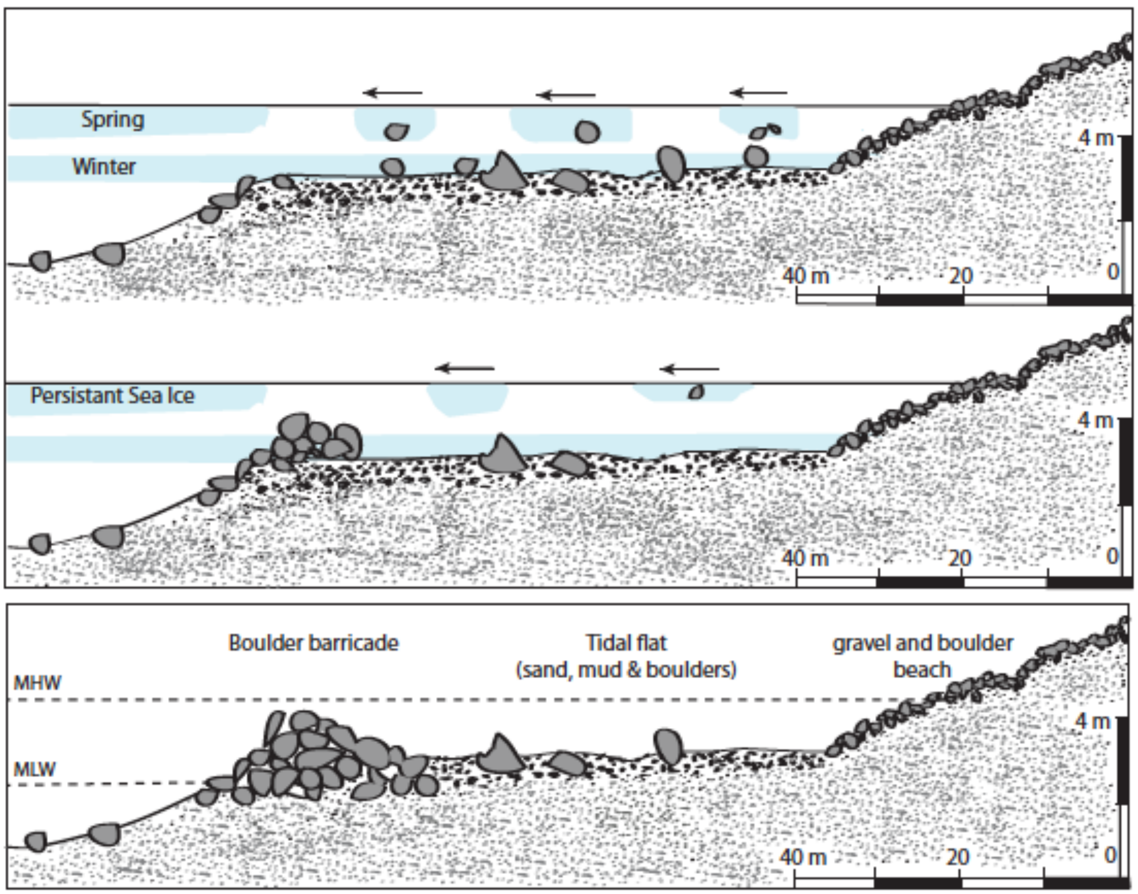


Figure A.56:Schematic diagram of the progressive formation of a boulder barricade through the seasons. Modelled from Kelletat, 1995 & Gilbert, 1990.

A boulder barricade is an elongate ridge of boulders that are emplaced at the low tide level, parallel to the coastline in arctic and subarctic settings, separated by a low gradient intertidal zone (Rosen, 1979; Dionne, 2002). The combined effects of downward freezing and surface melt of intertidal ice, during the late winter, result in the transportation of boulders up through the ice. During the spring ice melt-up the boulder laden ice rafts are transported to the limit of the floating ice against the more persistent sea ice, and grounded on the nearshore break in slope at the mean low water line (Fig. A.56). The sea ice and the deeper waters likely prevent the seaward migration of the ice rafts (Forbes et al, 1994, Aitken et al., 1988). At this strandline the boulders are deposited as the ice rafts melt, forming a concentration of boulders into a ridge over subsequent seasons, which continues to entrap successive ice rafts. Rosen (1979 & 1982) delimited three conditions necessary for the formation of a boulder barricade, these are: a) a rocky coastal setting to form the source of the boulders, b) sufficient winter ice and water level fluctuations in order to encase the boulders in the ice, and c) a distinct break in slope in the nearshore zone. Without the third condition, the boulders would deposit as random bouldery flats. Boulder barricades represent phases in sea-level stability (Gray et al., 1980), and have provided evidence to regional emergence as a sea level indicator (Loken, 1962). Loken (1962) interpreted the highest boulders in the barricade to indicate high tide level, which was observed to have estimated errors, but no more than those for other index points and suggest that this method for determining sea level can only be applied for regions with low tidal range. The submerged boulder barricade that was mapped during the first cruise season (Fig. A.5) is only found along the east coast of Broughton Channel at 16-17 m below sea level. No other submerged boulder barricades were observed throughout mapping surveys, and there are no known barricades at the modern shoreline within the region of Broughton Channel. Therefore this documentation is significant to the records of coastal change for the region, due to the lack of any similar modern or historic feature.

At present, Cumberland Peninsula is experiencing submergence, which began approximately 1000 ka (Pheasant et al., 1973). Physical evidence along the outer coasts of Cumberland Peninsula suggests that sea level was lower than present over the last 6 ka BP, and the present seas level is proposed as the marine limit for the easternmost coasts (Andrews et al., 1985: Andrews, 1980; Dyke, 1979; Pheasant et al., 1973). Andrews (1980) delimited the sea level changes over the last 125,000 years, which defined the period of 1-8 ka BP as the Inugsuin Regression. Clusters of raised marine terraces and delta deposits' C^{14} dates indicate major shoreline-building episodes during the Inugsuin Regression at 7800±, 6400±, 4800±, and 2800± (Andrews, 1980). The switch from emergence to submergence is predicted to be from the migration and collapse of the forebulge, a remnant crustal adjustment of the Laurentide Ice Sheet. The sea level curve for the Cumberland Peninsula is not well constrained, due to gaps in sea-level indicators, and therefore the sea level curves that have been presented for the region are speculative and present a hypothesis. The hypothesis states that the sea level history of the western Cumberland Peninsula is one of glacioisostatic rebound, and the history of the eastern Cumberland Peninsula is one of eustatic and hydroisostatic submergence (Pheasant et al. 1973: Dyke, 1979; Andrews, 1980; Clark, 1980; Andrews, 1989). This hypothesis is also instated in the isobase maps for the region, of which the zero isobase has been progressively moving westward, where it is believed to be along the westernmost extent of Cumberland Peninsula at present (Andrews, 1989; Andrews, 1980; Pheasant et al., 1973). This trend is also observed in the submerged dataset that is presented in this report (Fig. A.57), which shows the greatest submergence of the lowstand to be in the east. These submerged features are assumed to have formed at a single lowstand shoreline-building episode, and therefore express the crustal tilt across the peninsula. Miller and Dyke (1974) extrapolated the northern Cumberland submerged deltas to be of late Wisconsin-age from the absence of raised marine features of this age in the region, implying that it is outside the zero isobase for emergence, and because raised marine deltas located 140 km to the northwest are approximately 8,000 yr old. The majority of submerged features lie upon the trend line, however one lies below. This sea level indicator is located to the south of Clephane Fiord mouth, and from its southern location are interpreted to be at a greater depth because isobase lines are not straight but wrap around, contouring the shape of the peninsula.

The results of these two cruises adds to the bathymetric charting of safe arctic anchorage and transit corridors, to the baseline bathymetry for fisheries habitat research, and sea level indicators to interpret submergence trends for eastern Baffin Island.

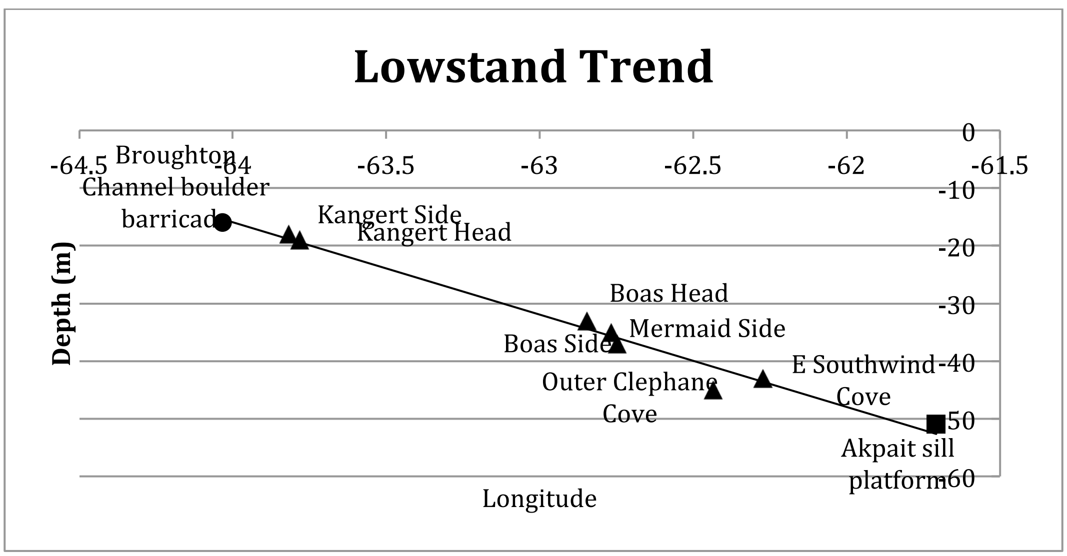


Figure A.57: Graph of the depths of all the significant submerged shoreline features along east-west coordinates of Cumberland Peninsula. A trend line exhibits the tilt of this lowstand from west to east across the peninsula, presuming that they have similar ages. Triangles: submerged delta; circle: boulder barricade; square: sill platform.

Table A.1: Grab sample locations and preliminary descriptions.

Site/ Sample number	Date	Location	Latitude	Longitude	Camera Time down	Camera Time at bottom	Depth (m)	Sediment Observations	Comments
1	11-10-2012	Boas Fjord	66.68463	62.83753	22:02:48	22:03:52	-29	soft brown, silty clay	2 brittle stars
2	11-10-2012	Boas Fjord	66.68604	62.85447	22:18:22	22:19:20	-29	similar to 1	sampled coral, observed brittle star
3	11-10-2012	Boas Fjord	66.65405	62.87221	22:53:32	22:54:10	-20	denser sediment, cohesive soft brown gritty silty clay	
4	12-10-2012	Giffs Cove-inner shelf	66.777064	62.73991	15:31:09	15:32:04	-22	soft, brown silty clay, full of organics	Clam picked up during cleaning, worm observed
5	12-10-2012	Giffs Cove-outer shelf	66.776993	62.749476	15:46:56	15:48:16	-34	Pebbly soft brown silty clay	3 clams picked up
6	15-10-2012	Bears Cove	66.406866	62.690849	21:30:43	21:32:50	-58.8	smooth, brown	worms
7	16-10-2012	close to shore	66.402635	62.236383	15:40:05	15:41:10	-20	not much sediment-rocky, coarse grained,	worms, clams, shrimp
8	16-10-2012	on terrace	66.395930	62.25833	16:18:45	16:20:09	-41	Didn't pick up anything	
8	16-10-2012	on terrace	66.395698 N	62.259620 W	16:28:10	16:29:20	-41	Soft brown silty clay with scattered pebbles	brittle star
9	17-10-2012	mermaids fjord	66.304930 N	62.805972 W	11:40:14	11:41:00	-30	didn't bring up anything	
9	17-10-2012	mermaids fjord	66.304692 N	62.806071 W	11:42:50	11:45:30	-30	cable wrapped around and opened the grab, sampled the remaining sediment- soft brown mud.	

Table A.2: Camera locations and descriptions.

Site	Date	Location	Time (UTC)	Latitude	Longitude	Longitude	Latitude	Recording time start	Recording time end	Depth (m)	Comments
2012-1	11-10-2012	Boas Fjord	21:45	66.68580	62.83503			0:00:00:00	0:04:50:00	-30	One light worked, though too bright
2012-2	11-10-2012	Boas Fjord	21:50	66.6845	62. 83477			0:06:09:00	0:11:51:02	-30	Turned lights off, though too dark
2012-3	12-10-2012	Boas Fjord	10:50	66.65405	62.87221			0:00:00:00	0:05:43:21	-20	6 sheets patchment paper over light to scatter it
				down		up					
2012-4	12-10-2012	Giffs Cove-inner	14:54	66.77695	62.74039	66.77703	62.74059	0:00:00:00	0:08:12:50	-24	Changes parchment paper to only 3 sheets.
2012-4	12-10-2012	Giffs Cove-inner	14:58	66.77710	62.74083	66.77714	62.74111	0:00:00:00	0:08:12:50	-24	lasers not working
2012-5	12-10-2012	Giffs Cove-outer	15:19	66.77744	62.74839	66.777682	62.748725	0:11:19:13	0:18:05:10	-35	back down with lasers working
2012-6	15-10-2012	Bears Cove	21:20	66.406622	62.690189	66.406717	62.690121	0:00:00:00	0:07:27:11	-63.3	wire stuck half way, had to unravel it.
2012-7	16-10-2012	Totnes Cove by shore	15:29	66.403152	62.235615	66.403070	62.236064	0:00:00:00	0:05:35:23	-20	
2012-8	16-10-2012	Totnes Cove on terrace	16:15	66.395996	62.259081	66.395720	62.260182	0:05:35:24	0:10:40:02	-41	
2012-9	17-10-2012	mermaid fjord	11:15	66.305684	62.807512	66.305684	62.807512	0:00:00:00	0:03:02:03	-29	light too dim.
2012-9	17-10-2012	mermaid fjord	11:24	66.305684	62.807512	66.305535	62.806381	0:03:02:03	0:11:44:11	-29	New batteries in light

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B COASTAL CLASSIFICATION

Appendix B summarizes the coastal mapping program which took place due to funds allocated by ArcticNet and Northern Student Training Program between August 20th and September 13th, 2013. The surveys were undertaken in Broughton Channel within the vicinity of Broughton Harbour and the Hamlet of Qikiqtarjuaq, Nunavut (Fig. B.1). The data was collected with Real Time Kinematic GPS and single beam sonar from both the coastline and seabed. The full field report and data can be accessed from the GSC-Atlantic: s5-dar-kayak; Cowan; THESIS_APPENDIX; Appendix B.

B.1 COASTAL MAPPING DATA SET

The sediment samples for coastal mapping, as well as the sonar, video and GPS raw and processed data are under the supervision of Trevor Bell at Memorial University of Newfoundland. The data can also be acquired from the Geological Survey of Canada s5-dar-kayak; Cowan; THESIS_APPENDIX. The previously acquired multibeam bathymetric data is under the supervision of Ocean Mapping Group, New Brunswick University and accessible through http://www.omg.unb.ca/Projects/Arctic/.

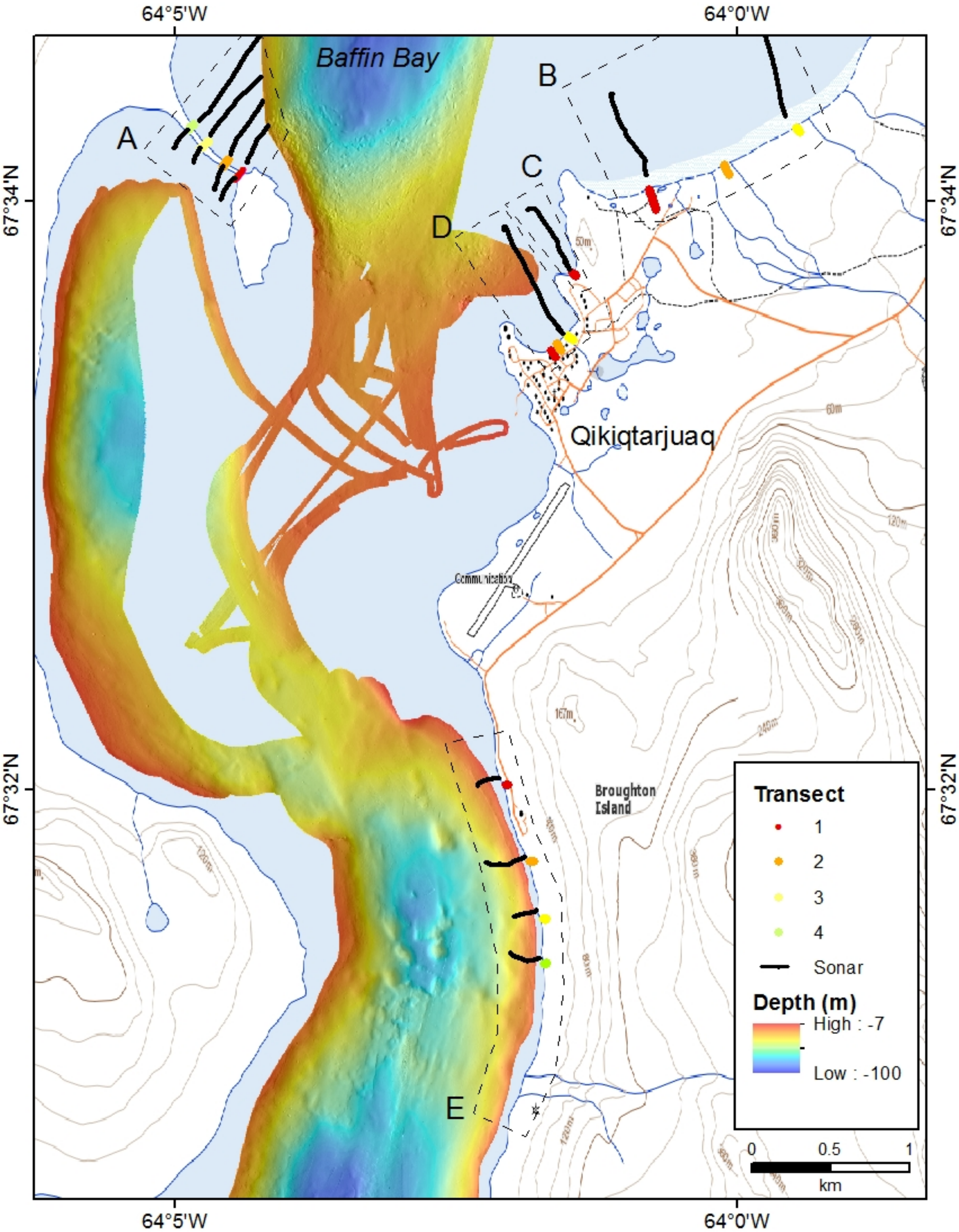


Figure B.1: Location map of sonar surveys and adjacent RTK surveys within Broughton Channel. Transects are labeled by beach (A-E) and colour coded transect number (1-4). Table B.1 provides a summary of the beach morphology, and Table B.2 summarizes the grain size results from each beach survey.

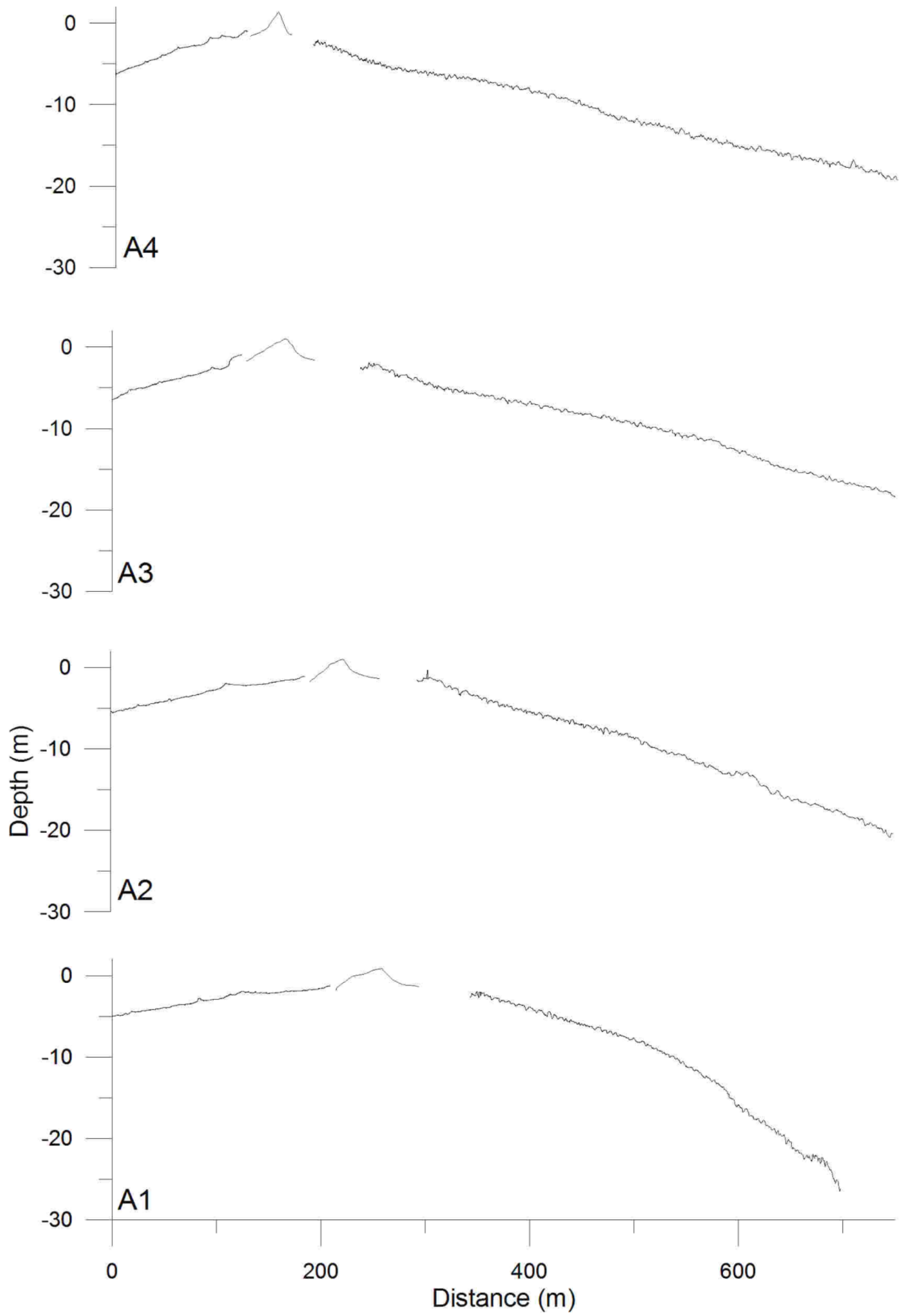


Figure B.2: Cross-profile of beach A and littoral zone to the north and south. 7.8x vertical exaggeration.

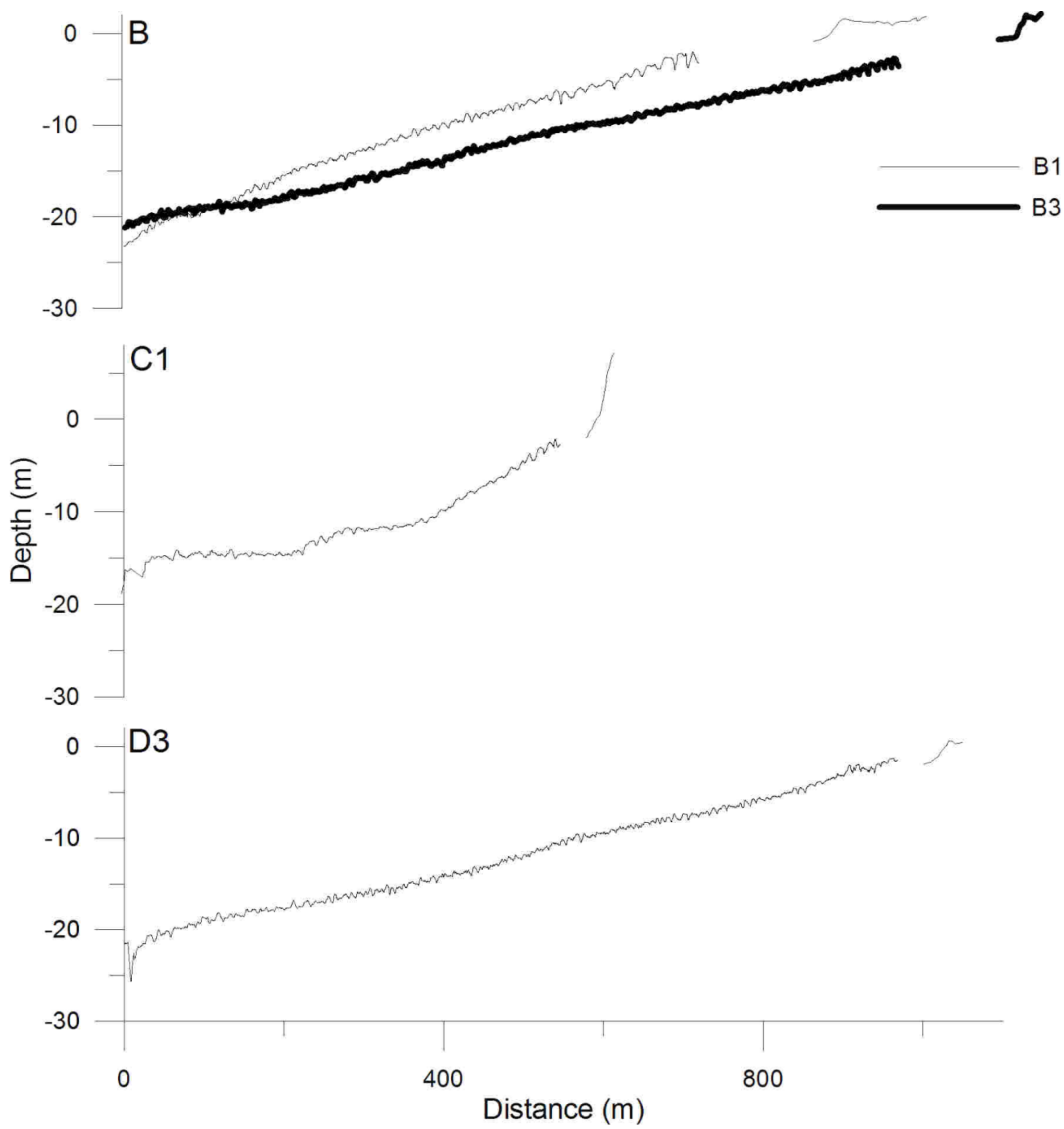


Figure B.3: Cross-shore profile of beaches B-D transects from littoral zone over the beachface. 11.5x vertical exaggeration.

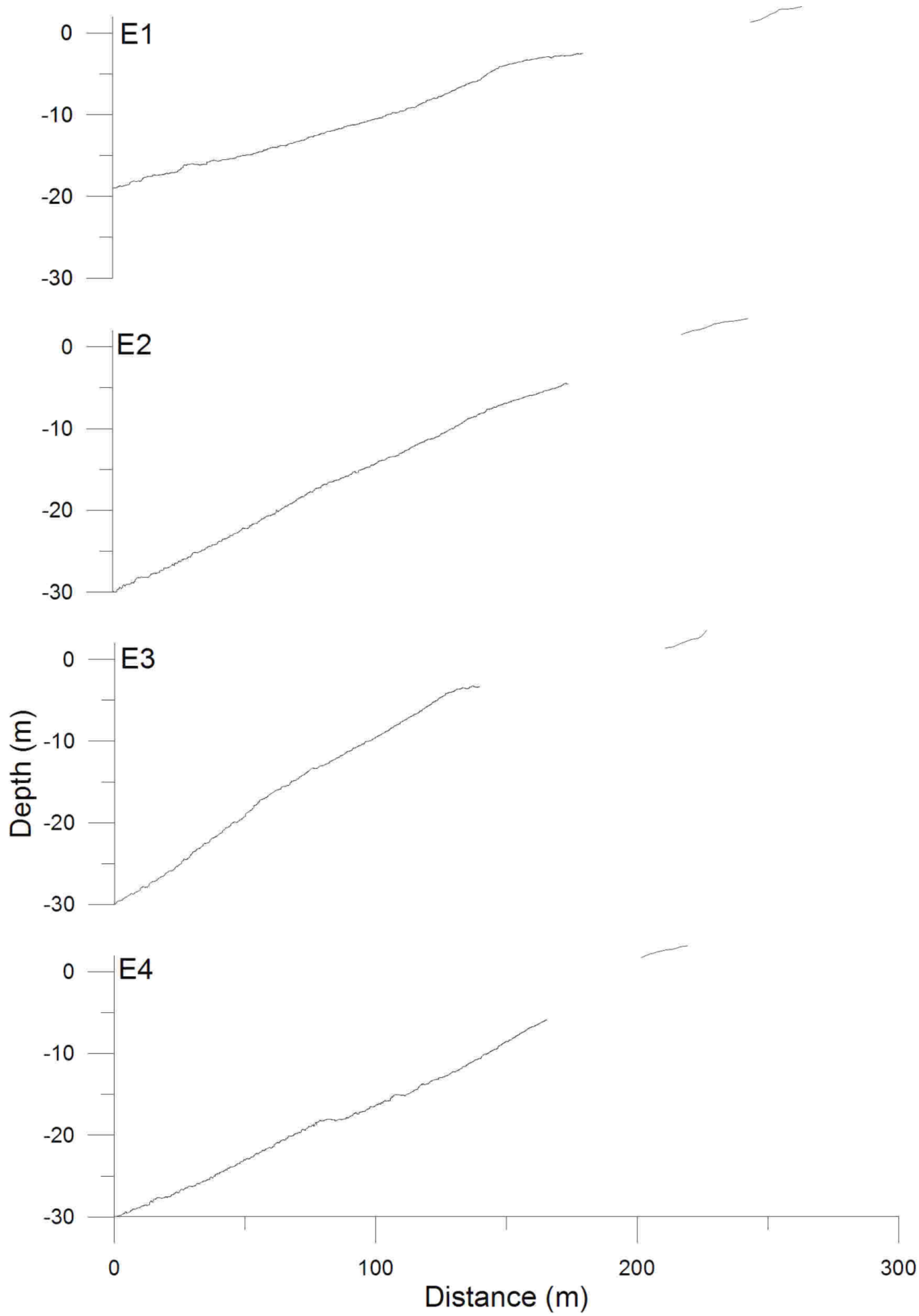


Figure B 4: Cross-shore profiles of beach E transects from littoral zone over the beachface. 3x vertical exaggeration.

Table B.1: Summary of beach morphology, sedimentology, with slope values for the five study locations surrounding Broughton Channel.

	Morphology			Average (°)			
Beach	Plan View	Cross-shore View	Sedimentology	Over-wash nearshore shoreface slope[1]	Backshore/ Over-wash beach[2] slope	Foreshore slope	Nearshore shoreface slope
A	Curvilinear continuous reflective barrier. Back barrier with intermediate exposure. Crest elevation, and foreshore slope increase towards the west. Beach width decreases towards the west.	1.4-2.2 m high, 35-50m wide barriers. Steeper foreshore vs. over-wash backface. Single crest. Over-wash clasts imbricated towards south. Oriented NE.	Predominantly sand in the east, with cobble-boulder lag in the washover. Transition to cobble-boulder beach in the west. Crests of well-sorted to moderately-sorted rounded-subrounded boulders. Beachface of moderately well-sorted rounded-subrounded cobbles with sand cusps on the over-wash beachface.	5.1	6.3	7.1	0.8

B	Curvilinear continuous reflective beach. Beach width decreases towards the east. Foreshore slope increases towards the east.	2-2.3 m high, 30-60 m wide beach. Gently sloping unconsolidated backshore plain. Oriented NNW.	Grain size increases towards the east. B1 is well sorted sand with scattered pebbles along the lower beachface, moderately sorted crest and backshore. B3 is moderately well sorted coarse sand with scattered pebbles on the lower beachface and moderately well sorted cobbly boulders on the berm, upper beachface, and crest.	1.86	10.7	3.8
C	Pocket gravel reflective beach between bedrock outcrops.	4 m high, 20 m wide pocket beach. Single berm crest. Moderately steep backshore (25°), bedrock cliff topped with eroding colluvium. Oriented NW.	Moderately well sorted subrounded-subangular cobble-boulder beachface. Clasts are predominantly bladed to elongate in shape. Overlying colluvium is made up of large subrounded clasts within a dark grey-brown silty matrix.	11.29	10.5	10.3

D	Continuous sand-gravel beach with boulder reef in the nearshore shoreface, between bedrock outcrop. Backbeach is a gently sloping turf plain with community development.	1.5-2 m high, 15-25 m wide beach. Gently sloping (6), unconsolidated backshore actively eroding. Swash limit observed overwashing backshore turf. Oriented NNW.	Moderately well sorted medium-coarse grained sand with scattered pebbles. With poorly sorted upper beachfaces and berms of pebbly-cobbly sand. Boulder reef at water line (av. 1 m).	3.8	6.8	5.6
E	Non-continuous pocket reflective beaches between bedrock outcrops. The northern beach is cut in the backshore by a pipeline and trail.	On average 1 m high, 10-15 m wide pocket beaches. Moderately sloping (22°), unconsolidated colluvium backshore cliff. Oriented WSW.	Poorly sorted, angular-subangular pebble and cobble on swash limits, along and below the waterline. Dominated by sand beachface in the north, and pebble-cobble in the south.	3.18	8.3	6.4

[1] The lower extent of the southern facing shoreface of the Tombolo barrier beach.
[2] The southern facing shoreface of the Tombolo barrier beach

Table B.2: Summary of grain size analysis from beach transects, located in Figure B.1. Statistics are calculated with Method of Moments by GRADISTAT v. 8.0.

Location		Size Fractions (%)[a]					(phi)[b]	
Transect	Facies	Mud	Sand	Pebble	Cobble	Boulder	Mean	SD
Tombolo Barrier								
A1	Crest	0	100	0	0	0	1.35	0.43
A1	washover	0	0	0	33	67	-6.28	0.78
A1	backshore	0	100	0	0	0	1.19	0.58
A2	lower beachface	0	100	0	0	0	1.59	0.45
A2	crest	0	0	0	72	28	-5.50	0.90
A2	backshore	0	100	0	0	0	1.55	0.39
A2	washover	0	0	0	72	28	-5.60	0.67
A3	lower beachface	0	100	0	0	0	1.85	0.54
A3	upper beachface	0	0	0	84	16	-5.47	0.53
A3	crest	0	0	0	52	48	-5.99	0.53
A3	backshore	0	100	0	0	0	1.87	0.49
A4	lower beachface	0	0	0	60	40	-5.64	1.08
A4	crest	0	0	0	20	80	-6.61	0.68
A4	backshore	0	100	0	0	0	1.70	0.47
Qikiqtarjuaq N								
B1	lower beachface	0	100	0	0	0	1.62	0.47
B1	mid-beachface	0	100	0	0	0	1.60	0.37
B1	crest	0	0	0	35	65	-6.13	0.80
B1	backshore	0	100	0	0	0	1.21	0.50
B1	backshore	0	0	0	26	74	-6.38	0.60
B2	mid-beachface	0	99.9	0.1	0	0	1.28	0.55
B2	crest	0	0	0	92	8	-5.23	0.58
B2	backshore	0	100	0	0	0	1.11	0.52
B3	lower beachface	0	99	1	0	0	0.52	0.50
B3	berm	0	0	0	34	66	-6.20	0.70

[a] Fraction abbreviations as follows: m, mud; s, sand; p, pebble; c, cobble; b, boulder.
[b] d[phi] = - $\log_2$(d[mm]) where d is grain size.

Location		Size Fraction (%)[a]					(phi)[b]	
Transect	Facies	Mud	Sand	Pebble	Cobble	Boulder	Mean	SD
Qikiqtarjuaq Beach								
C1	lower beachface	0	0	0	30	70	1.35	0.76
C1	berm	0	0	0	12	88	-5.62	0.67
C1	upper beachface	0	0	0	4	96	-6.62	0.83
D1	berm	0	79	21	0	0	1.47	0.63
D1	berm	0	0	0	100	0	1.25	0.67
D1	backshore	0	0	0	98	2	-0.12	1.20
D2	lower beachface	0	66	34	0	0	-3.96	0.58
D2	lower beachface	0	100	0	0	0	-4.56	0.88
D2	berm	0	0	0	98	2	-0.85	0.90
D2	upper beachface	0	80	20	0	0	1.38	0.43
D3	lower beachface	0	0	0	54	46	-4.53	0.63
D3	lower beachface	0	0	0	90	10	0.22	2.31
D3	mid-beachface	0	100	0	0	0	-5.97	0.96
D3	berm	0	100	0	0	0	-4.53	0.87
D3	crest	0	0	0	66	34	2.01	0.57
Broughton Channel East								
E1	lower beachface	0	0	0	76	24	-5.52	0.85
E2	lower beachface	0	16	84	0	0	-2.39	1.39
E2	berm	0	100	0	0	0	1.66	0.43
E3	mid-beachface	0	39	61	0	0	-1.27	1.41
E3	berm	0	100	0	0	0	1.61	0.52
E4	Upper beachface	0	0	0	100	0	-4.37	0.72

[a] Fraction abbreviations as follows: m, mud; s, sand; p, pebble; c, cobble; b, boulder.
[b] d[phi] = - $\log_2(d[\mathrm{mm}])$ where d is grain size.

B.2 SONAR SURVEYS

All data can be accessed from the GSC-Atlantic s5-dar-kayak; Cowan; THESIS_APPENDIX; SONAR. The measurements of transducer to water level, and date with start time were used to correct for tide with WebTide predictions.

Table B.3: Summary of sonar dataset within Broughton Channel. Locations of sonar surveys are shown in Fig. B.1.

File Name	Transducer to water level (cm)	Water level to GPS base (cm)	Date	Start Time (EST)	Transect	Location
KING01	43	108	09/02/13	3:05 pm	N/A	Kingnelling Fiord head
SONAR0002	47.5	108.5	09/05/13	3:27 pm	N/A	E Broughton Channel
SONAR0003	43	108	09/06/13	10:17 am	video	E Broughton Channel
SONAR0004	43	108	09/06/13	12:18 pm	video	E Broughton Channel
SAONR0005	43	108	09/06/13	12:50 pm	video	E Broughton Channel
SONAR0006	34.3	107.7	09/11/13	10:03 am	TS3	S Tombolo
SONAR0007	34.3	107.7	09/11/13	10:09 am	TS2	S Tombolo
SONAR0008	34.3	107.7	09/11/13	10:15 am	TS1	S Tombolo
SONAR0009	34.3	107.7	09/11/13	10:24 am	TS4	S Tombolo
SONAR0010	34.3	107.7	09/11/13	10:31 am	TS9	S Tombolo
SONAR0011	34.3	107.7	09/11/13	10:41 am	N/A	W Broughton Channel

SONAR0012	34.3	107.7	09/11/13	10:46 am	N/A	W Broughton Channel
SONAR0013	34.3	107.7	09/11/13	10:58 am	N/A	W Broughton Channel
SONAR0014	34.3	107.7	09/11/13	11:03 am	N/A	S Tombolo
SONAR0015	34.3	107.7	09/11/13	12:19 pm	TS1	N Tombolo
SONAR0016	34.3	107.7	09/11/13	12:28 pm	TS2	N Tombolo
SONAR0017	34.3	107.7	09/11/13	12:37 pm	TS3	N Tombolo
SONAR0018	34.3	107.7	09/11/13	12:47 pm	TS4	N Tombolo
SONAR0019	34.3	107.7	09/11/13	1:03 pm	TS5	N Tombolo
SONAR0020	34.3	107.7	09/11/13	2:38 pm	TS1	Qik Harbour E
SONAR0021	34.3	107.7	09/11/13	2:47 pm	TS3	Qik Harbour W
SONAR0022	33.5	108.7	09/12/13	10:47 am	TS1	Qik Back Beach
SONAR0023	33.5	108.7	09/12/13	11:01 am	TS3	Qik Back Beach

B.1 CAMERA TRANSECTS

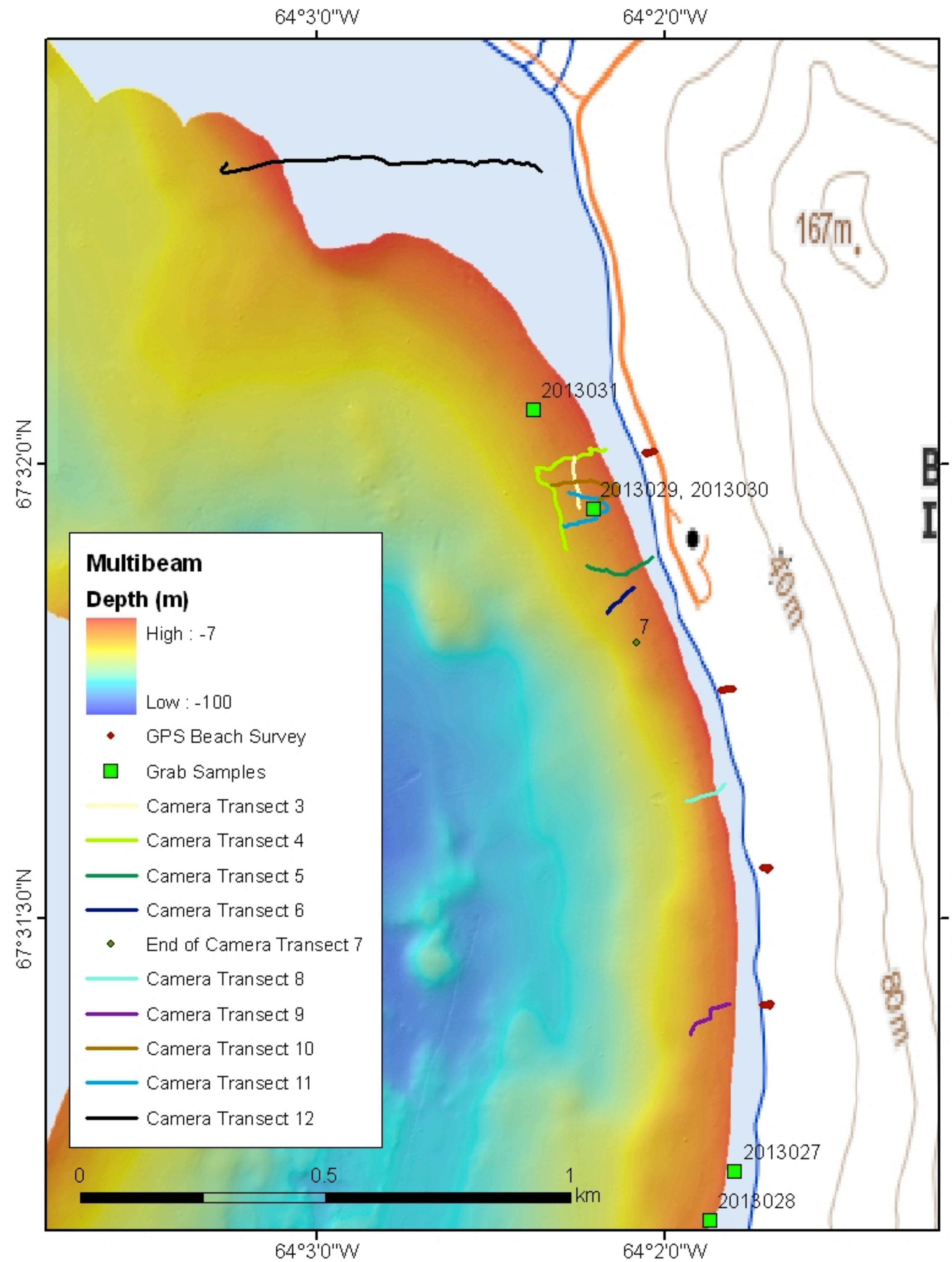


Figure B.5: Western shoreline of Broughton Channel, with locations of video transects (which follow a sonar track), beach surveys and grab samples.

All the data and screen shots for the camera transects can be accessed from the GSC-Atlantic s5-dar-kayak; Cowan; THESIS_APPENDIX; underwater Camera. Screen Shots are labelled by: transect number_shot number.

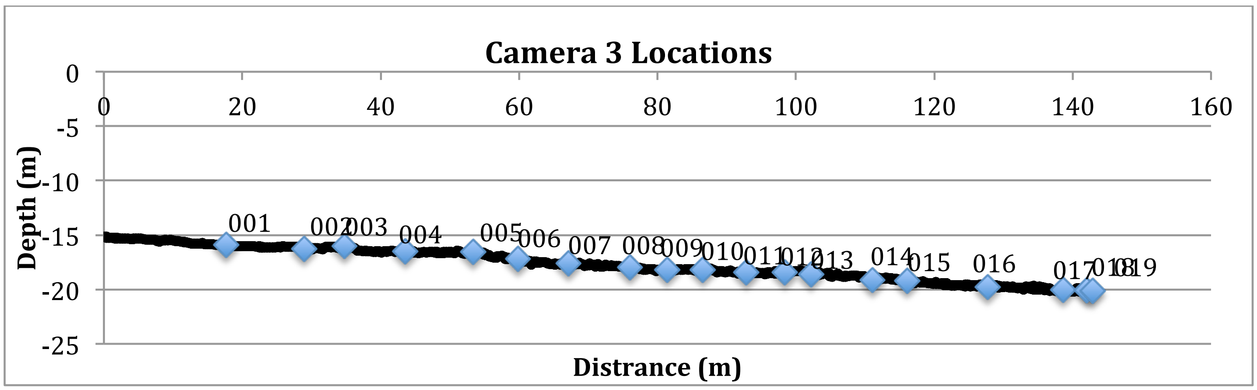
There was a problem with the Waypoint marker, if we were on the wrong screen the waypoint was collected for the position of the controller and not the position of the boat. This seems to have been a problem for Waypoints 55-60 & 75-87.

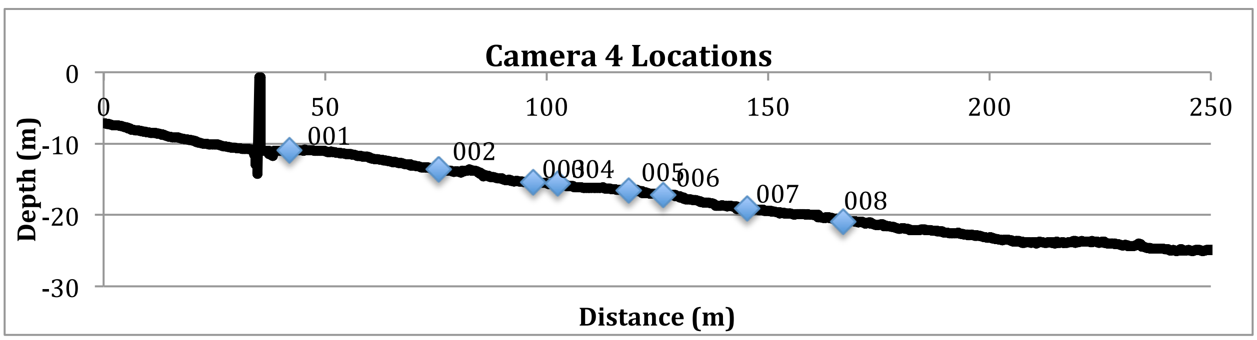
Table B.4: Summary of underwater camera transect and corresponding sonar transects.

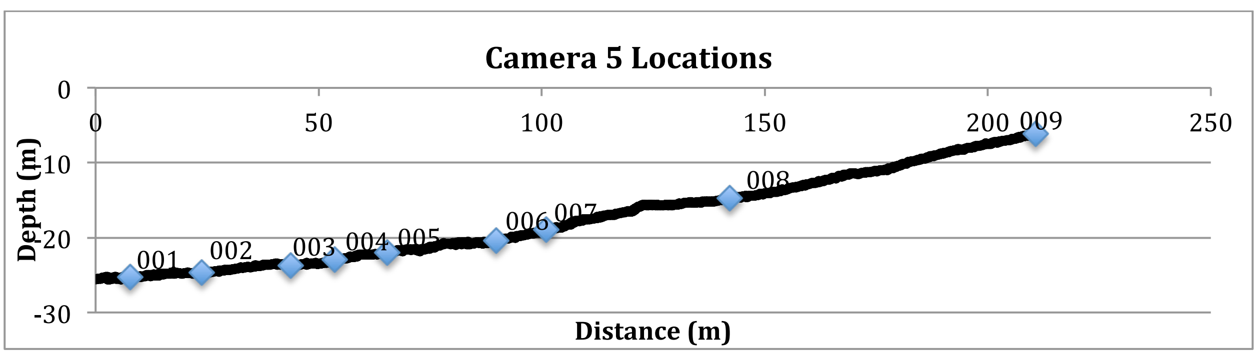
Sonar File	Way Point	Transect Number	Latitude	Longitude	Position
SONAR0003	39	1	67.53445534	64.03599502	Start & End.
SONAR0003	39	2	67.53445534	64.03599502	2nd try
SONAR0003	40	3	67.53343926	64.03767151	Start
SONAR0003	41	3	67.53250581	64.03744617	End
SONAR0003	42	4	67.53356326	64.03616627	Start
SONAR0003	43	4	67.53351504	64.03685129	Boulder Barricade
SONAR0003	44	4	67.53342204	64.03811316	Boulder Barricade
SONAR0003	45	4	67.53326015	64.03869002	Large boulder
SONAR0003	46	4	67.53320848	64.03951925	End of boulder concentration
SONAR0003	47	4	67.53174455	64.03805908	End

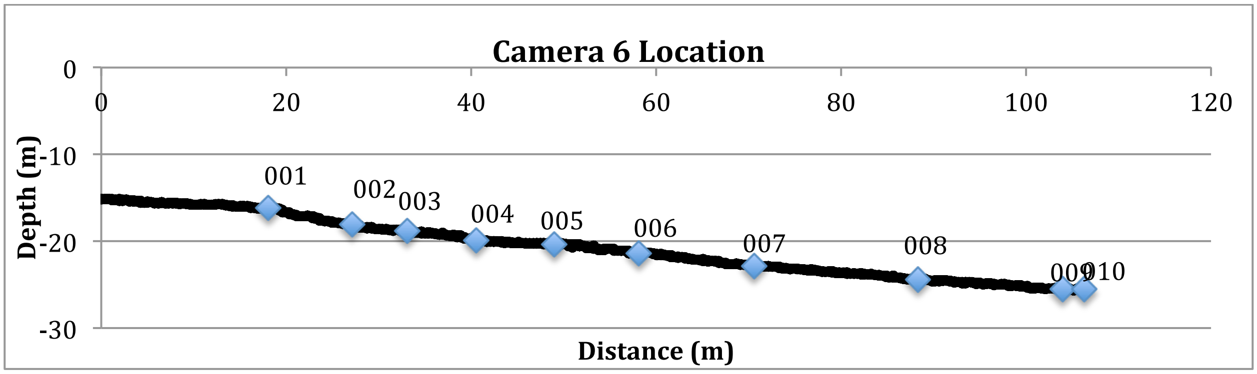
SONAR0003	48	5	67.53146898	64.03706761	Start
SONAR0003	49	5	67.53128985	64.03521085	Boulder barricade
SONAR0003	50	5	67.53162399	64.03392194	End
SONAR0003	51	6	67.53105905	64.03482328	Start
SONAR0003	52	6	67.53090748	64.03523789	Boulder Barricade
SONAR0003	53	6	67.53058367	64.03606712	End
N/A	56	7	67.53005661	64.03468808	Start
N/A	57	7	67.53005661	64.03468808	Boulder Barricade
N/A	58	7	67.53005661	64.03468808	Boulder Barricade
N/A	59	7	67.53005661	64.03468808	Leaving kelp concentration
N/A	60	7	67.53005661	64.03468808	End
SONAR0004	62	8	67.52714205	64.03226348	Start
SONAR0004	63	8	67.52721784	64.03155143	Boulder Barricade
SONAR0004	64	8	67.52746935	64.03043377	End
SONAR0004	65	9	67.52344493	64.03026251	Start
SONAR0004	67	9	67.52327952	64.03115484	Boulder barricade
SONAR0004	68	9	67.52286601	64.03212828	End
SONAR0005	75	10	67.5324817	64.03751828	Start
SONAR0005	76	10	67.5324817	64.03751828	End
SONAR0005	77	10	67.5324817	64.03751828	Start
SONAR0005	78	10	67.5324817	64.03751828	More scattered boulders
SONAR0005	79	10	67.5324817	64.03751828	End
SONAR0005	80	11	67.5324817	64.03751828	Start

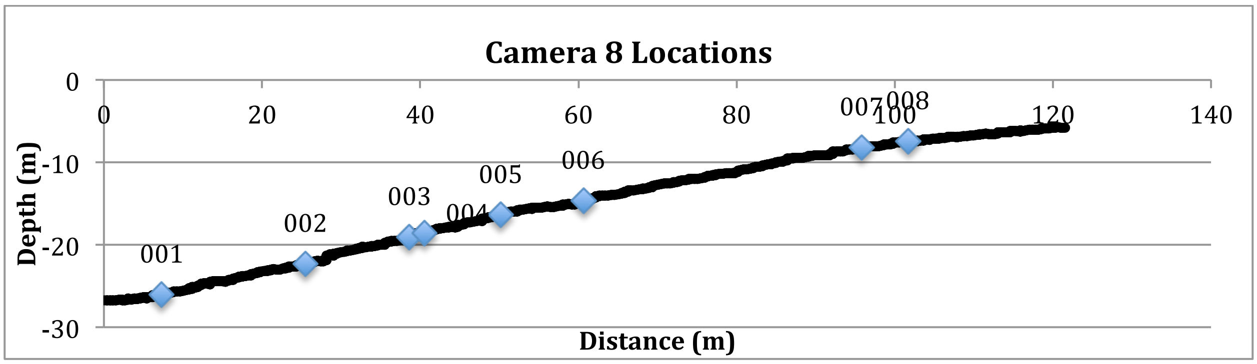
SONAR0005	81	11	67.5324817	64.03751828	Boulder barricade
SONAR0005	82	11	67.5324817	64.03751828	Boulder barricade
SONAR0005	83	11	67.5324817	64.03751828	Boulder barricade
SONAR0005	84	11	67.5324817	64.03751828	End
SONAR0005	95	12	67.53866385	64.03925786	Start
SONAR0005	96	12	67.5388257	64.05432822	End

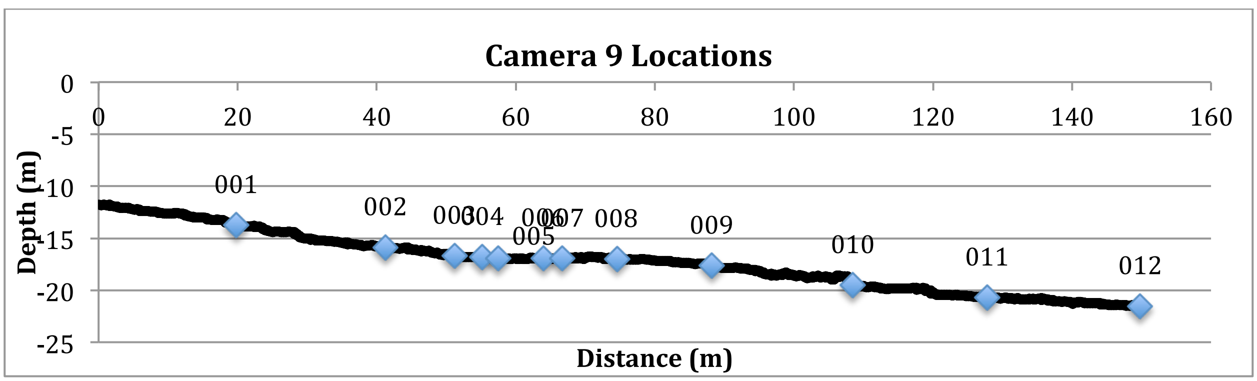


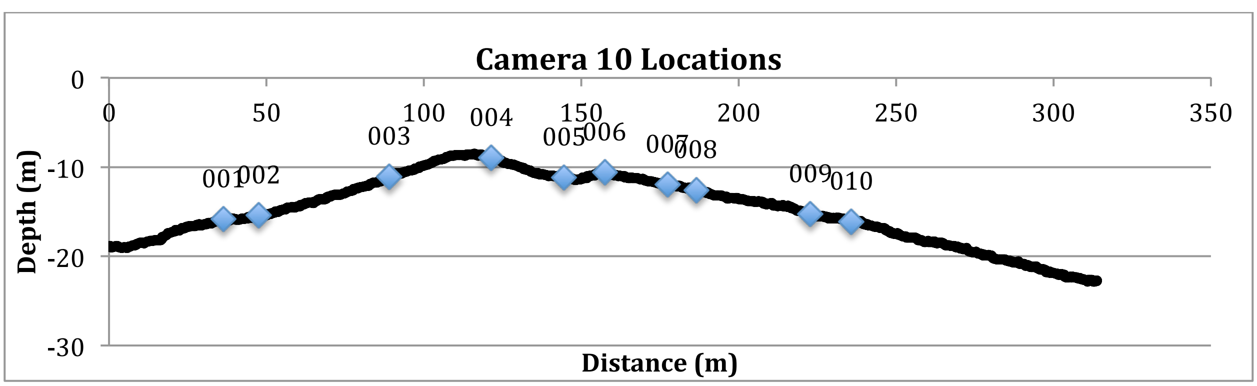


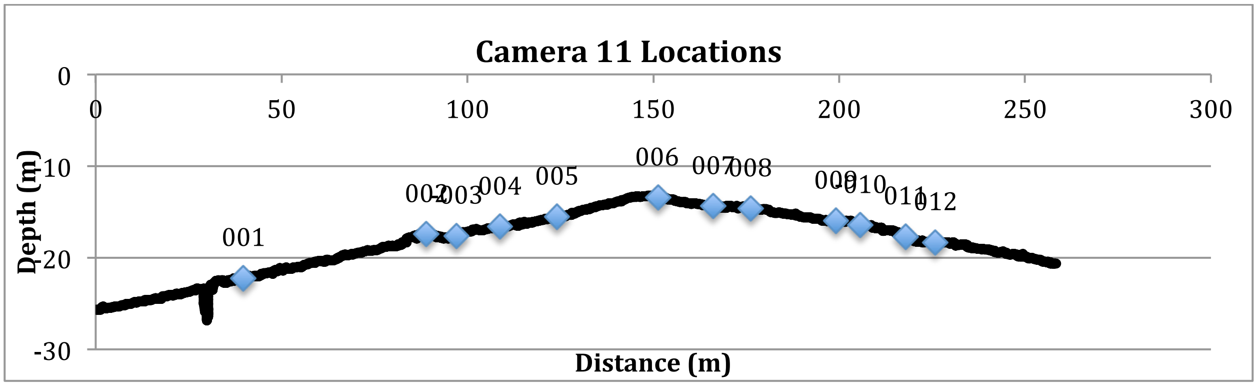



Camera 6 Location
0
-10
-20
-30
Depth (m)
0
20
40
60
80
100
120
001
002
003
004
005
006
007
008
009
010
Distance (m)


Camera 8 Locations
0
-10
-20
-30
Depth (m)
0
20
40
60
80
100
120
140
001
002
003
004
005
006
007
008
Distance (m)


Camera 9 Locations
0
-5
-10
-15
-20
-25
Depth (m)
0
20
40
60
80
100
120
140
160
001
002
003
004
005
006
007
008
009
010
011
012
Distance (m)


Camera 10 Locations
0
-10
-20
-30
Depth (m)
0
50
100
150
200
250
300
350
001
002
003
004
005
006
007
008
009
010
Distance (m)



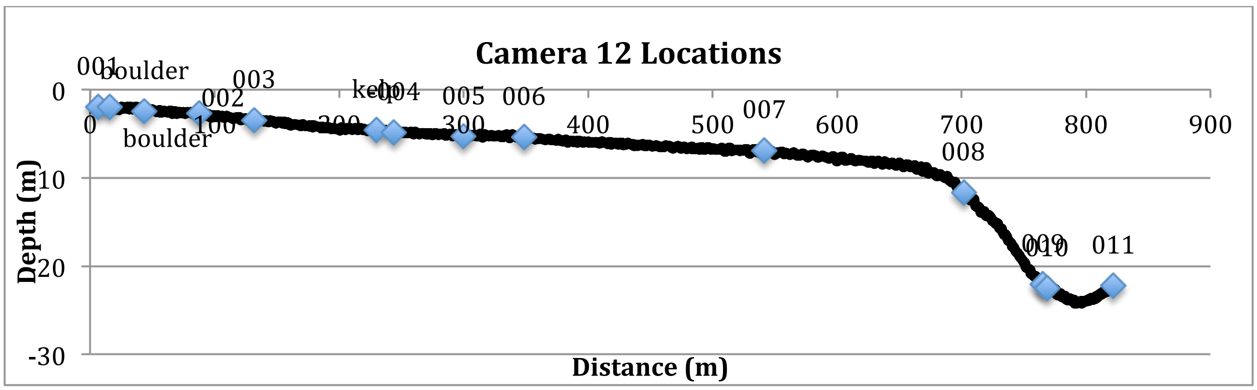


Figure B.6: Locations of video screenshots along the sonar transects.

B.2 COASTAL INFORMATION SYSTEM

All the shape files made for foreshore and backshore along Broughton Channel, Boas Fiord, and Akpait Fiord can be accessed from the GSC-Atlantic s5-dar-kayak; Cowan; THESIS_APPENDIX; CIS. The following figures show the extent of CIS coverage at each site.

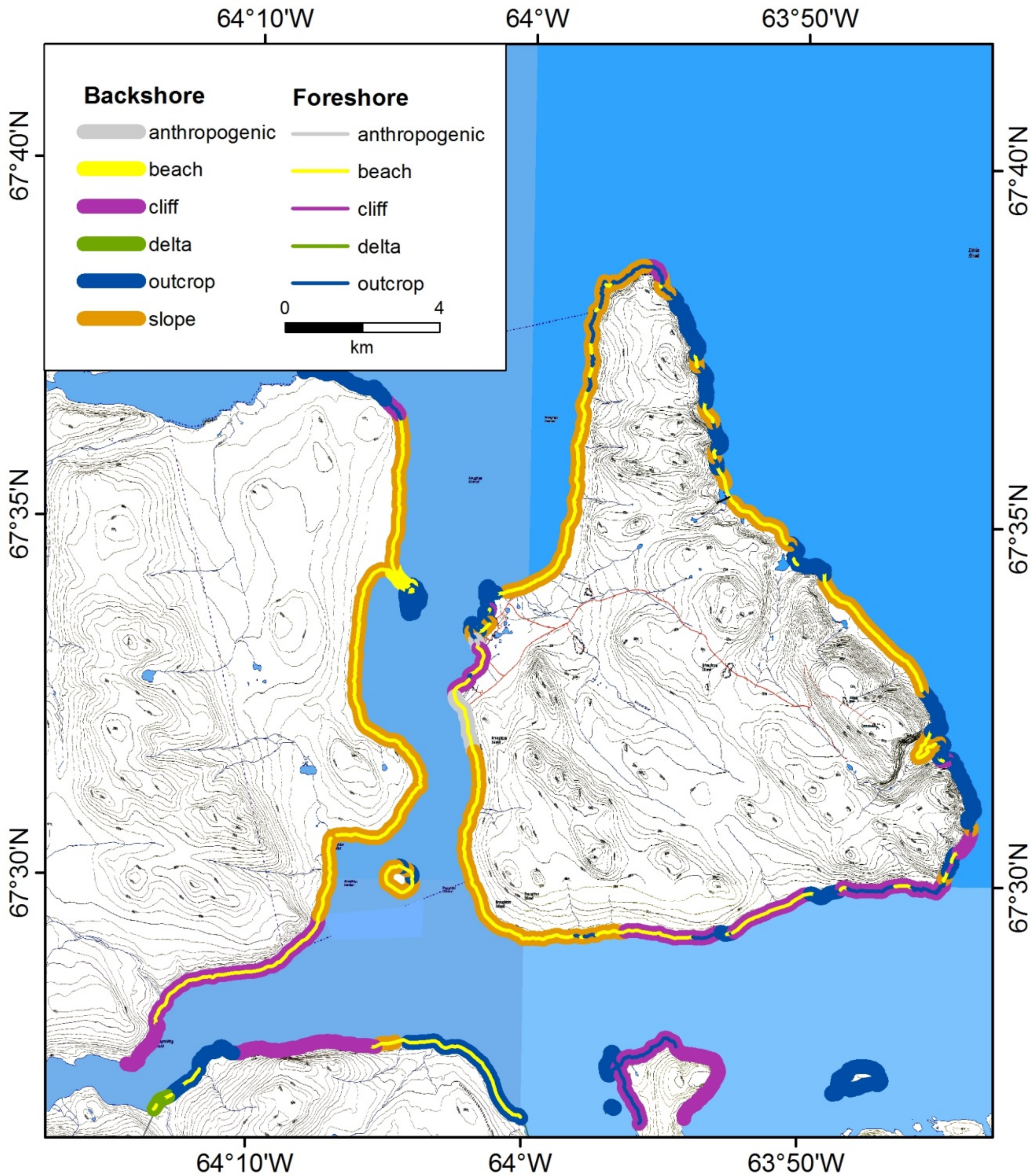
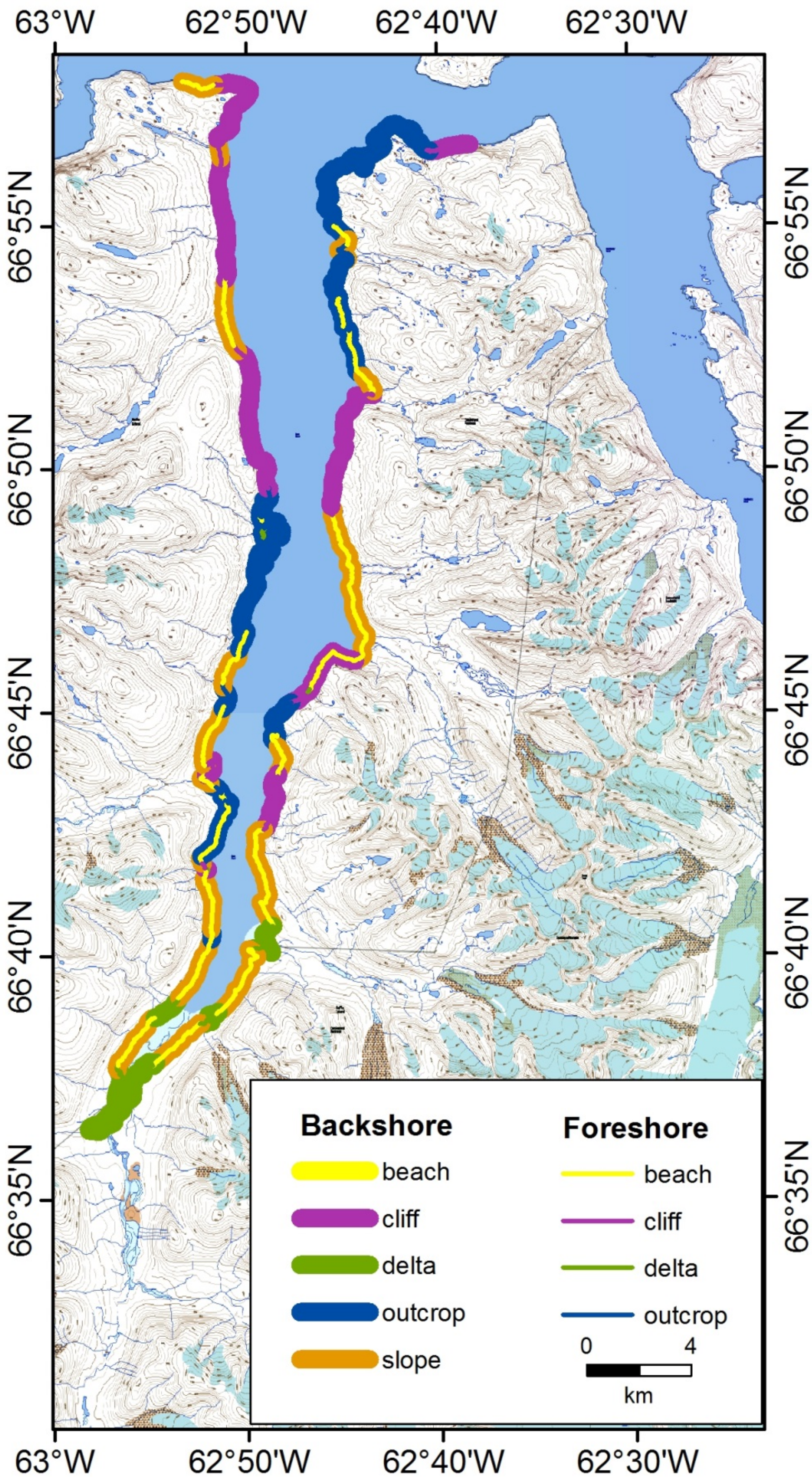


Figure B.7: Extent of CIS dataset along Broughton Channel and surrounding coastline.



63°W
62°50'W
62°40'W
62°30'W
66°55'N
66°50'N
66°45'N
66°40'N
66°35'N
Backshore
beach
cliff
delta
outcrop
slope
Foreshore
beach
cliff
delta
outcrop
0
4
km

Figure B.8: Extent of CIS dataset for Boas Fiord.

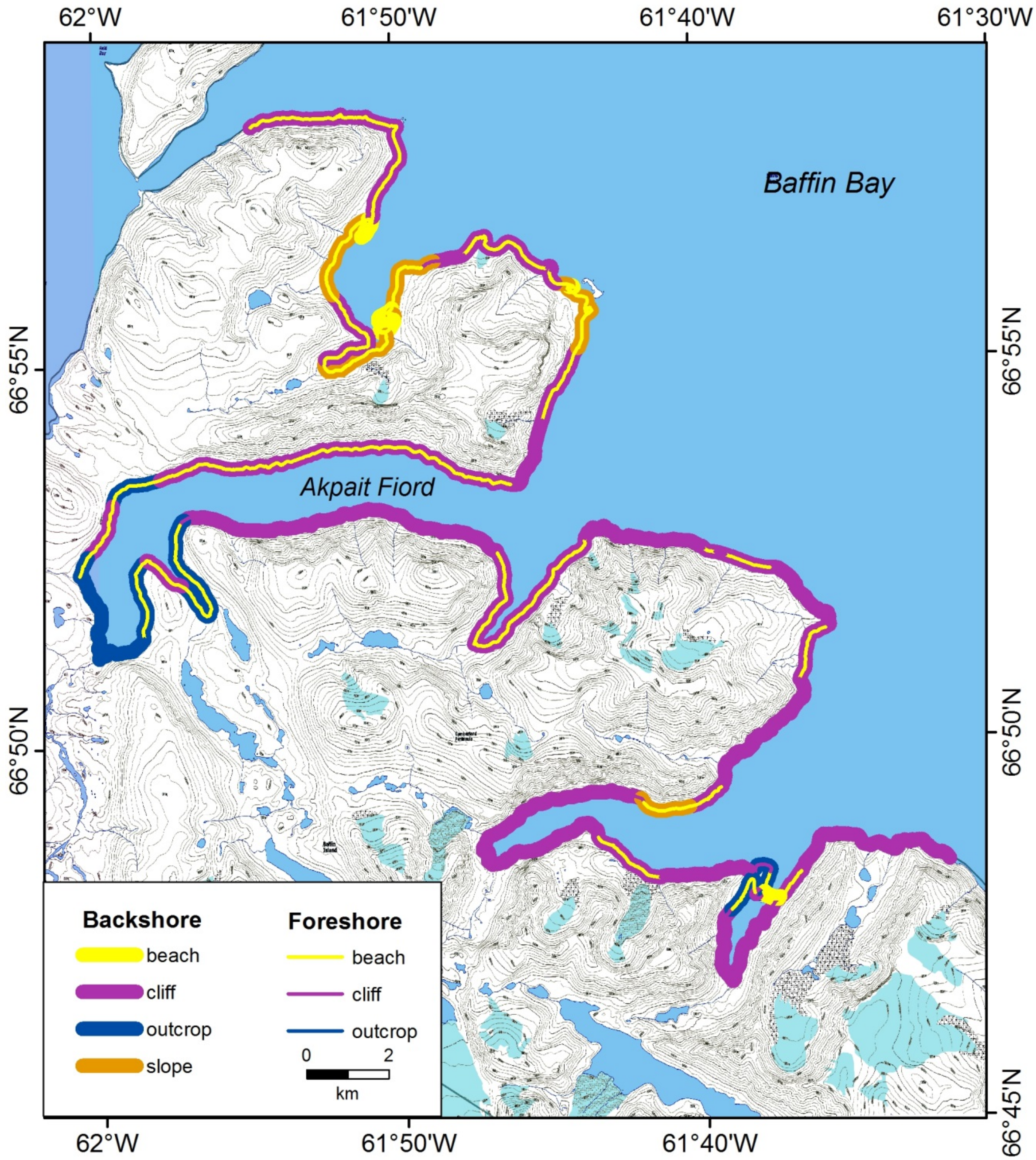


Figure B.9: Extent of CIS dataset for Akpait Fiord and surrounding coastlines.

C *MV NULIAJUK* CRUISE REPORT: PANGNIRTUNG TO CLYDE RIVER, NU

August 28- September 10, 2014

C.1 INTRODUCTION

This report is a summary of the *MV Nuliajuk* collaborative mapping surveys that took place from Pangnirtung to Qikiqtarjuaq, NU and continued to Clyde River, from August 28 to September 10, 2014. The surveyed regions are reported geographically, following the coastline from Pangnirtung, north to Qikiqtarjuaq, where the majority of mapping and sampling was undertaken along Cumberland Peninsula (Fig. C.1) and then transited to Clyde River. This report documents the geomorphology of the seafloor, as interpreted from multibeam bathymetric and backscatter maps.

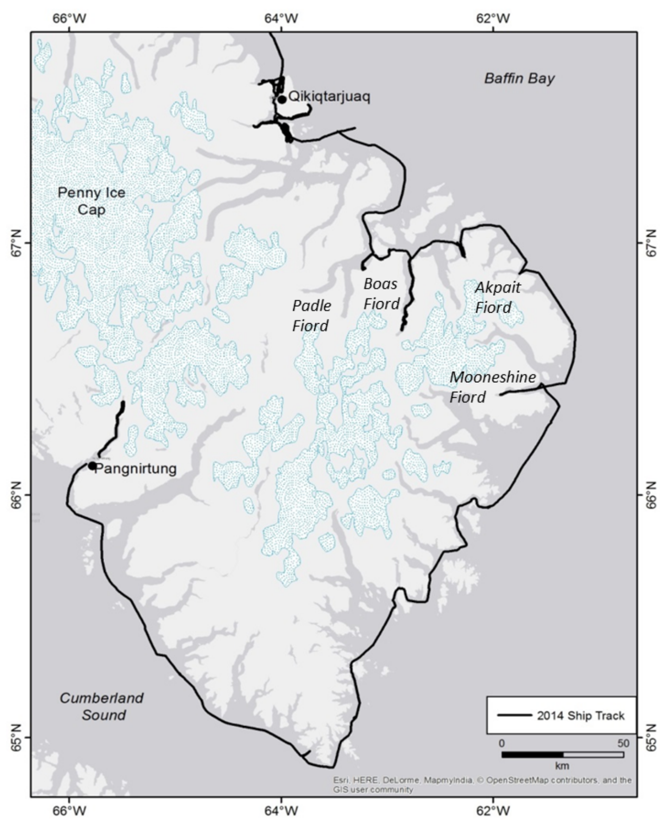


Figure C.1: Ship tracks of the *MV Nuliajuk* cruise between Pangnirtung and Qikiqtarjuaq, NU.

This cruise was made possible through the partnership of the Government of Nunavut (GN), ArcticNet, University of New Brunswick's Ocean Mapping Group, and Memorial University of Newfoundland and through the funding of GN, ArcticNet, and the Canadian Hydrographic Society. GN provided the *MV Nuliajuk*, which is equipped with geoscience/hydrographic survey equipment in 2012, including multibeam and subbottom echosounders. The Ocean Mapping Group processed and consolidated the data with previous multibeam surveys aboard the MV Nuliajuk, and provided raster files of the surveyed bathymetry.

Cumberland Peninsula is situated along southeastern Baffin Island, Nunavut. This peninsula is bounded by Cumberland Sound to the southwest and Baffin Bay, and is home to the Penny Ice Cap in the west and many local alpine glaciers. During the Last Glacial Maximum (LGM) the Cumberland Peninsula was the eastern limit of the Laurentide Ice Sheet (LIS). The eastern peninsula was not covered by the LIS at this time, its local glaciers expanded to overtake the valleys out to a terminus at the fiord-mouths and in some cases onto the continental shelf. As the eastern limit of the LIS and with a local glacial signature, the vertical motion and therefore relative sea-level history is complex. In 1979, Dyke put forward a hypothesis that the eastern peninsula experienced continuous postglacial submergence, in comparison to the emergence along the mainland and western peninsula. Some preliminary evidence of submerged deltas provided the foundation for this hypothesis along with the eastward tilted raised shoreline gradients in the southwestern peninsula. Collaborating with the research mandate to map uncharted regions of eastern Baffin Island, this cruise set out to test the hypothesis, to explore and map lowstand shorelines preserved on the seafloor in addition to the locations previously located in 2012 and 2013.

C.2 SCIENTIFIC OBJECTIVES

The 2014 cruise was a continuation of the charting efforts and research that began in 2012, and continued throughout the successive field seasons. The main objectives for the seabed mapping initiative along eastern Baffin Island have been to: A) develop full-coverage bathymetry maps of Broughton Channel and region for a benthic habitat mapping project, B) document submerged shorelines indicative of the Holocene lowstand in sea-level, and c) to grid the uncharted waters and create high-resolution bathymetry maps for transit corridors and anchorage sites.

The benthic habitat mapping project is taking place within the vicinity of Qikiqtarjuaq, NU, and has become a partnership between GN fisheries and sealing division, Memorial University of Newfoundland and the Ocean Mapping Group. This field season presents the first year of a four year plan in place to develop a community-based commercial clam fishery for the community of Qikiqtarjuaq. The multibeam surveys aim to add to the bathymetry dataset that has been developed over the last two years. The goals of this project are to fill in gaps in the multibeam coverage from the previous two years, and to create full-coverage multibeam bathymetry of regions that were previously sampled for clam abundance by Siferd (2005), and will be expanded upon throughout Ben Misiuk's M.Sc. research (Memorial University of Newfoundland). The final product will be a benthic habitat map of Broughton Channel and surrounding regions, to provide a comprehensive map of clam abundance and benthic distribution.

The 2014 cruise incorporated the data that was previously documented in the last two cruise reports (Forbes et al., 2012; Bell et al., 2013), and built off of their discoveries. With the addition of a gravity corer, the main target was to core three of the submerged delta terraces that were previously discovered in 2012. Though some are expected to have coarser sediments, cores are estimated to collect the top few meters of sediment upon the surface of the deltas. It is our goal to core the contact between the delta surface and post-depositional sediment; however some of the coarser surfaces may not be accessible. The target core locations are shown in Figure C.2 along with two possible submerged delta locations, A & B. Miller & Dyke (1974) mentioned a submerged delta in outer Padle Fiord, however the map and documentation were not clear as to where the delta was located. Therefore from the information at hand we narrowed down the scope to target locations.

C.3 CRUISE PERSONEL

Bob Bennett	Captain
Anton Starby	First Mate
Jeff Cheater	Crew Member
Becky Ottokie	Crew Member
Andy Kopalie	Crew Member
Amos Oqqallak	Crew Member
Dr. Trevor Bell	Memorial University of Newfoundland, Department of Geography
Mike Bremnar	University of New Brunswick, Ocean Mapping Group
Weston Renoud	University of New Brunswick, Ocean Mapping Group

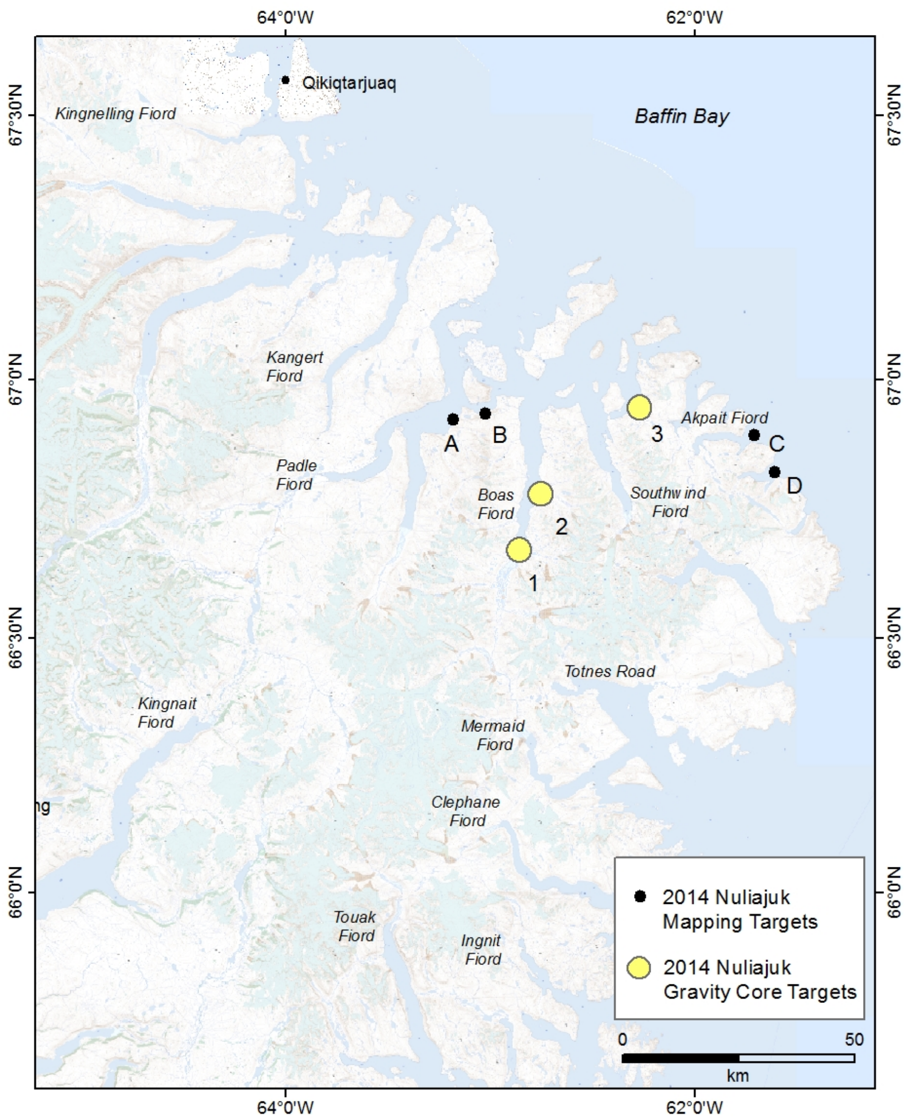


Figure C.2: Locations of core targets and submerged delta targets (A and B) within Cumberland Peninsula.

C.3.1 DAILY LOG

(Time in UTC)

Day 1: Thursday August 28, 2014:

- Trevor Bell arrives in Pangnirtung, all other crew except Amos Oqqallak are aboard

Day 2: Friday August 29, 2014:

- The brake on the crane winch was broken and the boat needed an operating crane to load fishery buoy weights here at the dock and also for safety reasons.
- Amos Oqqallak arrives in the afternoon
- Anchored in Pangnirtung Fiord for the night, to allow Kiviuit I to dock and offload bait.

Day 3: Saturday August 30, 2014:

- Replacement winch to arrive today
- 1130h Headed west up Pangnirtung Fiord to map the fiord head an build on existing multibeam lines
- Much of the inner basin was mapped, especially the delta front into which numerous channels eroded. The channels are cut into sand waves, and contain sand waves within themselves that extend a kilometer or so in the deeper basin. Knudsen shows up to 30 m thick stratified and poorly structured deposits.

Day 4: Sunday August 31, 2014:

- Clear sky with light winds.
- Waited for the replacement winch, arrived on the afternoon flight and was installed into the evening.
- Loaded 80 buoy anchors (200 lbs each) for OTN work off Clyde River.
- Anchored offshore Pangnirtung to depart thee next morning.

Day 5: Monday September 1, 2014:

- Clear sky, calm waters.
- Departed at 0930h, saw whales inside of Kekerten.
- Reached Miliakdjuin Island by noon.

- Trevor Bell took photos of cirque valleys (Wareham Island & north of Queens Cape) at or near sea level, and lichen-free zones on upland and remnant valley glaciers.
- Anchor down at 0000h at 64 56.746°N, 63 43.507°W in bay below radar station, west of Cape Mercy, full day of transit 188 km.

Day 6: Tuesday September 2, 2014:

- Anchor up at 0600h, transit.
- Trevor Bell took photos of submerged cirques on Leopold Island
- Inside Kekertuk Island and at the mouth of Exaluin Fiord are several colonies of walrus.
- Decision made to carry on to Mooneshine Fiord this evening to get closer to Cape Dyer.
- Anchor down at 0600h

Day 7: Wednesday September 3, 2014:

- Overcast, with low ceiling
- Anchor up at 0705h, transit to Mooneshine Fiord
- Topography is steeper and higher to the south with scree covered slopes and well developed debris and alluvial fans. Low rolling bedrock to the north gives way to steeper slopes 1 km or so from the shore.
- Head of fiord has small proximal drainage basin with a low rise to an inlet of Totnes Road to the west.
- Isolated glaciomarine terrace or kame deposit on the northern shoreline near the fiord head (Trevor Bell photographs).
- Leaving Mooneshine Fiord at 1330h and heading east to intersect the innermost multibeam track and heading north past Cape Dyer. Trevor Bell photo of Castle and Camel islands off the mouth of Sunneshine Fiord.

- 1800h arrive at Akpait Fiord, with two lines planned- one in and one out over the spit-like formation and sill platform.
- Left Akpait at 1900h
- Station Nuliajuk-001, arrived at after supper with light rain and low cloud ceiling.
- Attempted several cores and grabs without success. Subbottom suggests hard surface.
- Anchor down at 2200h behind Block Island.

Day 8: Thursday September 4, 2014:

- Anchor up at 1000h, fresh snow on mountaintops with light wind.
- Transit back to Station Nuliajuk-001 in Big Nose, to target #2 on the upper delta surface, where a transparent unit is ponded behind a small ridge.
- Recovered a grab with small volume of silty sand, but no success with gravity cores.
- Instead, transited to Boas Fiord where sediment recovery is presumed higher, departed at 1130h
- In hindsight, should run an underwater video transect along the delta surface to understand the surficial material.
- South of Padloping Island, the narrow interisland channels reach depths >625 m.
- Giffs Cove has a Neoglacial moraine at the coast.
- Station Nuliajuk2014-002, targeted upon the delta at Boas Fiord-head (1245h), gravity core retrieved 98 cm core, and again 143 cm. Targets 2 & 3 recovered 76 & 64 cm, respectively (Appendix Table 1).
- Station Nuliajuk2014-003, targeted at Giffs Cove submerged delta, received less success due to coarser sediments. At target 1 recovered 13 & 19 cm cores. Target 2 recovered 20 cm core. At this station the core cutter was dented on a rock, and slightly buckled the top of the 6' core barrel.

- Anchor down at 0000h in Giffs Cove.

Day 9: Friday September 5, 2014:

- Low cloud cover with sleety rain. Anchor winch failed.
- Was fixed by offloading thee remainder of anchor cable and pulling aboard the stern using the capstan and crane.
- 1230h transit to our two mapping targets A & B.
- Site A: two glaciated valleys feeding into single embayment, very steep slope to the coast in the eastern valley, less so in the west. Moraines observed at upper break of slope. Lots of evidence of extensive ice across the coast- smoothed bedrock. Didn't find a marked delta terrace indicative of lowstand positions.
- Site B: a wide valley drains several smaller basins that are potentially glacierized. A single bedrock incised stream enters the bay, where we mapped a flat terrace at -27 to -29 m. At least one delta front channel roughly aligned with the current river mouth. Informally named Cod Cove (large schools of fish in the water column over the terrace).
- Transited out of Merchant's Bay, where a 2-3 m swell hit intensely over the shallow nearshore platform (20-25 m depth).
- Mapping stopped at 0100h.

Day 10: Saturday September 6, 2014:

- 0930h Transited west to the first target area, south of Kingnelling Fiord-mouth.
- Arrived at 1130h, the interisland channel to the southwest was <10 m deep, therefore had to go around islands.
- 2315h finished survey along southern shore of Kingnelling Fiord.

Day 11: Sunday September 7, 2014:

- Anchor up at 0945h. Overcast, with low cloud ceiling and drizzle.

- Finishing mapping of Kingnelling Fiord, retraced the nights survey, and ran a shallow water route along cliffed shoreline on southern Kingnelling Fiord.
- CTD revealed a shift in temperature and salinity at 10 to 20 m depth- the presence of a freshwater layer (27 ppt) warmer than the more saline (36 ppt) deeper water package.
- Finished the survey of outer Kingnelling Fiord 1315h. Transit to Broughton Island.
- 1630h detoured to the small inlet used as a landing harbor for radar supply to investigate some interesting bathymetry around the 15 m lowstand depth from Broughton Channel.
- Not able to fully map the pocket cove because of its size and the swell, but determined it to be relatively flat bottomed.
- Finished survey of south Broughton Island
- Late afternoon transited up to North Baffin Island region of clam habitat map.
- Lots of icebergs grounded in this area, therefore the westernmost section was not mapped and had to detour around those in the survey track. Implied heavily disturbed seabed, which could be the cause of low to medium clam density, in an otherwise ideal coastal environment.
- Mapped close to the coast to cover some of the sample locations from Siferd (2005).
- Anchor (Trawl blade) down at 2300h in central Broughton Channel.

Day 12: Monday September 8, 2014:

- Anchor up at 0930h. Overcast, with light winds and calm waters, with fresh snow on the mountaintops.
- Pick up Ben Misiuk's sampling gear from Qikiqtarjuaq, NU. Cores moved to cool storage.
- Finished mapping North Baffin site and started to run lines in and out over Siferd's (2005) sample points. Also ran a line along -15 m isobaths to see if any submerged shoreline features stood out. Finished at 1500h.

- Went to Qikiqtarjuaq, NU for groceries. Trevor Bell picked up the samples and equipment for Ben Misiuk.
- Returned from Qikiqtarjuaq at 1830h, added survey lines to the deeper side (western) of Northern Broughton Island area.
- Anchor down at 2130h.
- Added foam inserts to cores, and drained of excess water. Secured in cool storage room along with Ben Misiuk's benthic and sediment samples and the algae encrusted rock for Evan Edinger.

Day 13: Tuesday September 9, 2014:

- Anchor up at 0950h.
- Transit north of Qikiqtarjuaq, 1400h off Kangeeak Point is an inner cross-shelf trough dropping from 40-80 m banks to >300 m trough.
- 2100h well off Cape Hooper heading northwest.

Day 14: Wednesday September 10, 2014:

- 1130h off Cape Hewett, with extensively exposed coastal bluffs along this stretch of coast.
- 160 m deep sill at the mouth of Clyde Inlet, near Burns Island.
- Arrived at Clyde River at 1430h

C.3.2 Issues

Conducting fieldwork in the Canadian Arctic comes with many issues revolving around weather, remote locations, and broken equipment. When the MV Nuliajuk met up in Pangnirtung with all of its crew, they were also awaiting the replacement brake for the crane winch. The ship could not load buoy weights without it, as well it is important for safety procedures. Therefore a few days were spent around Pangnirtung while the equipment was shipped.

This year was the first year that the gravity corer was used aboard the *MV Nuliajuk*. It proved to work well in the finer sediments, however did not core some of the coarser delta terraces. As well, the core cutter was dented on Sept. 4, which slightly buckled the top of the 6' core barrel. This occurred after all the targeted coring locations had been completed and therefore the gravity corer was not used since.

The anchor winch failed to bring up the anchor on Sept. 5 and after several hours attempting to fix it, eventually the remainder of anchor cable was offloaded and pulled aboard with the capstan and crane. Therefore the ship was unable to anchor at night, and dependent on the conditions would drift, at more enclosed settings the trawl blade was used as an anchor.

C.4 Equipment

The geoscience/hydrographic equipment were installed upon the *M.V. Nuliajuk* in 2012:

F-185 IMU (SN: F0505026) from Coda – inertial measurement unit for the motion correction (pitch, roll and heave) of sonar data

C&C Technologies CNav 3050 DGPS

C&C Technologies CNav 2000 DGPS

Seatex MRU-6 (SN: 1532) – inertial measurement unit for the motion correction (pitch, roll and heave) of sonar data

CTD: AML Oceanographic SVP&T (surface velocity profiler and temperature) sensor: SN7210 (up to 500m depth)

Sub-bottom Echosounder: KNUDSEN chirp 3200 echosounder 3.5 kHz

- Frequency: 3.5 kHz
- Software: SoungerSuite:EchoControlClient-2.64
- Ship speed: average 4 knots, range 1-8 knots

Multibeam Echosounder: Kongsberg EM3002 multibeam transducer (SN: 426) and transceiver (SN 1582)

- Frequency: 300 kHz
- Number of beams: 254
- Width of beams: 1.5 °
- Angle: 65 °
- Software: SIS
- Software for processing: OMG/UNB swath editor
- Ship speed: average 4 knots, range 1-8 knots

Single Beam Echosounder: Furuno FCV-30 & Furuno CH300 searchlight sonar

- Frequency: 38 kHz
- Bottom tracking: up to 1500 m depth

Additional equipment added during this survey includes:

Van Veen grab sampler, run off the hydraulic winch

- 24L
- 0.1 m^2 sampling area

Gravity corer (NRCan)

- 6 lead donut weights
- 8-foot, 7-foot, and 6-foot core barrels
- 9x 10-foot core liners
- 4 core catchers

- 2 core cutters

C.5 MAPPING & PRELIMINARY INTERPRETATION

The following includes all the mapped locations of the 2014 *MV Nuliajuk* cruise, catalogued geographically from Pangnirtung Fiord, NU and following the coast to Qikiqtarjuaq, NU (Fig. C.1). The processed and gridded multibeam data are provided by UNB's Ocean Mapping Group. The background topographic map is from ArcGIS v. 10 basemap, World Topo Map. Each mapped location includes an overview of the geographic location, and image of the multibeam bathymetry with hillshade effect, and a preliminary interpretation of the geomorphology.

C.5.1 Pangnirtung Fiord

The head of Pangnirtung Fiord was surveyed while the ship was docked at Pangnirtung, awaiting replacement parts for the winch system (Fig. C.3). Pangnirtung Fiord is located on the southern coast of Cumberland Peninsula, opening into Cumberland Sound to the south, it is also the location of the Hamlet of Pangnirtung, NU. The fiord is ca. 40 km long, and on average 2.6 km wide. The fiord valley continues to the northeast, where it crosses the peninsula and enters into North Pangnirtung Fiord, known as the Pangnirtung Pass. The steep sidewalls of the fiord-head are occupied by cirque and alpine glaciers, whereas the outer fiord has sloped sidewalls with many side-entry valleys and drainage rivers.

The fiord-head delta exhibits active deforms and chutes, as it slopes down to the basin floor (90 m bsl; Fig. C.4). Near the fiord-head, a headland extends to the southwest and the seafloor rises to a depth of 40 m before it slopes down to the mid-fiord basin (>130 m bsl).

4.5 km north of the community is a sill that reaches 50 m bsl, separating the mid-fiord basin from the outer-fiord basin (>150 m bsl).

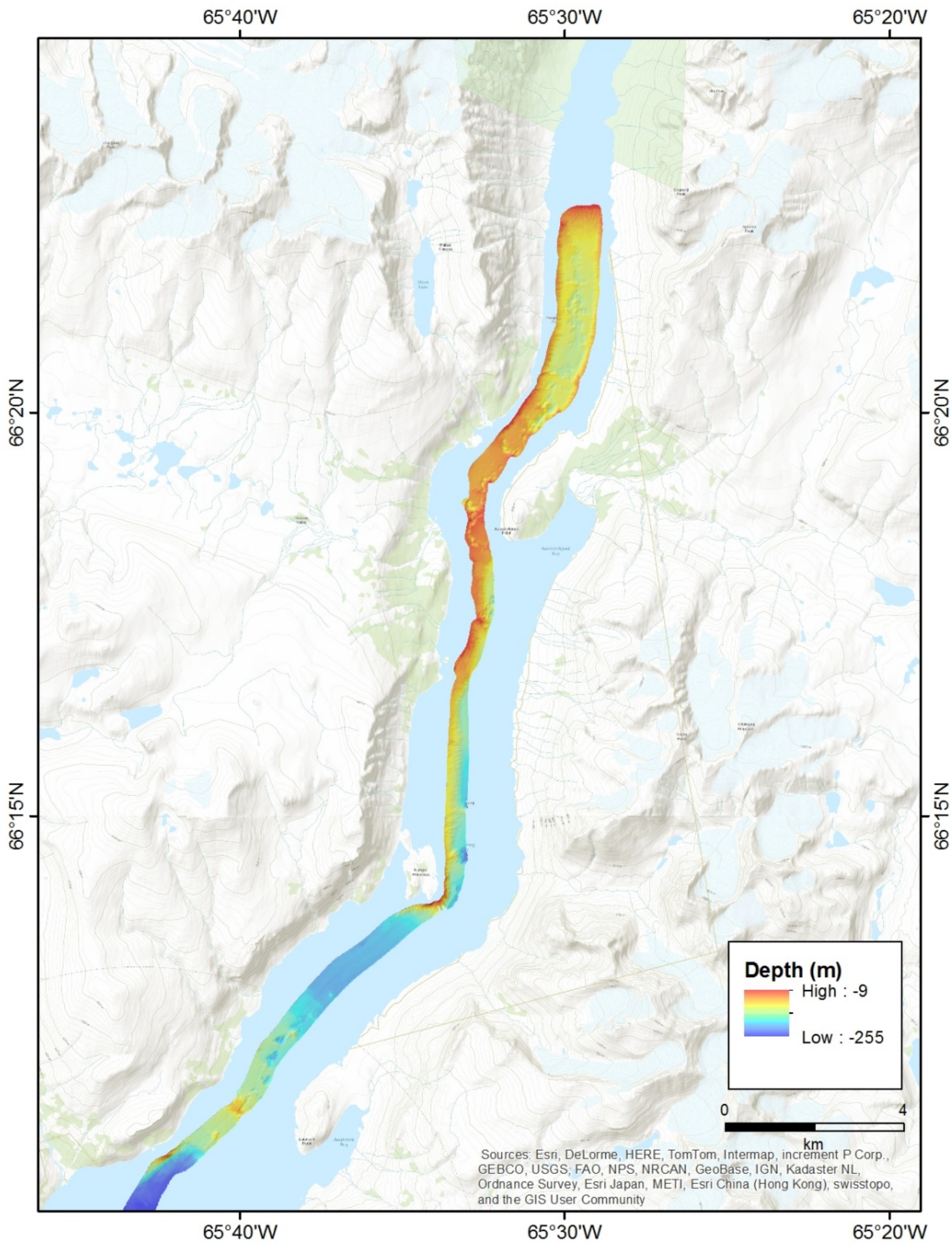


Figure C.3: Overview of multibeam coverage for inner Pangnirtung Fiord.

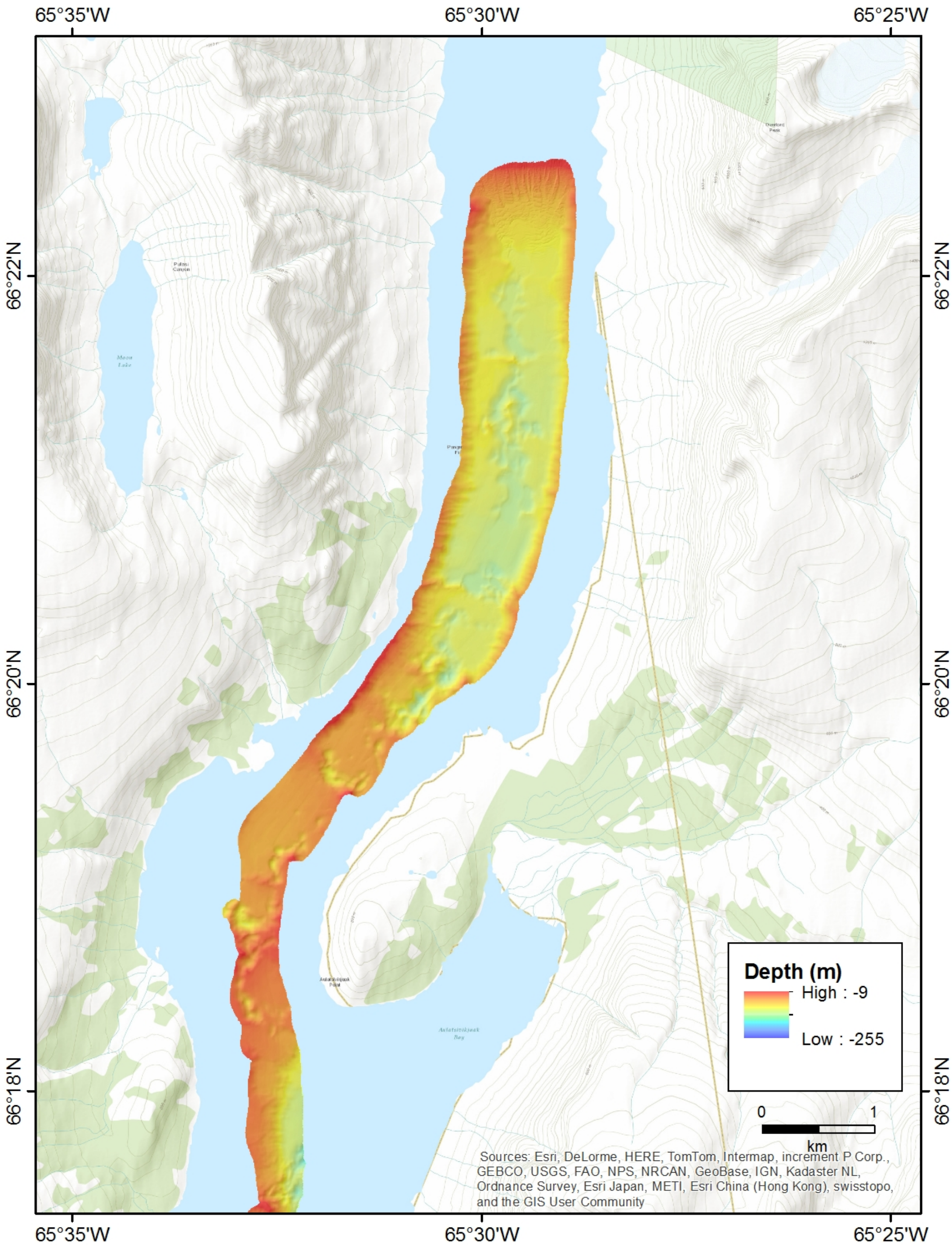


Figure C.4: Multibeam bathymetry coverage at the head of Pangnirtung Fiord.

C.5.2 Mooneshine Fiord

The upper third of the fiord is a relatively flat-bottomed basin between 25 and 35 m deep. The topography is steeper and higher to the south with scree covered slopes and well developed debris and alluvial fans. To the north, some low rolling bedrock gives way to steeper slopes a kilometre or so back from the shore. Higher basins feed down to Mooneshine on the north side the side inlet near the head was not explored due to time limitations. The head of the fiord has a small proximal drainage basin with a low rise to an inlet of Totnes Road to the west. On both sidewalls are nice exposures at mouths of tributary valleys and canyons, with stratified deposits over darker finer material. There are also some gravel beaches developed around these exposures and what appears to be an isolated glaciomarine terrace or kame deposit on the northern shoreline near the fiord head.

The basin at the mouth of Mooneshine Fiord reaches 50 m bsl, which shallows towards the head of the fiord where the shallowest seabed was mapped at 18 m bsl. Mostly a flat-bottomed basin with iceberg scours. Survey included one line in and out, with two extra lines at the fiord-head for better coverage (Fig. C.5).

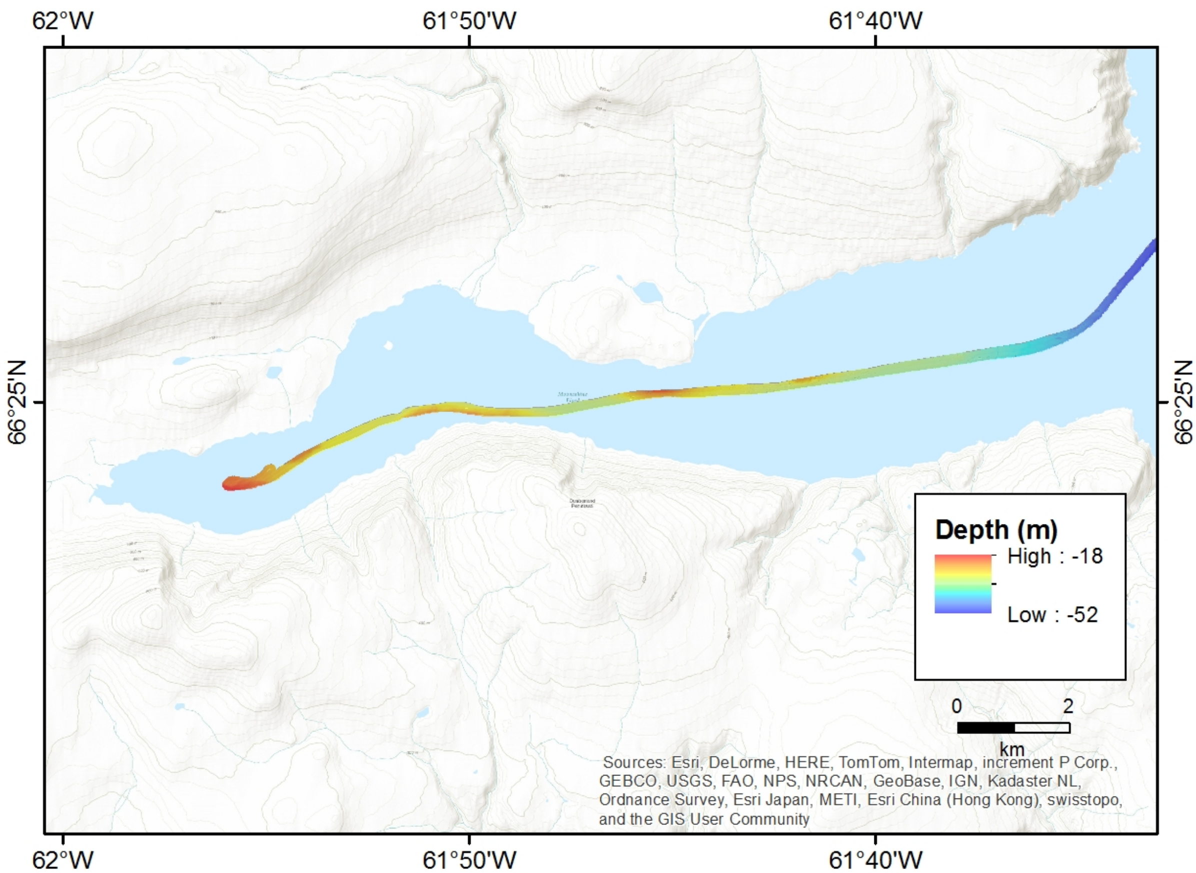


Figure C.5: Multibeam transect of Mooneshine Fiord.

C.5.3 Akpait Fiord-mouth

Akpait Fiord is located on the east coast of Cumberland Peninsula, opening into Baffin Bay to the east. The fiord was mapped in 2013, and an extensive sill platform was discovered at the fiord-mouth. Along the 2014 transit, two lines were surveyed to broaden the approach and are added to the 2013 survey in Figure C.6. See Bell et al. (2013) for a full description of the bathymetry in Akpait Fiord.

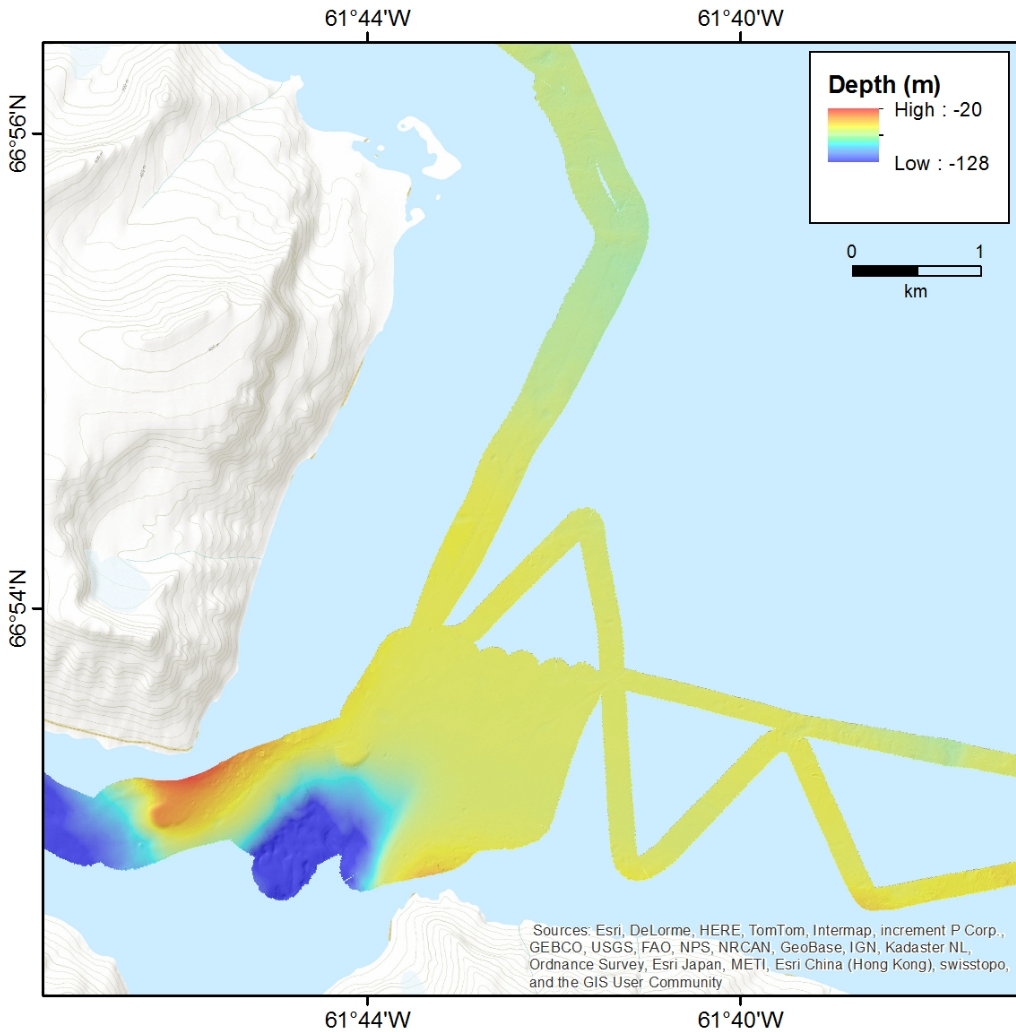


Figure C.6: Complete coverage of 2013 and 2014 multibeam bathymetry at the mouth of Akpait Fiord.

C.5.4 Inner Durbhan Harbour

The embayment along the southern coast of Merchant's Bay, to the east of Southwind Fiord, has been named inner Durban Harbour. The embayment is located at the mouth of several drainage rivers sourced from high altitude lakes, cirque and alpine glaciers. The modern shore does not have a delta deposit.

This is the site of a submerged delta, 43 m bsl, which was first surveyed in 2012 (Forbes et al., 2012). The main goal for the 2014 survey was to collect gravity cores of the delta terrace. Core-0008 was taken near the edge of the delta terrace, and from preliminary core logs it looks to have only sampled post-depositional mud and did not sample the underlying delta material. Along the traverse to the target site, the survey widened the approach to inner Durban Harbour (Fig. C.7).

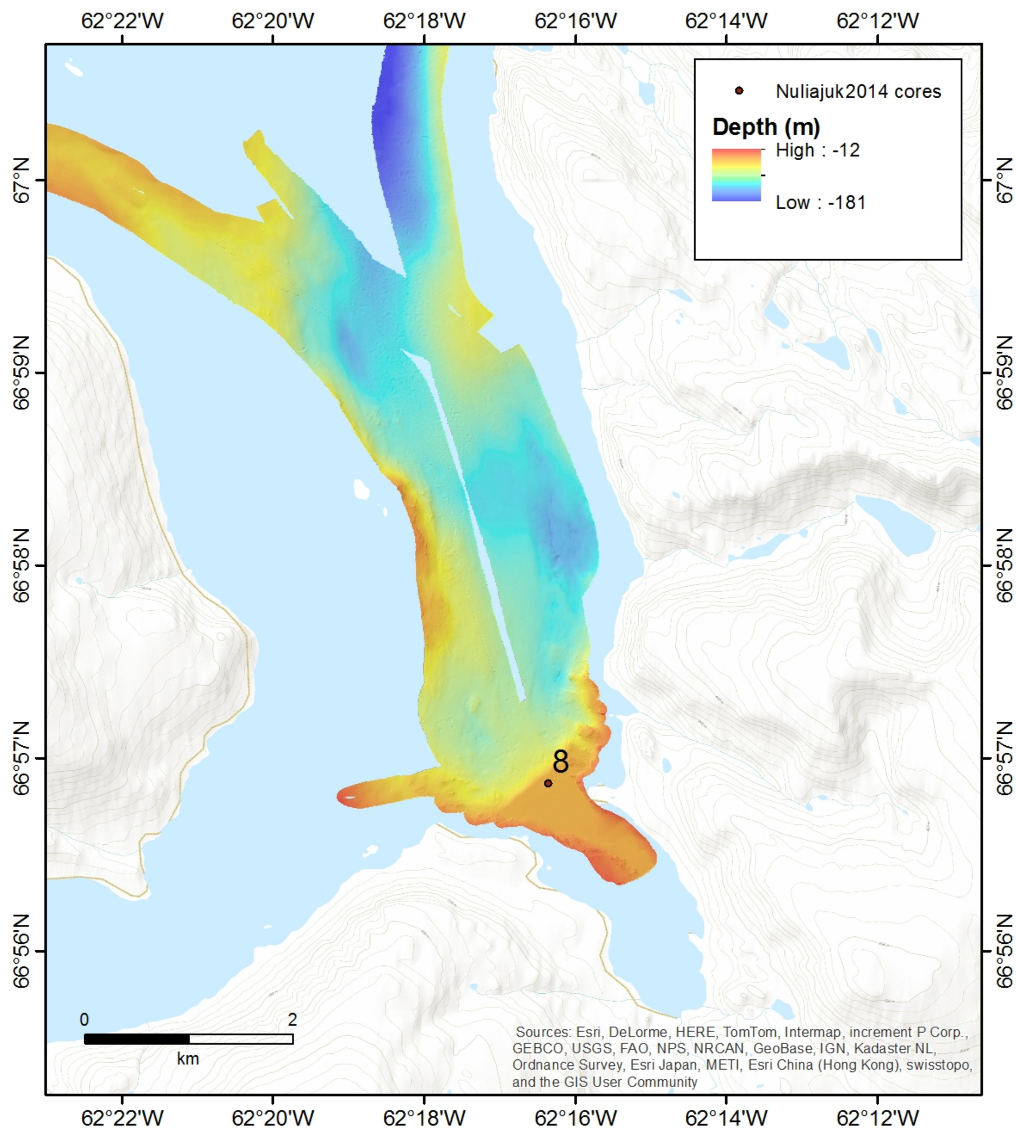


Figure C.7: Multibeam bathymetry of inner Durban Harbour with location of gravity core.

C.5.5 Boas Fiord

Boas Fiord trends north-south in northern Cumberland Peninsula, which opens into Merchant's Bay from the south. The majority of multibeam surveys were done in 2012, which documented two submerged deltas, at the fiord-head (33 m bsl) and at an eastern side-entry valley (37 m bsl; Forbes et al., 2012). The 2014 survey targeted both delta terraces for gravity core locations, as well as to broaden the approach to along the fiord (Fig. C.8).

Four gravity cores were taken from the fiord-head terrace (0001-0004; Fig. C.9a), and three cores were taken of the side-entry submerged delta (0005-0007; Fig. C.9b). From these targets, the fiord basin has been mapped in full-coverage, which has a depth of 315 m bsl (Fig. C.9b). The approach to the fiord-head has been widened, especially around the sill, which has a minimum depth < 10 m bsl (Fig. C.9a).

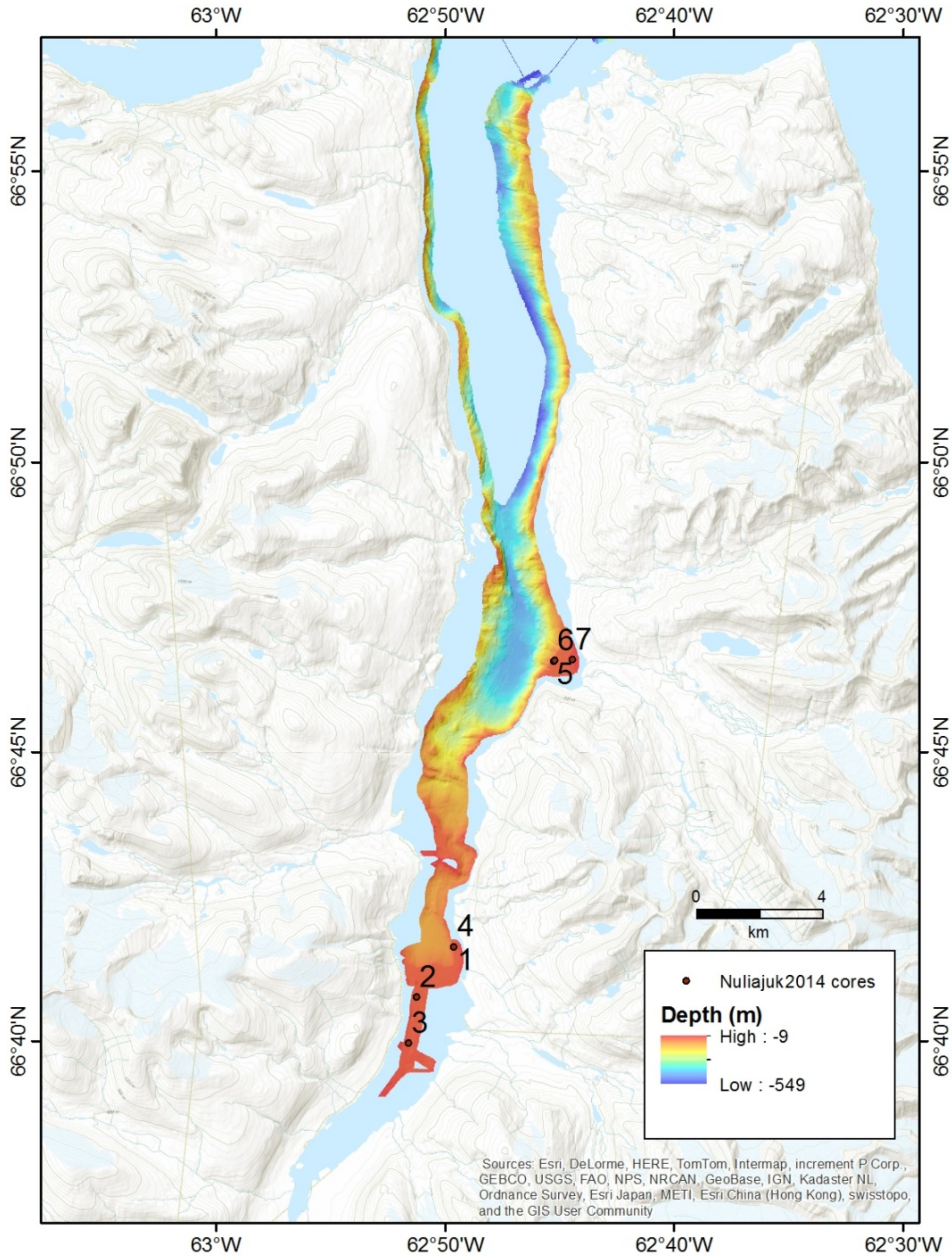


Figure C.8: Overview of the multibeam bathymetry coverage for Boas Fiord, with gravity core locations.

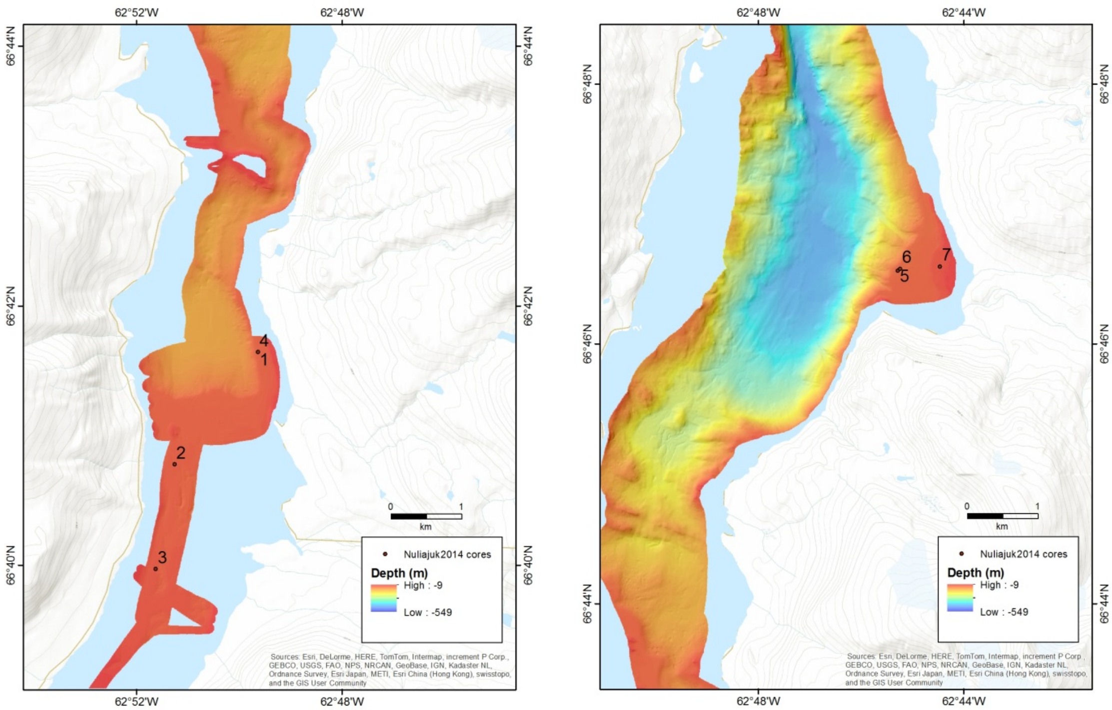


Figure C.9: A) Multibeam coverage of the submerged delta and fiord-sill at the head of Boas Fiord. B) Multibeam coverage of the side-entry submerged delta in Boas Fiord. Gravity core locations are labeled on the submerged delta terraces.

C.5.6 Outer Padle Fiord

Outer Padle Fiord was targeted because of the referral to a submerged delta in Miller & Dyke (1974). This report did not include a location, which resulted in two target areas, each with moraine deposits up-valley along a glaciofluvial drainage system (Fig. C.2; A and B). At site B is two glaciated valleys feeding into a single embayment, the eastern valley has a very steep drop to the coast, less so in the western one. Moraines are obvious at upper break of slope, with evidence of more extensive ice across the present coast; e.g., smoothed bedrock.

At site A is a wide valley that drains several smaller basins that are potentially glacierized. A single bedrock incised stream enters the bay. A flat terraced delta was mapped at -27 to -

29 m water depth at the mouth of the current river (Fig. C.10). There is at least one delta front channel roughly aligned with current river mouth.

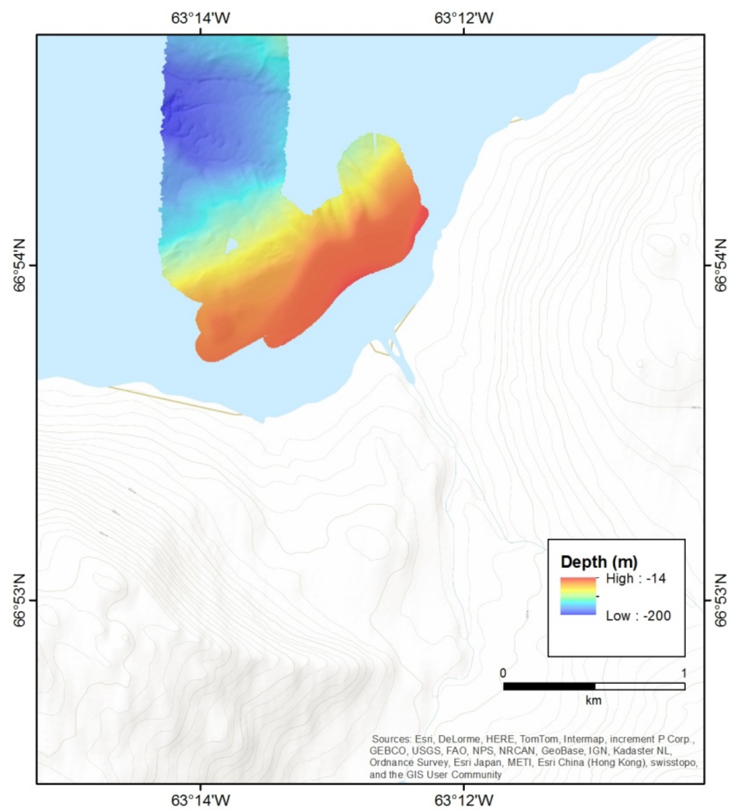


Figure C.10: Outer Padle Fiord, target site A.

C.5.7 Outer Kingnelling Fiord & Southern Broughton Island

Kingnelling Fiord was first surveyed in 2012 (Forbes et al., 2012).The 2014 survey aimed to broaden the multibeam at the fiord-mouth, and continue along the southeastern coast into the island region to the south (Fig. C.11). There is a central deep channel at the mouth of Kingnelling Fiord that is around 150 m deep, and an abrupt rise to a 75 m platform in the east. On the eastern shoreline, there are moderate to steep slopes with scree and geliflucted slope deposits reaching down to the shore. The coast is predominantly bedrock, however. On the western shoreline, there are two different coastlines. To the south is an extremely high, steep-cliffed coast with talus slopes at the base, including protalus ramparts and a hanging valley that once drained ice higher up in the mountains. Bedrock islands covered in scree jut out from the otherwise flat basin floor (270 m bsl).

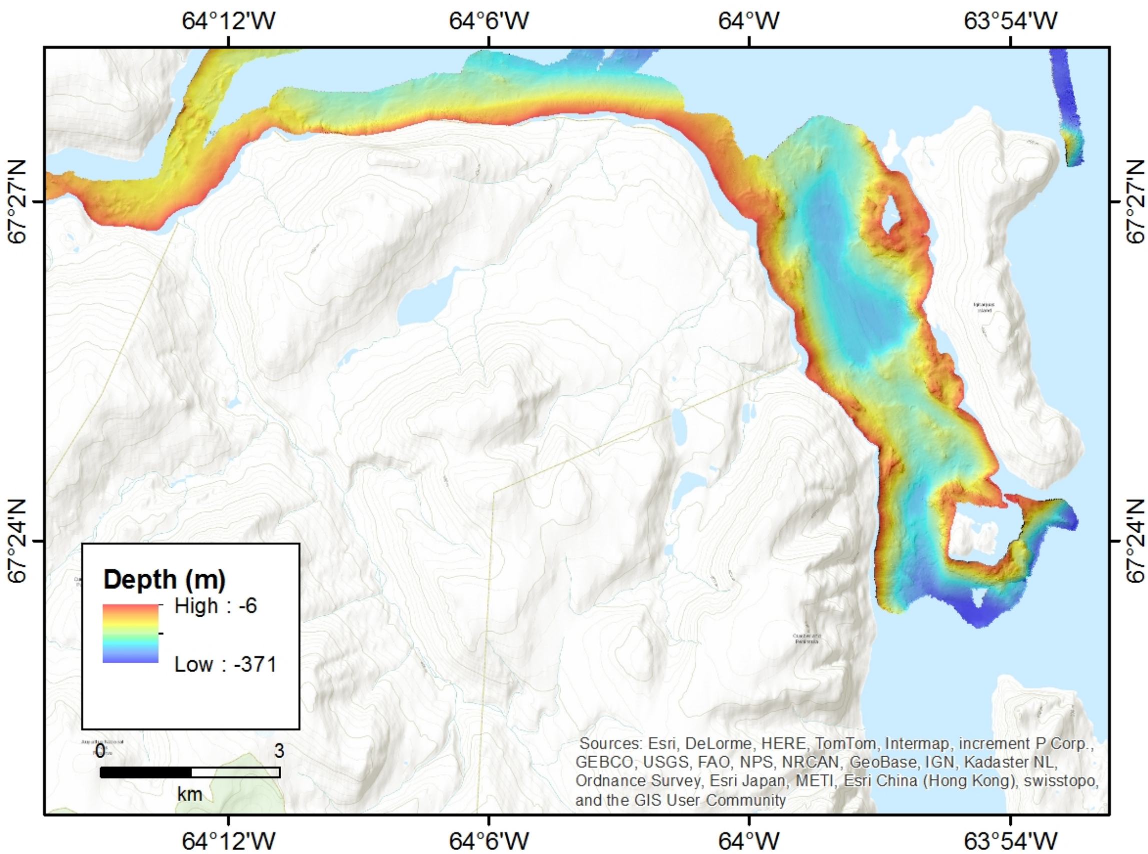


Figure C.11: Coverage of multibeam bathymetry at the mouth of Kingnelling Fiord, following the southern coast into the island region.

To the north, along the southern shore-zone of Broughton Island, the coast is more moderately high and less steeply sloped but bedrock cliffs are present, as is rubble covered slopes and talus. Here the island cliffs follow below sea-level, to > 320 m bsl (Fig. C.12). These locations were mapped to have full coverage of important locations for benthic clam habitats in the region.

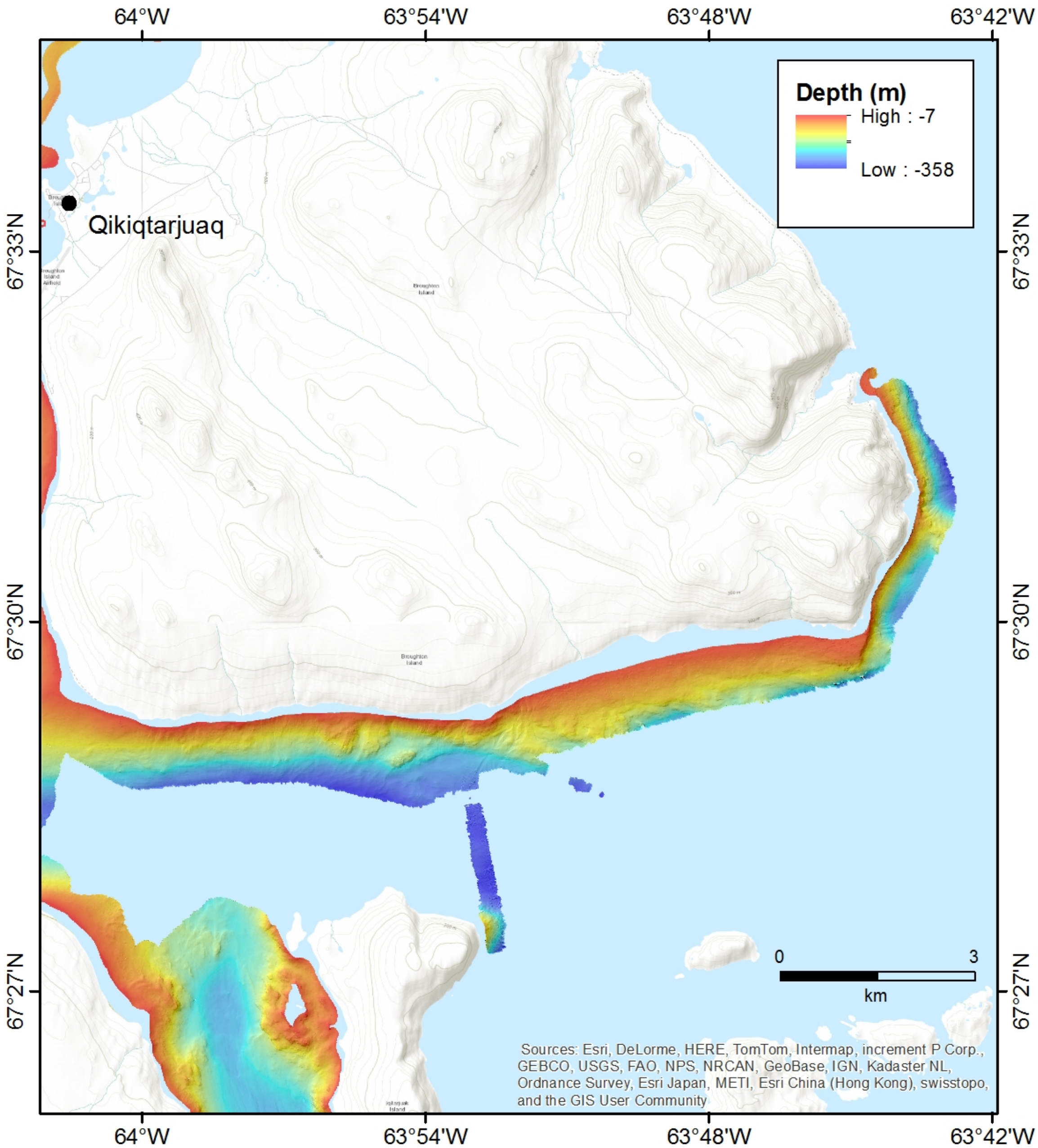


Figure C.12: Survey coverage of southern Broughton Island.

C.5.8 Northern Baffin Island region

The region to the north of Qikiqtarjuaq, NU was previously mapped in Forbes et al. (2012), the aim of the 2014 survey was to expand the multibeam coverage to the west, and to run a few lines in the east (Fig. C.13). The transects in the east were to search for submerged terraces indicative of a -16 m shoreline, which has been presented by the boulder barricade along the eastern nearshore of Broughton Channel (Forbes et al., 2012). The eastern transects do not present any terraces features, but a continuous gradient from the coast down to the outer basin (110 m bsl). In the west are some streamlined features that trend to the northeast into Baffin Bay. The western region was expanded on to encompass the regions set out for clam habitat mapping.

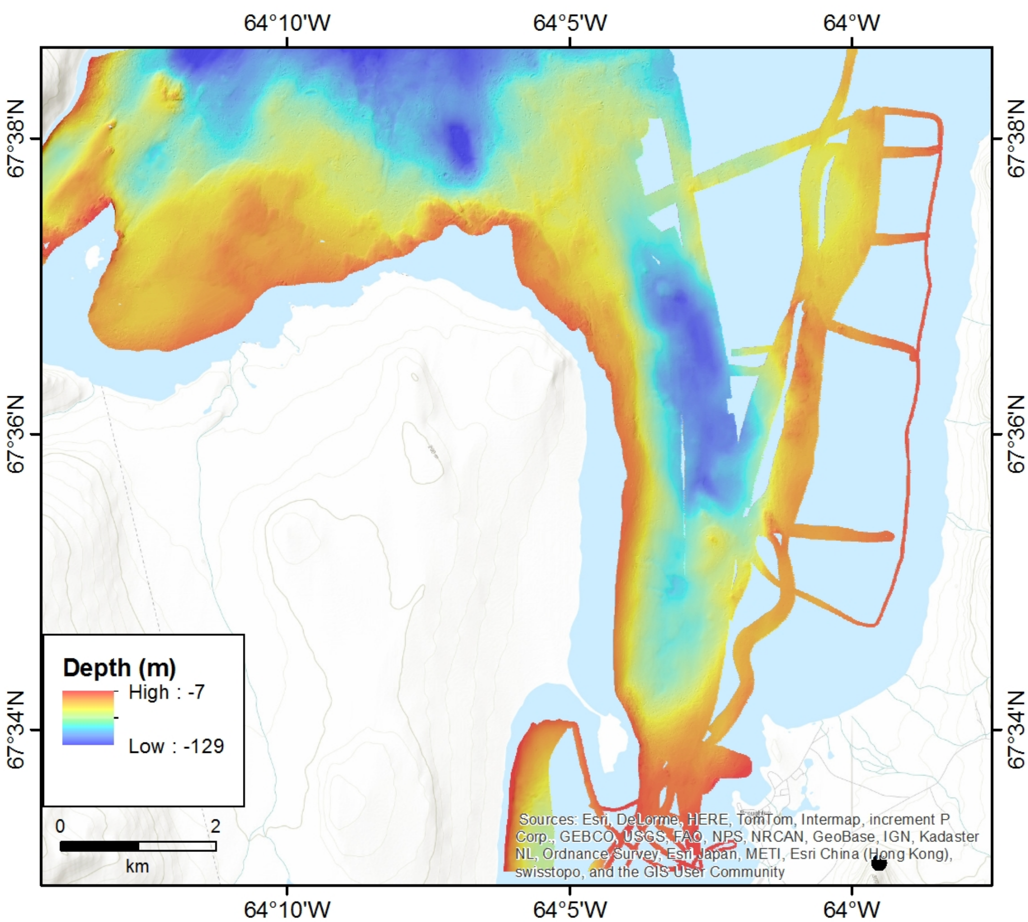


Figure C.13: Overview of survey to the north and west of Broughton Channel and the Hamlet of Qikiqtarjuaq.

C.6 Samples

Table 1: Gravity cores taken during the cruise: 2014Nuliajuk. All cores were made up of one section (with two core catchers) and were stored and transported vertically to the Geological Survey of Canada-Atlantic for processing, sampling and storage.

Latitude	Longitude	Date	Time (UTC)	Depth (m)	Station number	Apparent penetration (cm)	Length (cm)	Comment	Core catcher
66.694087	-62.82743	2014-09-04	17:05:05	31.2	0001	>98	95.5-96	inclined surface	no
66.67964	-62.85447	2014-09-04	18:11:58	28.9	0002	>78	73-78	inclined surface	no
66.666221	-62.86051	2014-09-04	19:03:56	27.8	0003	>64	61.5		no
66.694098	-62.82741	2014-09-04	20:04:25	31.2	0004	>143	140		no
66.776107	-62.75483	2014-09-04	22:26:20	36.1	0005	>13	8.5-13	inclined surface	no
66.77634	-62.75402	2014-09-04	23:08:22	36.0	0006	>19	18		yes
66.776629	-62.74116	2014-09-04	23:37:24	24.8	0007	N/A	20		yes

Table 2: Grab sample location. Stored at the Geological Survey of Canada- Atlantic.

Latitude	Longitude	Date	Time (UTC)	Depth (m)	Station number
66.947874	-62.272625	2014-09-04	00:38:00	43.2	0008

C.7 SCIENTIFIC FINDINGS

A series of high-resolution bathymetric maps were produced for five fiords and many coastal inlets in Cumberland Peninsula. This survey provides important charts for safe anchorage and transit corridors; adds another submerged delta terrace to the submerged sea-level history of Cumberland Peninsula and eight gravity cores from the submerged delta terraces.

The submerged delta terrace mapped in outer Padle Fiord has a terrace lip at 28 m bsl. It also includes a secondary level on top of the terrace, which is likely a depositional fan. The delta front slopes (16°) down into the outer basin, which has a maximum depth of 290 m. The submerged delta in outer Padle Fiord can be added to the suite of submerged deltas that have been discovered and mapped in Cumberland Peninsula throughout the *MV Nuliajuk* surveys from 2012 to 2014. Figure C.14 adds the submerged delta terrace from outer Padle Fiord to the overall depth vs. longitude graph for Cumberland Peninsula. The location of a submerged delta 28 m bsl fits directly in line with the trendline for submerged postglacial deltas. The discovery of this delta, with a depth and longitude that fit directly on the shoreline gradient, gives further evidence for the use of the gradient to predict locations and depths of similar features.

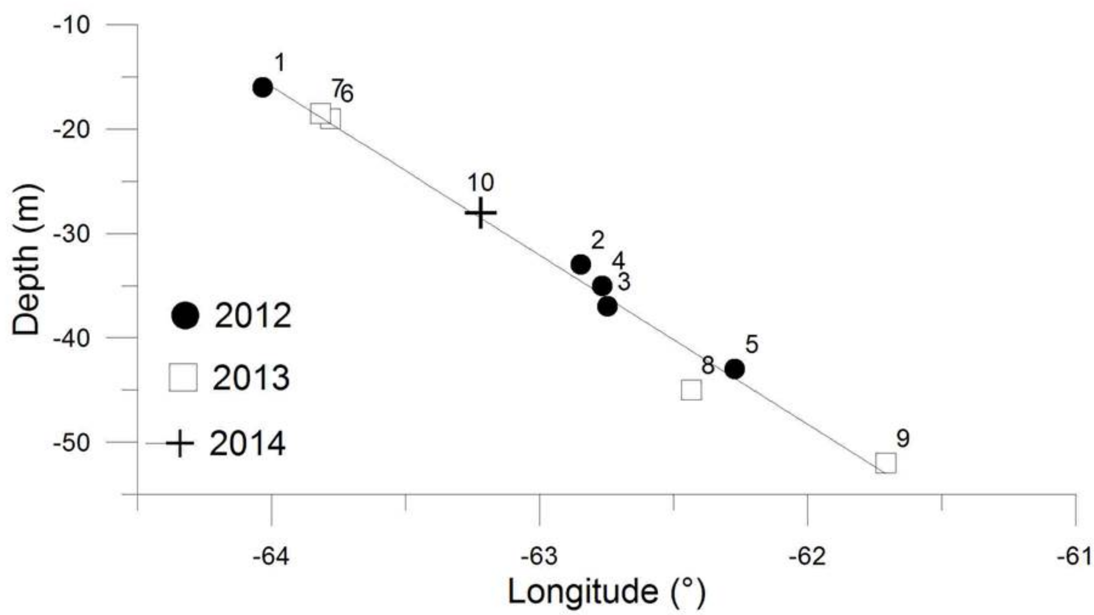


Figure C.14: Depths vs longitudinal location of outer Padle Fiord submerged delta (#10) along the east-west shoreline gradient developed from 2012-2013 multibeam survey (Forbes et al., 2012; Bell et al., 2013).

Eight gravity cores were collected from the surface sediments of submerged delta terraces previously mapped at the head of Boas Fiord, the side-entry in Boas Fiord, and inner Durban Harbour. These cores were shipped to the Geological Survey of Canada-Atlantic, where they were split, logged, sampled and are now housed in the core laboratory managed by Kate Jarrett. Preliminary interpretations of these cores suggest that they did not penetrate into the delta sediments, but only cored the post-depositional fine-grained sediments on top. Further research into these cores could still tell us much about the depositional history of the submerged deltas, from sedimentation rates and perhaps constrain the ages of transgression.

C.8 REFERENCES

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