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2013

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The shallow stratigraphy and geohazards of the northern Baffin Island shelf: studies to 2012

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2013

doi:10.4095/292614

This publication is available for free download through GEOSCAN (http://geoscan.ess.nrcan.gc.ca/).

Recommended citation
Bennett, R., Campbell, D. C., and Furze, M .F. A., 2013. The shallow stratigraphy and geohazards of the northern Baffin Island shelf: studies to 2012; Geological Survey of Canada, Open File 7355, 42 p. doi:10.4095/292614

Publications in this series have not been edited; they are released as submitted by the author.

Table of Contents

Introduction

Preliminary resource assessments of the Baffin Bay–Lancaster Sound region suggest hydrocarbon resource potential similar to or greater than the Beaufort-Mackenzie (Harrison et al., 2011) and Jeanne d'Arc basins. Prior to determining if exploration will proceed in this frontier area, scientific understanding of regional geological constraints to exploration and development is essential. Collaboration between the Geological Survey of Canada (GSC) and the ArcticNet program (www.arcticnet.ulaval.ca) has resulted in the acquisition of multibeam echosounder and sub-bottom profiler data in northern Baffin Bay and Lancaster Sound since 2004. In 2008, the GSC and partners at the University of Quebec at Rimouski and the University of Quebec at Montreal completed a joint research cruise to northern Baffin Bay and Lancaster Sound, collecting seabed sediment samples and high resolution seismic reflection data. These new data have been used in conjunction with archived high-resolution seismic data collected by the GSC during the 1970's and 1980's in an effort to compile all the currently available information relating to the surficial geology, shallow stratigraphy and seabed geohazards of the northern Baffin Island shelf (see study area in Figure 1). Through this information compilation, data and knowledge gaps regarding seabed hazards will be recognized which will be used to make recommendations for future research.

Geological Setting, Geomorphology, and Shallow Stratigraphy

Baffin Bay is the northwestern extension of the North Atlantic – Labrador Sea rift system. As seafloor spreading in the North Atlantic progressed to the north, rifting developed in the incipient Baffin Bay area (MacLean, 1990) and Cretaceous - Paleogene horst blocks and half grabens were formed as a result of this rifting (Harrison, 2011). Seafloor spreading was initiated in the area during the Selandian (Oakey, 2005) and appears to have terminated by the Oligocene (MacLean, et al., 1990). Transformation of faults by inversion occurred in the later Paleocene and Eocene (Oakey, 2005). A major depocenter, Baffin Fan, offshore Lancaster Sound (Figure 1) has been collecting fluvial and deltaic sediments from the Eocene to the Pliocene (Harrison et al., 2011).The upper portion of the Baffin Fan is comprised of glacially-derived Quaternary sediments of the Lancaster Sound Trough-Mouth Fan (TMF).

The Canadian Baffin Bay margin is a passive continental margin that lies offshore four large islands of the Canadian Arctic Archipelago: Baffin Island, Bylot Island, Devon Island, and Ellesmere Island. However, only Baffin Island has a conventional continental shelf (Figure 1). The shelf off Baffin Island is about 50–60 km wide with the shelf break occurring at about 300 m water depth. It is crossed by several transverse troughs located at the mouths of major fiords and inlets. Both Bylot and Devon islands are surrounded by steep slopes from the shoreline down to the Baffin Fan that covers the bottom of northern

Baffin Bay and Lancaster Sound. A distinct continental shelf is not recognized off Ellesmere Island, where the seabed slopes gently at an average of 0.4° from the shoreline to the abyssal plain without significant changes in gradient (Aksu and Hiscott, 1989). Sedimentation in deep water of Baffin Bay is different than that of glacially dominated margins farther south in eastern Canada. Sedimentation rates are low, leveed deep-water channels are absent and sediment supply is largely derived from the break-up of ice shelves (Aksu and Piper, 1987). The area is very seismically active compared to other passive margins. The M 7.3 earthquake of November 20, 1933 (Figure 1) is the largest instrumentally recorded passive margin earthquake in North America, possibly the world, and it is also the largest known earthquake north of the Arctic Circle (Bent, 2002). The shallow geology in the area of the M 7.3 earthquake is dominated by the widespread deposition of glaciogenic debris flows (Li et al., 2011) on the Lancaster Sound TMF. While no evidence of slope failure in the 1933 earthquake area was observed in the limited data collected during the 2008 expedition, widespread slope failure is observed on the continental slope offshore Clyde Inlet (Aksu and Hiscott, 1989).

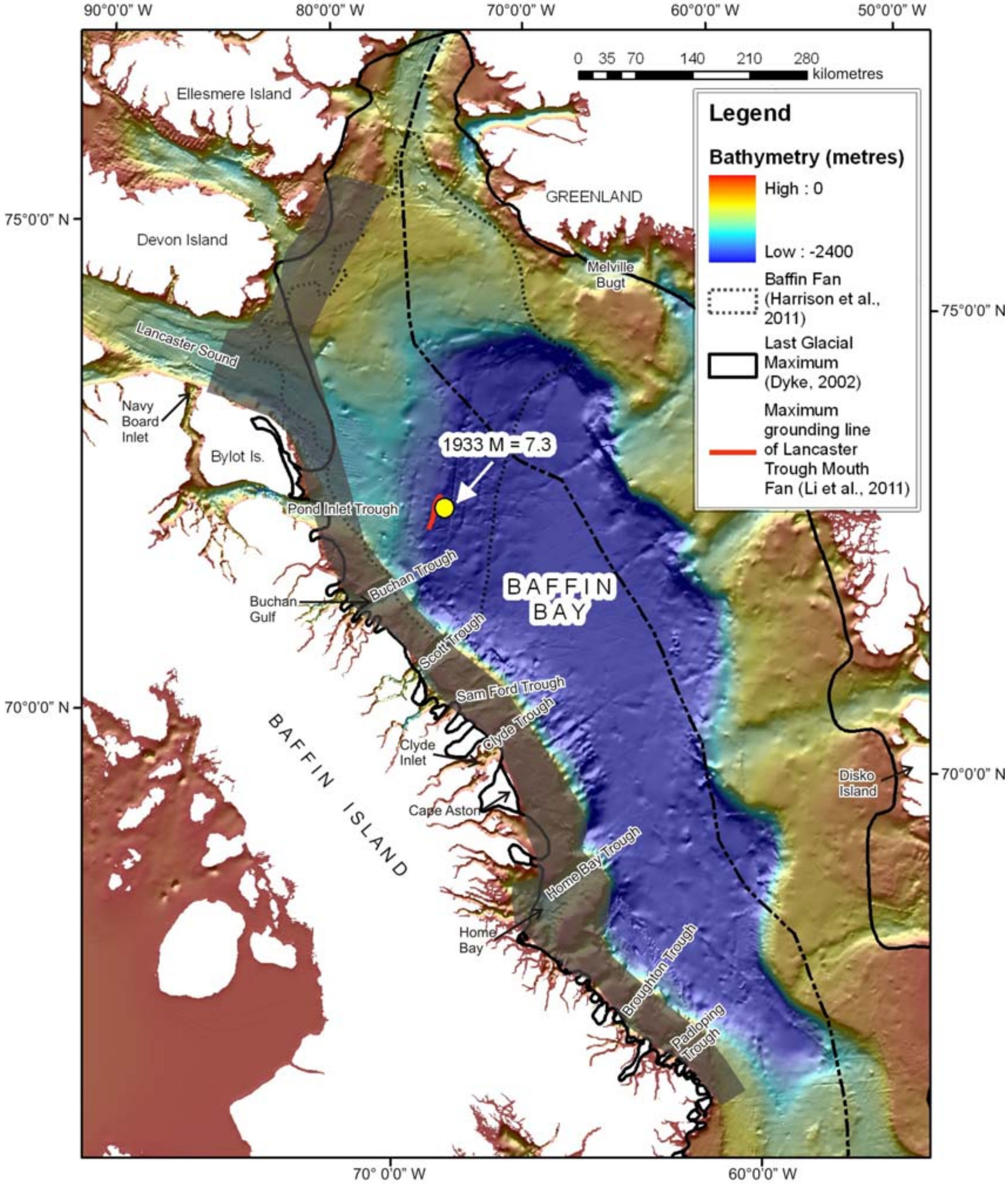

Figure 1: Canadian Baffin Bay margin; study area outlined by grey shaded area (Bathymetry data from unpublished Canadian Hydrographic Service database, not for navigation purposes)

The shallow stratigraphy of a large portion of the northern Baffin Island shelf is described in Praeg et al. (2007). This report presents a synthesis of the Quaternary geology of the northern Baffin Island shelf between Cape Aston and Buchan Gulf based on acoustic data (shallow seismic, sidescan sonar, and echosounder profiles) and sediment samples (piston cores, box cores, bottom photographs, and submersible observations) collected during GSC expeditions between 1974 and 1985. The report describes the morphology of the shelf and upper slope, the stratigraphy of sediments overlying bedrock, and the character of seabed sediments. The following description of the shallow stratigraphy of the northern Baffin Island shelf is summarized from Praeg et al. (2007).

The northern Baffin Island shelf is cut by eight major transverse troughs that lie offshore fiords or large inlets. While all eight troughs record glacial erosion by outlet glaciers (Shepard, 1931; Pelletier, 1966), they were probably influenced by prior fluvial erosion (Fortier and Morley, 1956; Pelletier, 1966; Gilbert, 1982) or graben-style faulting (Andrews and Miller, 1979; Gilbert, 1982; England, 1987). The troughs are characterized by steep sides (Pelletier, 1966; Loken and Hodgson, 1971) with slope gradients up to 25° observed along the margins of some of the deeper troughs. All of the troughs have been over-deepened by glacial erosion as evidenced by seaward decreasing axial water depths (Praeg et al., 2007). Quaternary sediment accumulations are generally thinner on the walls of the troughs (<25 m) and thicker (up to 180 m) in bedrock depressions on the trough floor. The inter-trough areas of the shelf are marked by a system of longitudinal ridges and depressions developed within the Quaternary succession. The depressions were excavated by glacial erosion while the ridges are lateral moraines deposited by outlet glaciers occupying the troughs (Løken and Hodgson, 1971; Gilbert, 1982).

The surficial sediments in the bottom of the transverse troughs mostly consist of soft postglacial hemipelagic muds of the Tiniktartuq Mud unit. This unit, which is up to 7 m thick, consisting of grayish-brown to olive gray clay with 5 to 30% sand and coarser material. The adjacent bank tops consist of the glacial ice contact sediments of the Baffin Shelf Drift unit and the glaciomarine sandy mud and gravel of the Davis Strait Silt unit with localized concentrations of the postglacial Cape Aston Sand unit. The Baffin Shelf Drift Unit consists of glacial ice-contact sediment that may include glacial till, ice-marginal dump material or ice-loaded sediment that has been deposited or remoulded in contact with grounded glacial ice (Syvitski and Praeg, 1989). The Davis Strait Silt Unit is interpreted to be of glaciomarine origin and consists of a massive olive gray to black, very poorly sorted sandy mud with gravel, generally occurring in water depths greater than 150 m. This unit is usually 2–4 m thick but can reach local thicknesses of 7 m. Debris flow deposits observed in the Davis Strait Silt record a history of sediment failure in Scott Trough during the Pleistocene. The Cape Aston Sand Unit occurs in water depths less than 80 m and consists of ~80 % sand with variable gravel and clay. The unit is correlative in age to the Tiniktartuq Mud Unit but is likely the result of the deposition of coarse grained material from eroded coastal forelands of Baffin Island. Bedrock interpreted to be basement highs composed of Precambrian crystalline rocks (MacLean et al., 1981) occasionally outcrops at the seabed on the shelf (Figure 2 and Figure 3).

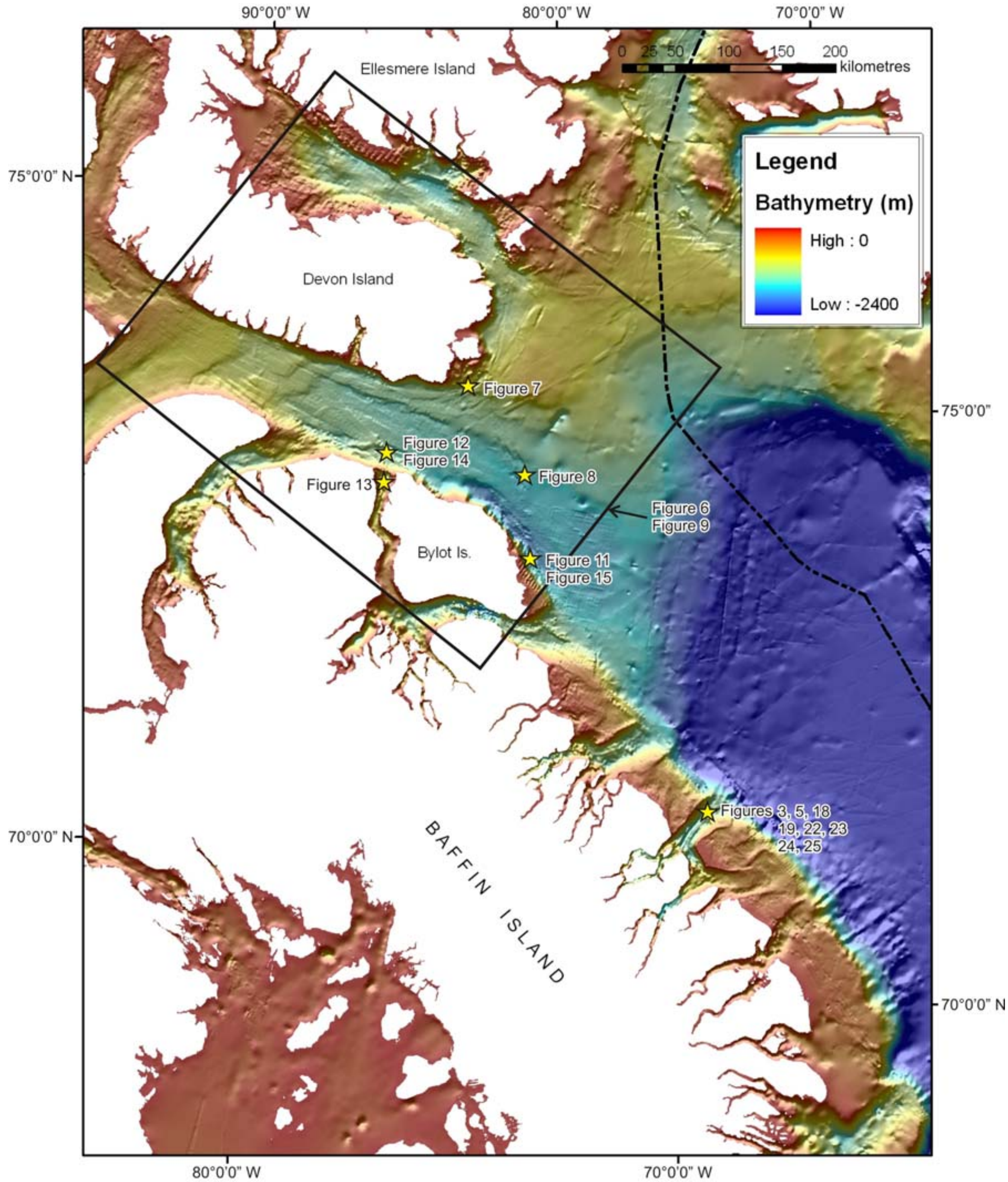

Figure 2: Locations of detailed bathymetry maps (Bathymetry data from unpublished Canadian Hydrographic Service database, not for navigation purposes).

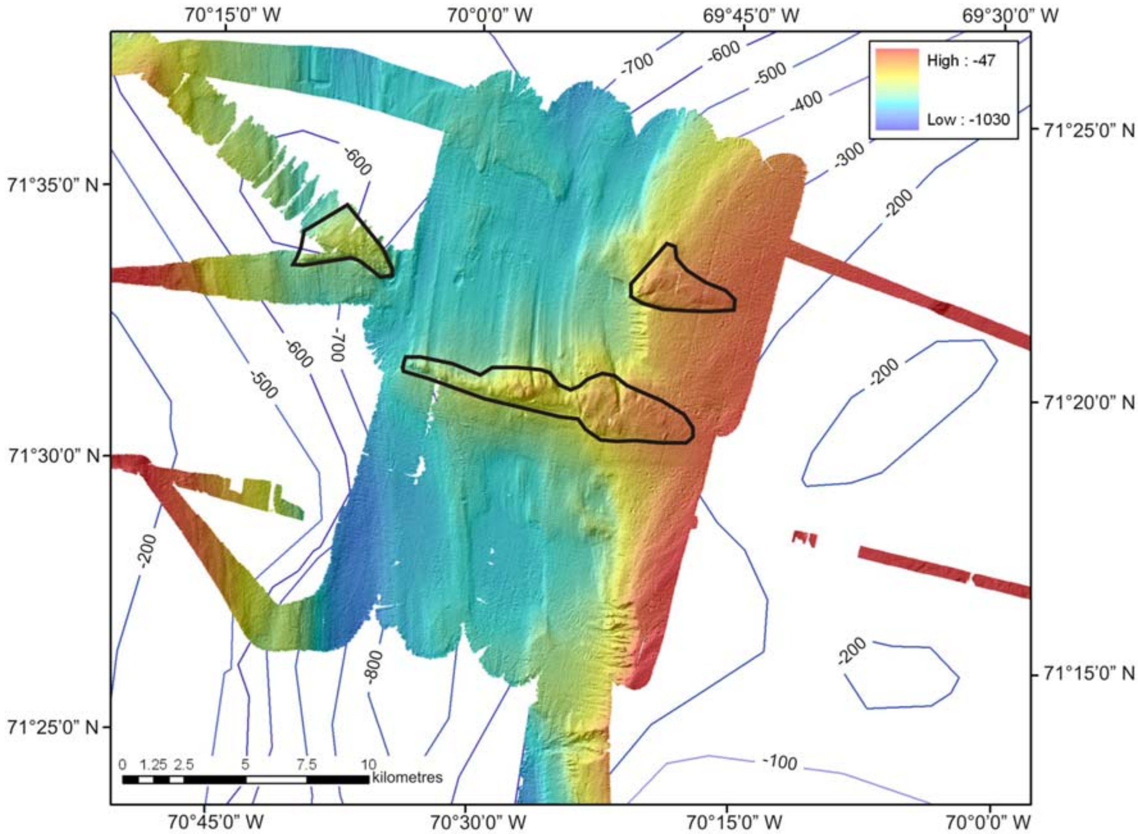

Figure 3: Seabed expression of bedrock in the Scott Trough area (Contours in metres; multibeam bathymetry data source: University of New Brunswick–Ocean Mapping Group (UNB-OMG)).

The most recent geological data on the northern Baffin Island shelf were acquired in 2008 (Campbell and de Vernal, 2008). A series of piston cores was collected during this expedition in northwestern Baffin Bay and Lancaster Sound that provide insight into the shallow stratigraphy of the area (Figure 4). The lowermost sediment penetrated by these cores is glacial till. This till is a very dark brown sandy clay with sandy laminations and pebbles. The till is overlain by laminated glaciomarine sediments consisting of carbonate-rich gray silty clay with occasional sandy layers and pebbles. The uppermost sedimentary unit is comprised of post-glacial bioturbated olive gray silty clay. Similar stratigraphy is observed in western Lancaster Sound, Barrow Strait, as well as Wellington, Byam Martin, and Austin channels (MacLean, 1989).

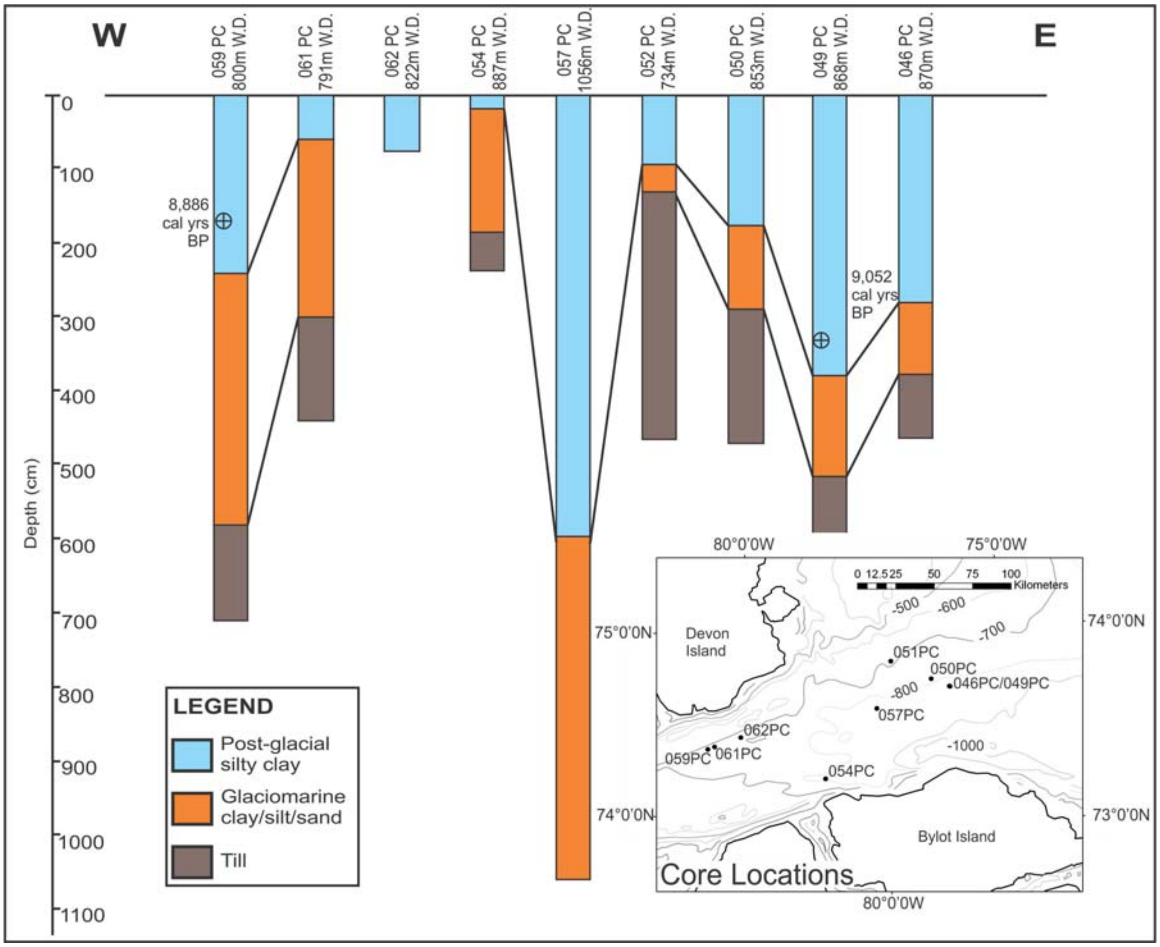

Figure 4: Schematic diagram of piston cores collected in outer Lancaster Sound and Baffin Bay during expedition 2008029 (Contours in metres). Radiocarbon dates are summarized in Table 1.

Geohazards

An assessment of available data as of 2012 suggests that the following geohazards exist on the northern Baffin Island shelf: ice scour, hydrocarbon venting features, steep uneven seabed caused by glacial features, and slope failures on transverse trough margins. These hazards are observed on other glaciated continental shelves. An additional hazards present on the northern Baffin Island shelf that makes it unique is its high level of seismic activity. Baffin Bay experienced the largest recorded passive margin earthquake in North America (Bent, 2002) and Canadian seismic hazard maps show that Baffin Bay has a level of hazard comparable to that of coastal British Columbia (Basham et al., 1997; Adams and Halchuk, 2003).

Ice Scour

Much of the seabed of the northern Baffin Island shelf has been disturbed by iceberg scour. These scours are caused by icebergs with drafts that are deep enough to contact the seabed and cause long scours with side berms (Figure 5) as the ice is moved by wind and current action (Pelletier and Shearer, 1972). Between 20,000 to 40,000 icebergs are calved into Baffin Bay each year (Murray, 1969; Markham, 1981), most of which are produced from fast-flowing tidewater glaciers north of Disko Island and Melville Bugt, western Greenland (Dinsmore, 1972). The number of icebergs over the last decade could be higher however due to climate warming that has caused an increase in ice discharge from the Greenland ice sheet (Sasgen et al., 2012).The West Greenland Current and Baffin Island Current bring icebergs from Greenland waters to the Canadian side of Baffin Bay where about 80 icebergs a year (Dirschl, 1982) enter Lancaster Sound. Only about 5% of icebergs in Lancaster Sound originate from Ellesmere, Devon, and Bylot Island glaciers and ice shelves (Dirschl, 1982). Most icebergs (~80%) only intrude about 100 km into Lancaster Sound before being turned around in a counterclockwise drift pattern and pushed back out into Baffin Bay to continue south with the Baffin Island Current and later the Labrador Current (Dirschl, 1982). An average of 4300 icebergs traverse the northern Baffin Island shelf annually (Ebbesmeyer et al, 1980).

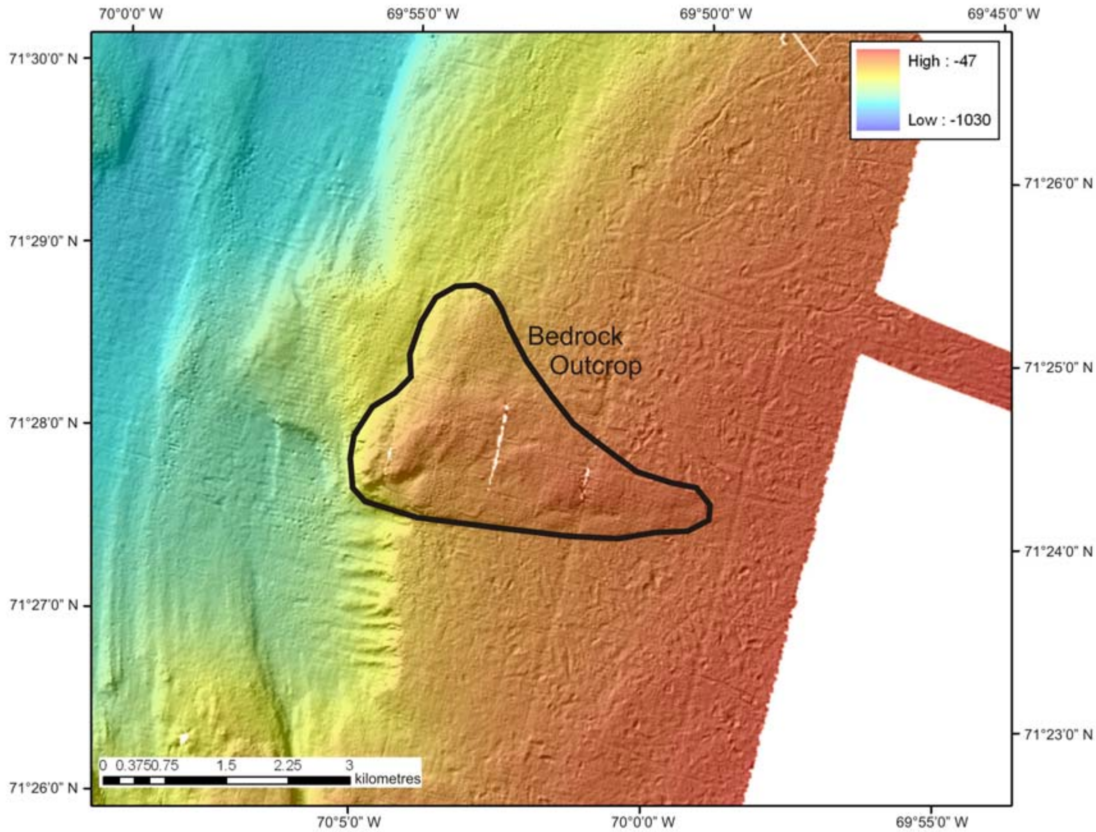

Figure 5: Example of heavily scoured seabed on the southern bank top adjacent to Scott Trough. No scours are present on the bedrock outcrop (Contours in metres; multibeam bathymetry data source: UNB-OMG).

The large modern icebergs in Baffin Bay usually have drafts between 100 and 200 metres (Dinsmore, 1972) but occasionally can be much deeper. The deepest ice keel observed in Northern Baffin Bay destroyed acoustic monitoring equipment on the seabed in 427 m of water during the 1967-1968 ice season (Milne, 1969). However, icebergs with keels as deep as ~500 m are observed offshore Labrador (Harris, 1974), Eastern Greenland (Dowdeswell et al., 2007, Syvitski et al., 1996) and Antarctica (Barnes and Lien, 1988). These large modern icebergs cannot account for the entire scour population observed in Northern Baffin Bay and Lancaster Sound

Relict iceberg scours are scours that occur in areas where icebergs are no longer found, or in areas where icebergs can no longer reach the seabed due to an increase in water depth or a decrease in iceberg size (Lewis and Woodworth-Lynas, 1990). Previous work has identified iceberg scour to depths of 715 m water depth off the northern Baffin Island shelf (Praeg et al., 1987). Other studies have observed features that might be interpreted as ice scour at depths over 1000 m (Kuijpers et al. 2007). While the age of these scours is unknown, their occurrence in water depths beyond what can be scoured by the modern-day iceberg regime and their superposition on glacial sediments suggest that they were likely formed during deglaciation of Late Pleistocene ice shelves and ice sheets (Lewis and Woodworth-Lynas, 1990).

Multibeam echosounder data were used to map the distribution of ice scour in Northern Baffin Bay and Lancaster Sound (Figure 6). Due to the discontinuous coverage of multibeam data, the boundaries of the ice scour distribution in Figure 6 are assumed in areas where there is no data coverage. Using the multibeam data set gridded at 10 m horizontal resolution, ice scour was observed over most of the study area in water depths ranging up to 850 m. Scours typically have an incised depth of 1–4 m into the seabed but can occasionally be greater with the maximum scour depth observed being 19 m (Figure 7). The width of the scours ranges from ~65 m across up to ~500 m across. Due to the incomplete multibeam coverage it is difficult to measure the length of the scours as the start and end points are typically not visible but the scours that do have large sections imaged in the multibeam data set are several tens of kilometres long.

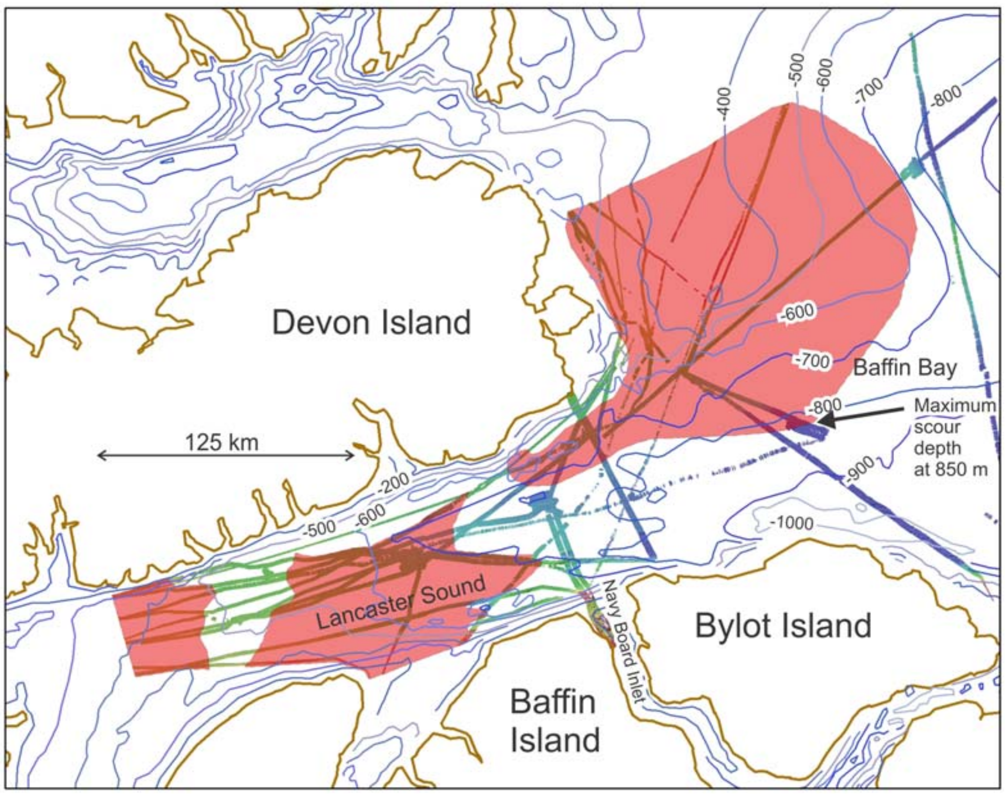

Figure 6: Ice scour distribution of modern and relict scours in Northern Baffin Bay and Lancaster Sound (Contours in metres; multibeam bathymetry data source: UNB-OMG).

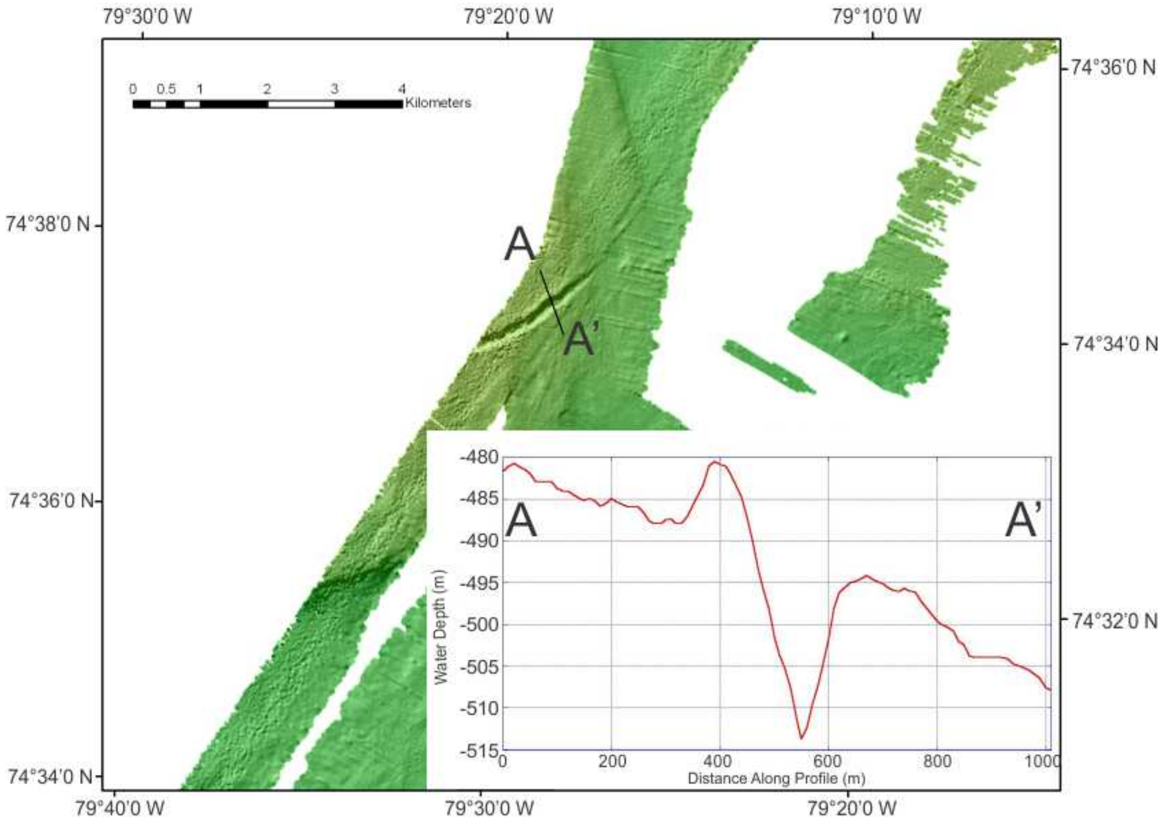

Figure 7: Bathymetric profile of 19 m deep scour in outer Lancaster Sound (400 m water depth) (Multibeam bathymetry data source: UNB-OMG)

The deepest water depth in which ice scour is observed in the data set used for this study is 850 m (Bennett, 2010). This ice scour was first mapped by multibeam echosounder in 2005 (Figure 8) and in 2008 high-resolution seismic (Huntec) data and a piston core were collected in order to obtain an estimate of the age of the scour. The Huntec profile shows the ice scour has been incised into the sub-surface glaciomarine unit that is has been draped by ~4 m of acoustically transparent post-glacial sediment since the formation of the scour (Figure 7). Piston core 2008029-049 PC was collected inside the scour and is comprised of 379 cm (Top to 379 cm downcore) of post-glacial bioturbated olive gray silty clay overlying 135 cm (379 to 514 cm downcore) of glaciomarine laminated light colored olive gray silty clay with occasional pebbles overlying 80 cm (514 to total depth, 594 cm, downcore) of glacial till composed of very dark brown sandy clay with sandy laminations and pebbles (Figure 8). A bivalve shell (*Yoldiella fraterna*) was retrieved from this core just above the transition from postglacial to glaciomarine sediment at 332 cm and was submitted for radiocarbon dating. This shell yielded a measured radiocarbon age of 10,670 +/- 50 yr BP (Table 1). However *Yoldiella fraterna* is prone to the "*Portlandia* effect" which can give erroneous radiocarbon dates often 1000 years older and up to 2200 years older than their actual age (England, 2003). A correction of 745 +/- 600 years (England,et al., 2012) was applied to this sample to correct for the *Portlandia* effect giving the sample a corrected age of 9,052 Cal yr BP. To confirm this age, a

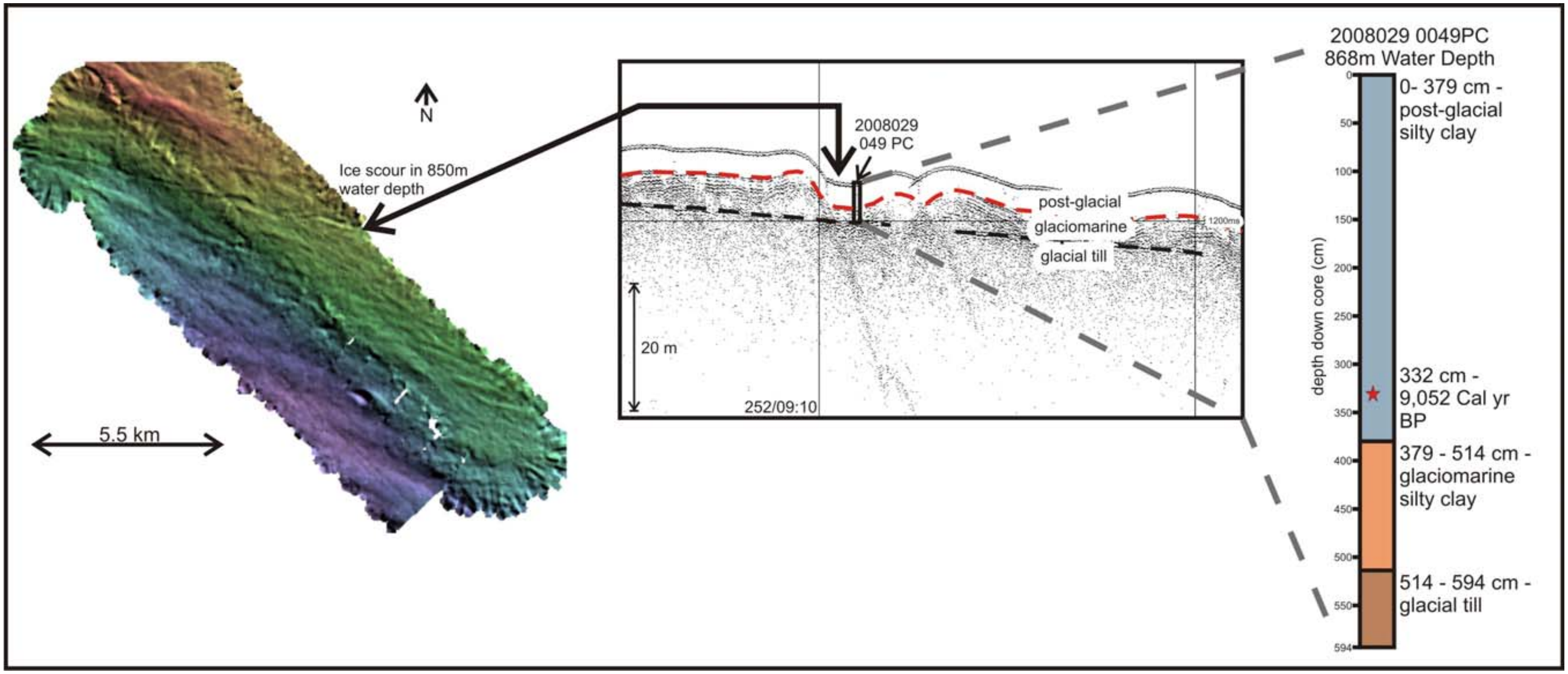

Figure 8: Multibeam bathymetry, sub-bottom profiler data and core stratigraphy at an ice scour located in 850 m water depth in outer Lancaster Sound (Multibeam bathymetry data source: UNB-OMG).

second bivalve shell (of a species not subject to the *Portlandia* Effect) just above the postglacial to glaciomarine transition in piston core 2008029-059 PC (Figure 4), located 160 km away, was radiocarbon dated yielding a date of 8,886 Cal yr BP (Table 1). Since the ice scour in 850 m of water is draped by the post-glacial unit it was formed more than ~9,000 years ago and it is relict. It also illustrates that old scours draped by young sediment may appear "fresh" in multibeam images.

Using observations from the data available at present, modern icebergs are capable of scouring to water depths of at least ~430 m in Baffin Bay and Lancaster Sound. Icebergs are capable of creating scours in water depths up to ~500 m elsewhere in the Labrador Sea–Baffin Bay system so additional data and analyses are required to refine the bounding water depth for modern scours.

Table 1: Radiocarbon dates from piston cores in Lancaster Sound

Core #	Depth downcore (cm)	Material dated	Lab #	Measured Radiocarbon age (^{14}C years BP)[a]	Adjusted Radiocarbon age (^{14}C years BP)[b]	Calibrated ages (cal years BP)[c]
2008029-049 PC	332	Bivalve shell - *Yoldiella fraterna*	Beta - 283439	10,670 +/- 50	8,725 +/- 600	9,052
2008029-059 PC	171	Bivalve shell - *Thyasira gouldi*	Beta - 283442	9,870 +/- 50	8,670 +/- 50	8,886

[a]AMS ^{14}C ages as measured from the laboratory.
[b]All dates adjusted for 1200 ^{14}C year deep water enhancement (Hanslik et al., 2010, Schlosser et al., 1997). Additional adjustment to Beta–283439 for *Portlandia* effect = 745 +/- 600 ^{14}C years (England et al., 2012).
[c]Calibrated ages obtained using Calib Rev 6.0.1 (Stuiver et al., 1993) and the MARINE09 calibration database (Reimer et al. 2009) with a ΔR value of 335 +/- 85 years (Coulthard et al. 2010). The calibrated ages are calculated from the average of the calibrated age range based on two standard deviations (95% confidence).

Glacial Features

Lancaster Sound and parts of Baffin Bay were occupied by glacial ice during the last glaciation (Klassen and Fisher, 1988; Dyke, 2003) and there is evidence of previous glaciations back as far as the early Pleistocene (Srivastava et al., 1989, Li et al., 2011). Multibeam echosounder data have been used to map the distribution of glacial features such as fluting, sediment wedges, and ice scour in Northern Baffin Bay and Lancaster Sound (Figure 9).

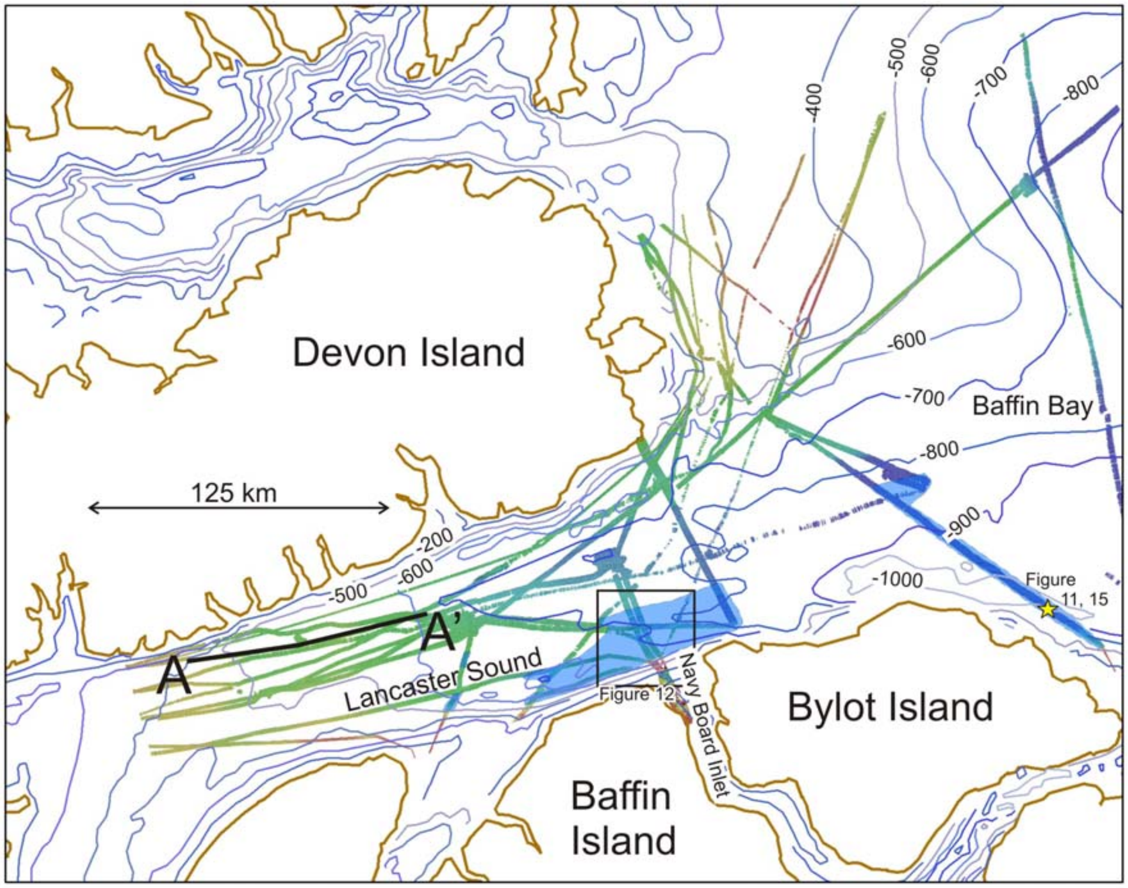

Figure 9: Glacial feature distribution in Northern Baffin Bay and Lancaster Sound (Contours in metres; multibeam bathymetry data source: UNB-OMG).

Three large sediment wedges are observed in the western end of Lancaster Sound (Figure 10). The wedges are ~50 to 200 m high and together they cover ~5400 km^2 of the seabed. Similar seabed morphology is also observed seaward of these wedges in Baffin Bay where a succession of till deltas and wedges have been deposited on the Lancaster Sound TMF (Li et al., 2011). Li et al. (2011) show that the Lancaster Sound TMF has been collecting glacial sediment as far back as MIS 22 up to and including the last glaciation. These wedges were likely deposited during late Pleistocene retreat of ice in Lancaster Sound.

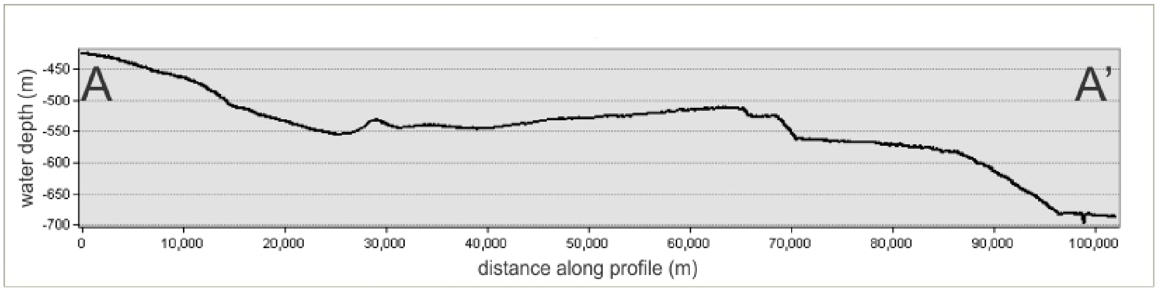

Figure 10: Seabed profile over sediment wedges located in western Lancaster Sound (see Figure 9 for location).

Lancaster Sound has been interpreted as the site of a large paleo-ice stream during the last glaciation (de Angelis and Kleman, 2005). Moraines on Bylot island and submarine escarpments offshore the northern Bylot Island coast suggest glacial ice in Lancaster Sound was over 1600 m thick (Klassen and Fisher, 1988). Glacial fluting consisting of streamlined drumlins (Figure 11) and seabed lineations (Figure 12) is observed along the southern portion of Lancaster Sound, in northern Navy Board Inlet, and northeast of Bylot Island in Baffin Bay. These features are similar to other glacial sole marks observed in Amundsen Gulf (Stokes at al., 2006; Bennett et al., 2007) and Peel Sound (MacLean et al., 2010) that have been attributed to glacial ice streams. The lineations in northern Navy Board Inlet occur at the crest of a bedrock ridge and are oriented in a north–south direction (Figure 13). The height of the lineations decreases to the north suggesting a northerly flow direction. Very large lineations in southern Lancaster Sound are oriented in an east–west direction (Figure 14) but show no preferred flow direction through their morphology, however, previous work by Klassen and Fisher (1988), Dyke at al. (2003) and de Angelis and Kleman (2005) indicates ice flow direction from west to east in Lancaster Sound during the last glaciation. Streamlined drumlins and lineations located northeast of Bylot Island in Baffin Bay indicate an ice flow direction to the southeast (Figure 15). Together, these features show the movement of ice out of Navy Board Inlet to join with the Lancaster Sound ice stream which flows to the east, and curves southerly around the north side of Bylot Island.

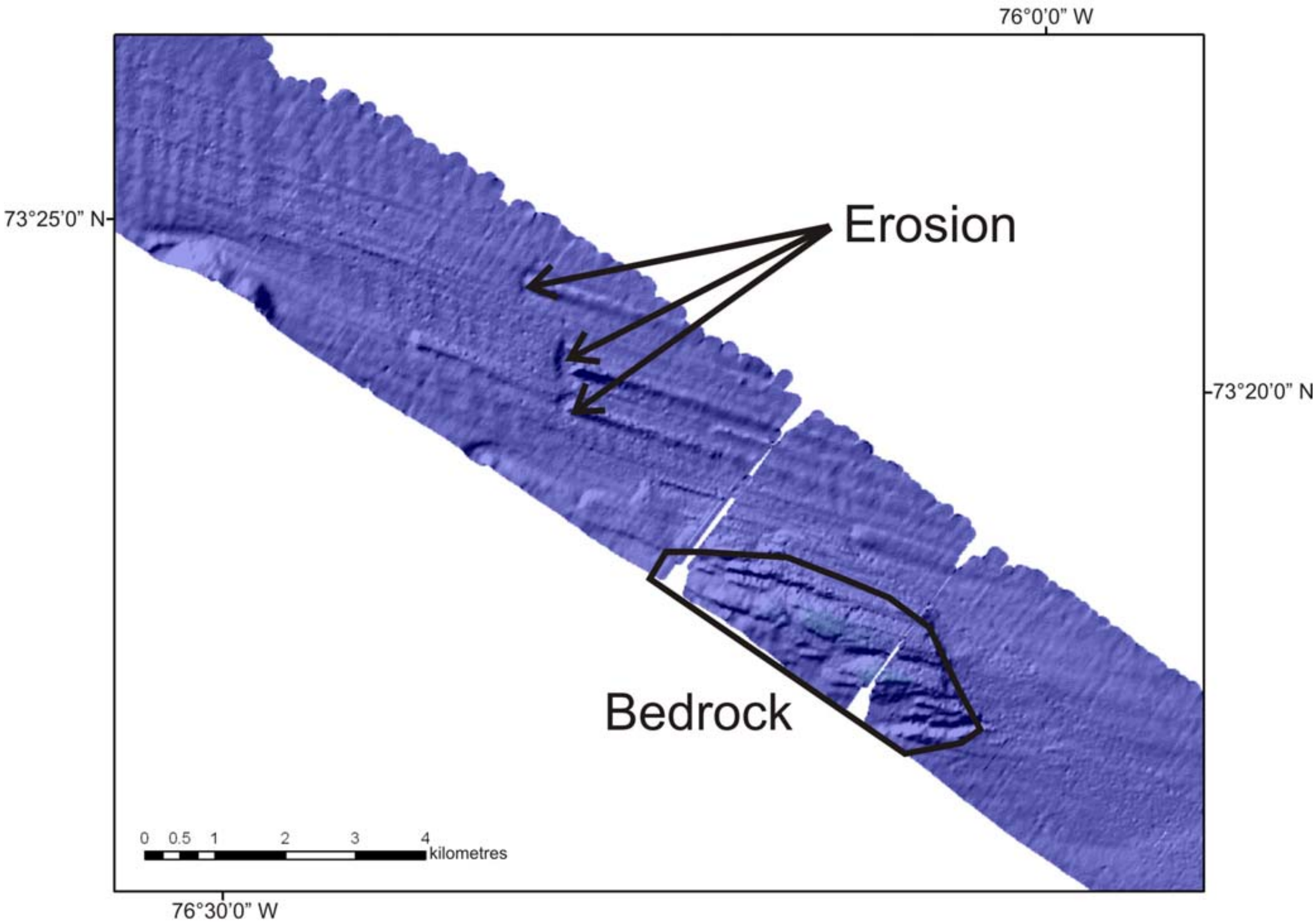

Figure 11: Streamlined drumlins located in outer Lancaster Sound. Bedrock is also observed to be at or near the surface in this area (Multibeam bathymetry data source: UNB-OMG).

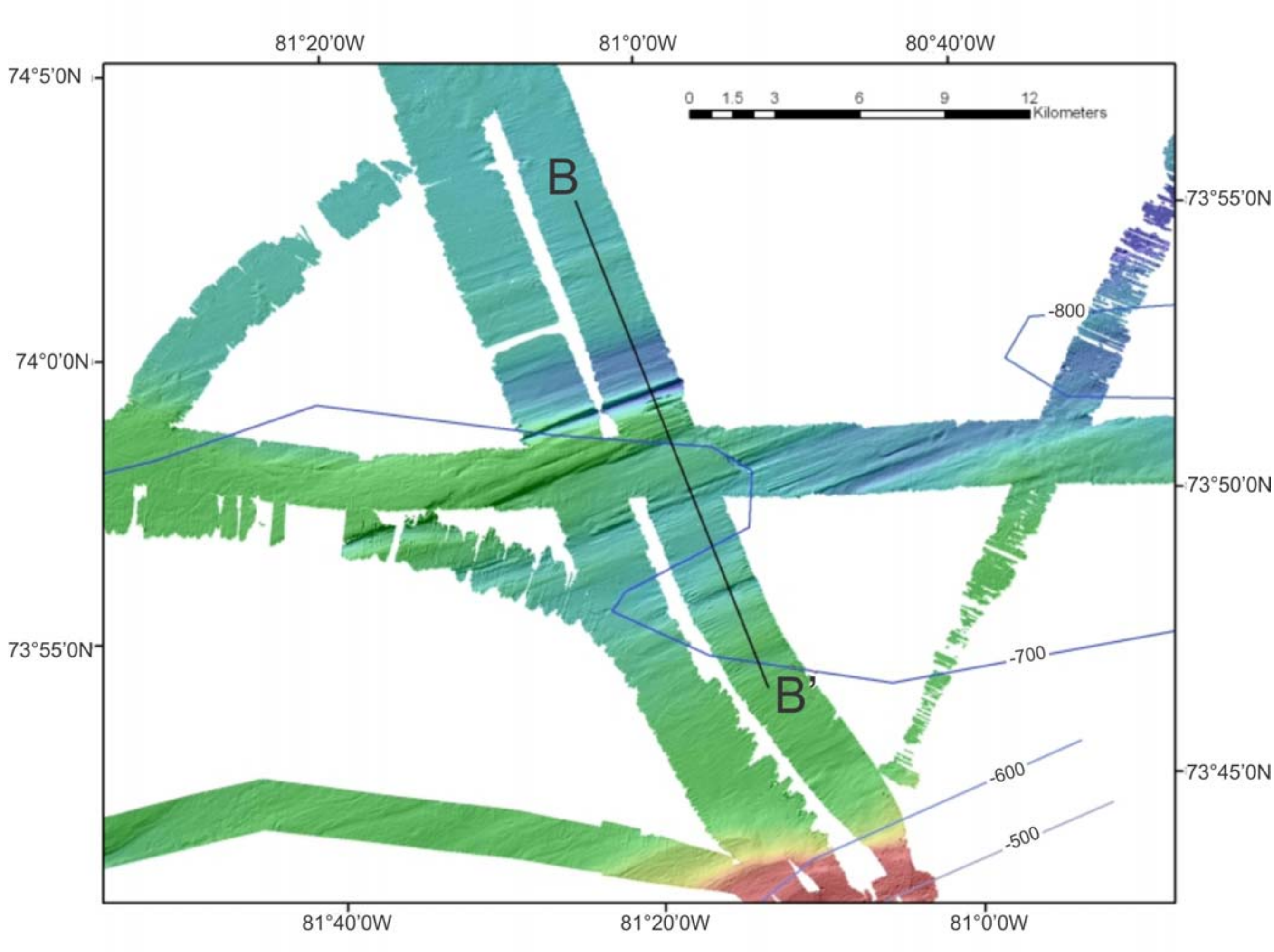

Figure 12: Glacial lineations in Lancaster Sound, B–B' is the location of the profile in Figure 16 (location of this figure is shown in Figures 9 and 14) (Contours in metres; Multibeam bathymetry data source: UNB-OMG).

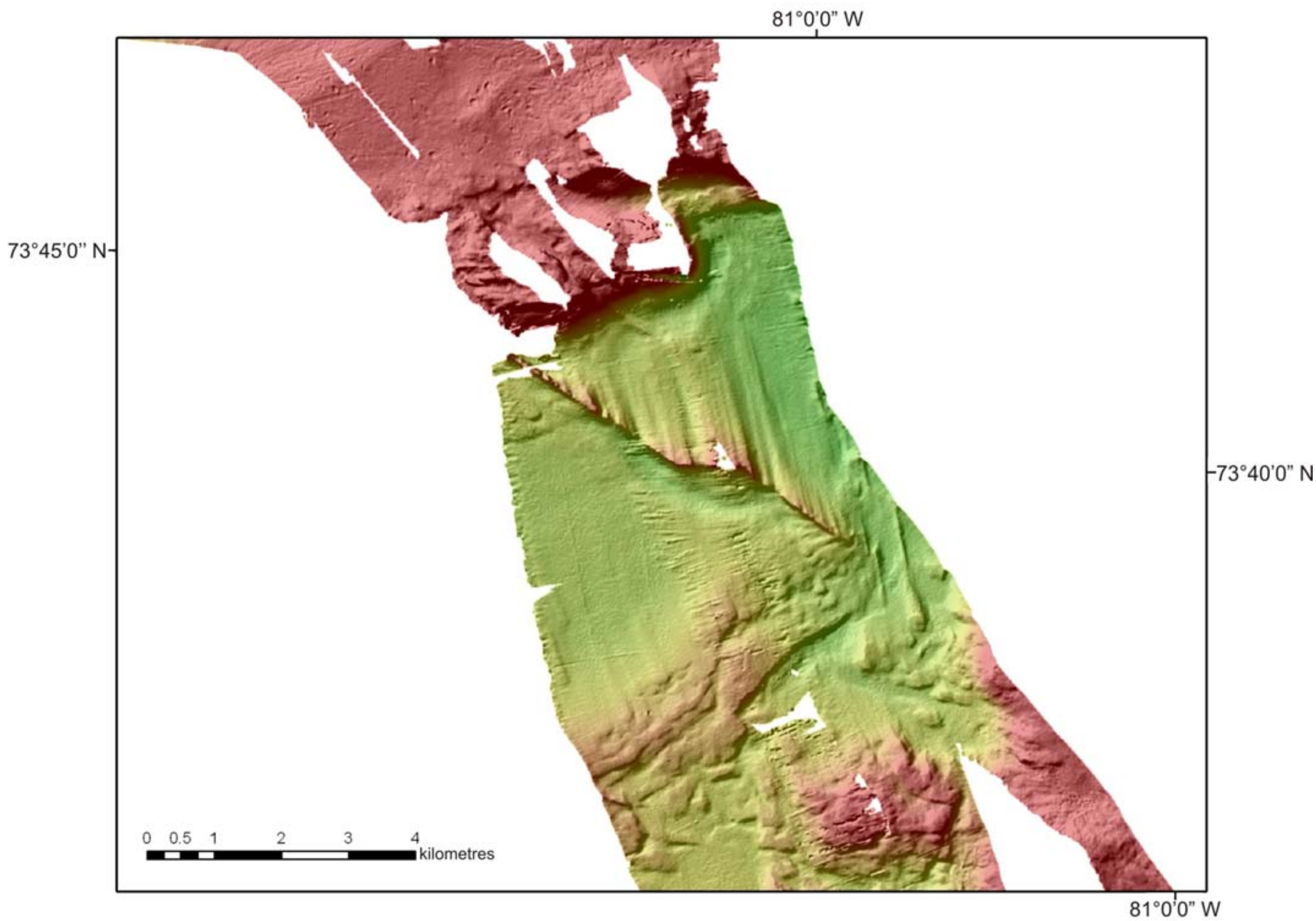

Figure 13: Glacial lineations located on a bedrock ridge in Navy Board Inlet (location shown on Figure 14) (Multibeam bathymetry data source: UNB-OMG)

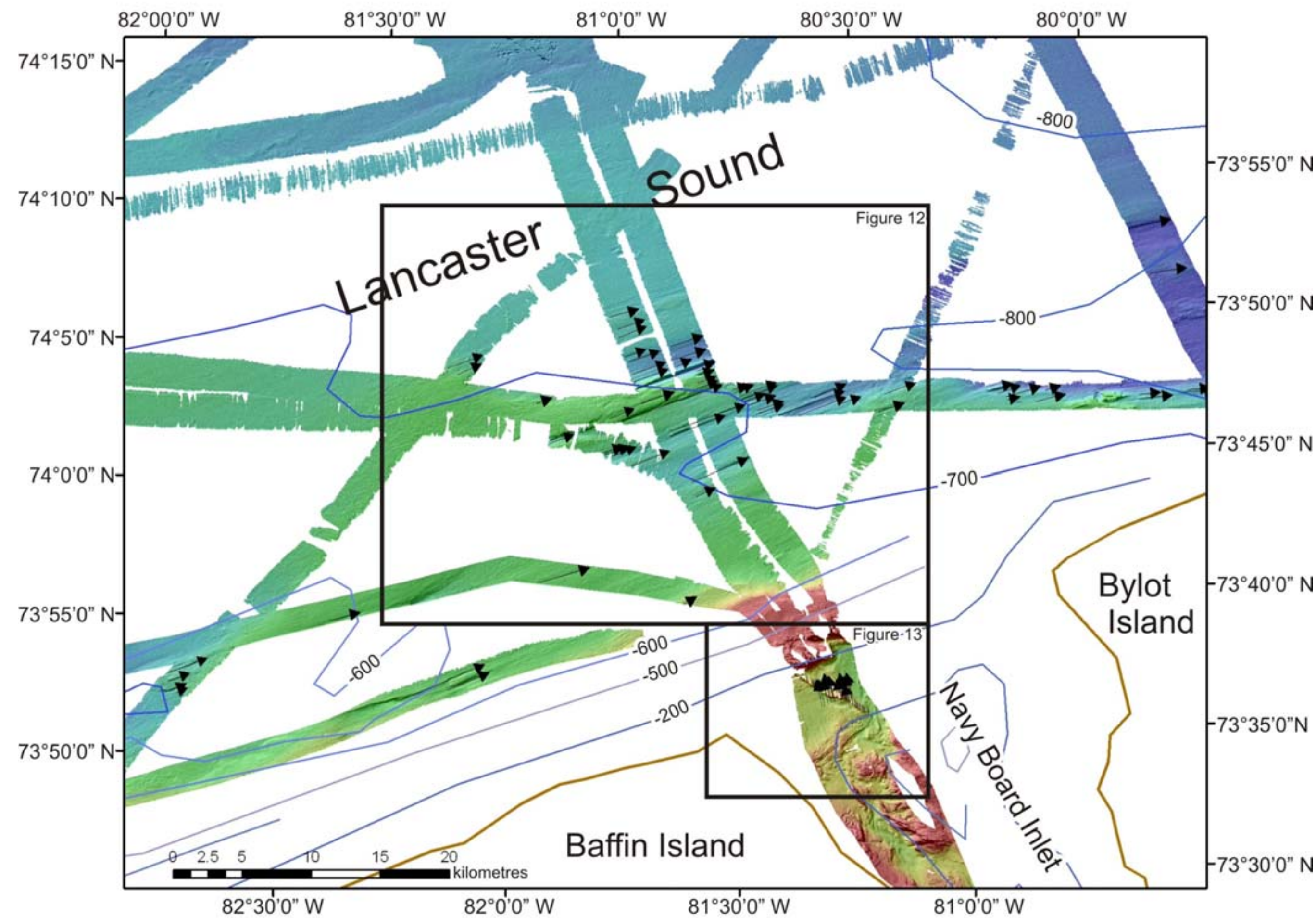

Figure 14: Glacial flow direction interpreted from seabed lineations in Lancaster Sound and Navy Board Inlet (Contours in metres; Multibeam bathymetry data source: UNB-OMG).

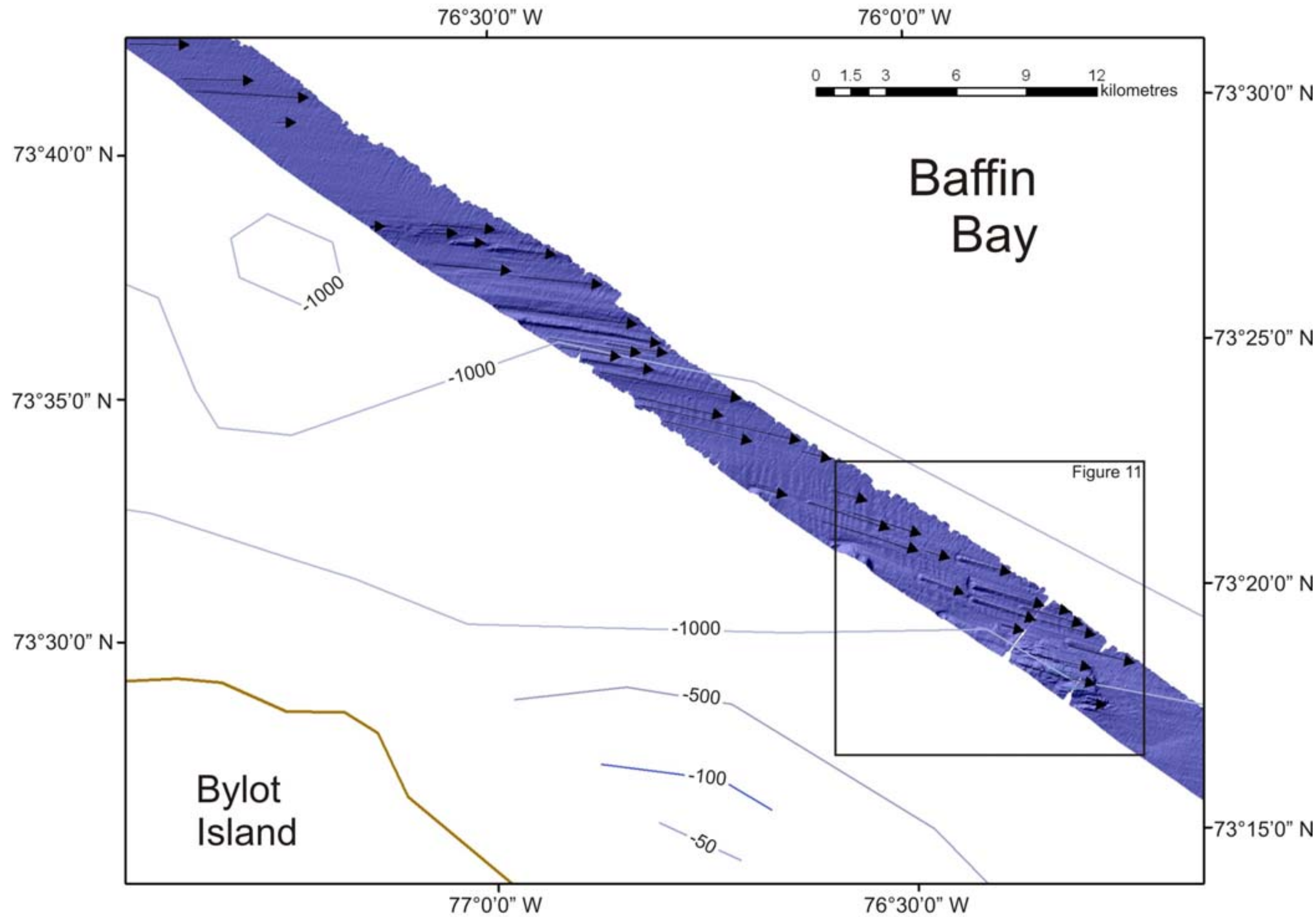

Figure 15: Glacial flow direction interpreted from seabed lineations in outer Lancaster Sound / Baffin Bay (Contours in metres; multibeam bathymetry data source: UNB-OMG).

The length of the lineations cannot be measured due to incomplete multibeam data coverage but flutes are up to ~1000 m wide. Flutes rise up to 75 m above the seabed or incise as deep as 75 m into the subsurface, creating slope angles as great as ~60° (Figure 16). The lineations and drumlins are observed over approximately 3,100 km^2 of the sea floor but additional multibeam data coverage is required to determine the full extent of glacial fluting. The high slope angles associated with some of these features could pose a hazard to seabed infrastructure giving importance to understanding the glacial history and distribution of glacial fluting in Baffin Bay.

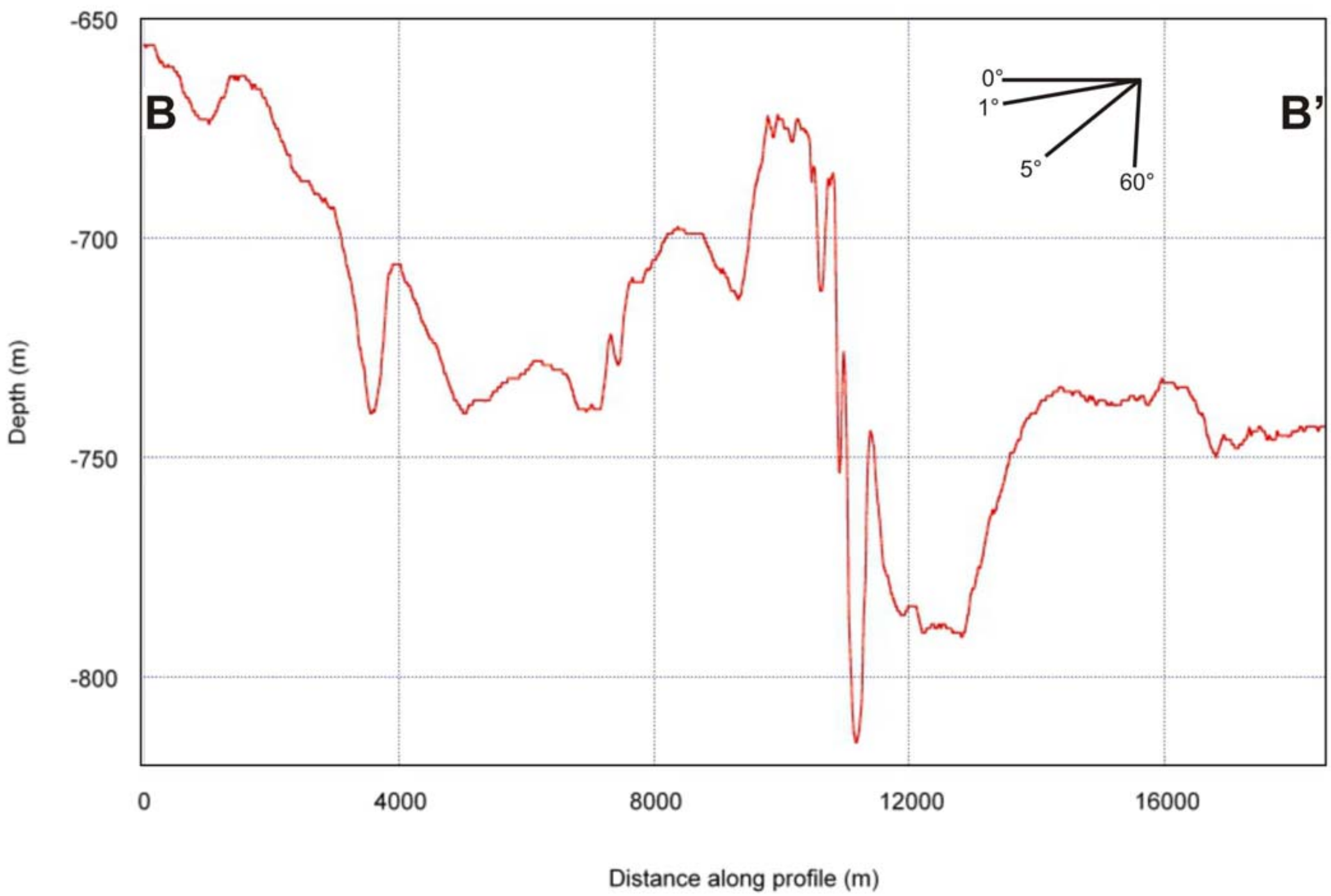

Figure 16: Bathymetric profile of glacial lineations in Lancaster Sound (see Figure 12 for location). The most severe slopes are up to 60° from horizontal.

Ice scours occur throughout Lancaster Sound but have not been observed overprinting glacial fluting. Modern ice streams that show the best preservation of glacial fluting are those that retreat rapidly by ice stream floatation and iceberg calving as the ice thins so that flutes are not modified by recessional glacial features (O'Cofaigh, 2008). However, seabed evidence for grounded glacial ice exists both to the east of the glacial fluting in Lancaster Sound (Li et al., 2011) and to the west (Figure 10). At the Last Glacial Maximum, thick ice was grounded 270 km from the mouth of Lancaster Sound in about 1300 m water depth (Li et al., 2011; zone A in Figure 17). During deglaciation, the ice would have thinned sufficiently enough that it was floating in eastern Lancaster Sound (zone B in Figure 17) and would have protected the seabed flutes from modification by ice scour. In the shallower water depths of western Lancaster Sound (zone C in Figure 17) glacial ice would have been grounded contemporaneously with the floating ice in zone B or may have been subsequently re-grounded later during deglaciation.

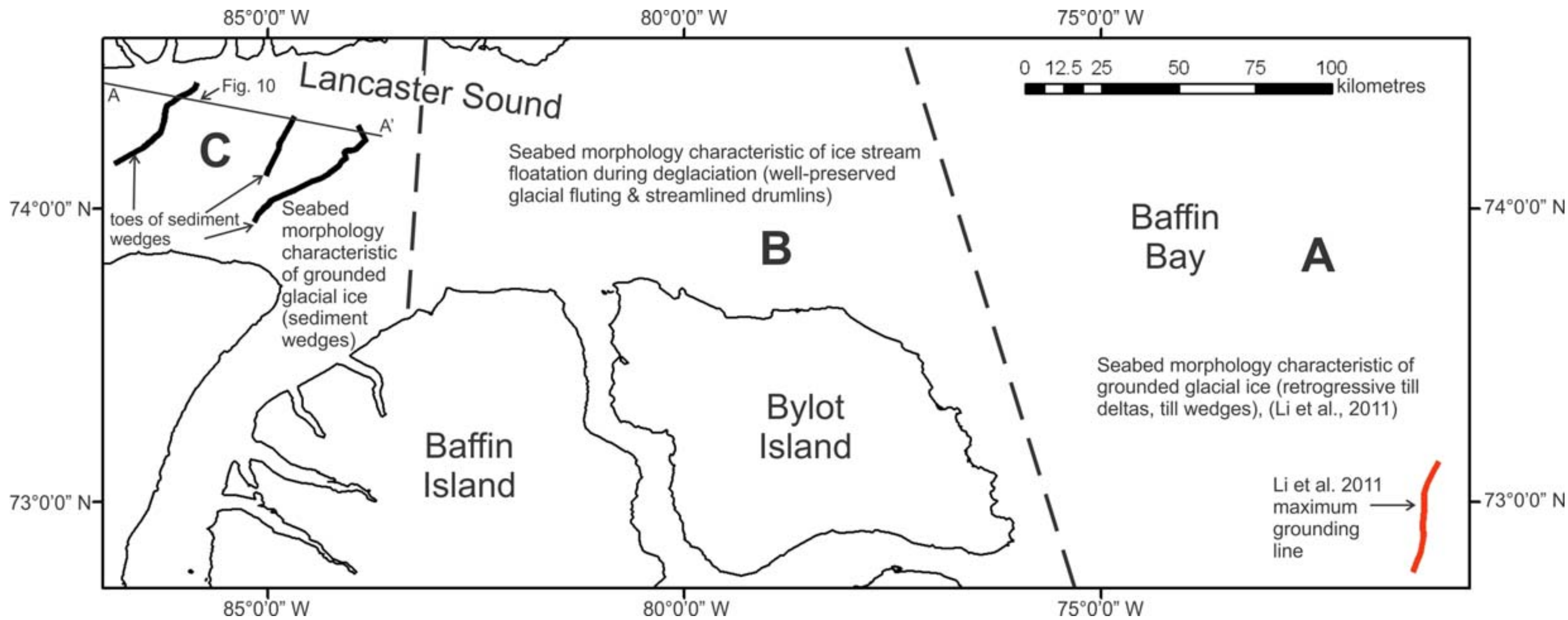

Figure 17: Schematic representation of deglaciation in Lancaster Sound based on seabed morphology

Glacial lineations are also observed throughout the bottom of Scott Trough (Figure 18). Individual lineations can be up to 35 km long, 750 m wide, 45 m high and are shown from seismic profiles to be comprised of till. The lineations in Scott Trough are interpreted to be glacial sole marks formed due to an ice stream which flowed out of Scott Inlet likely during the last glaciation. Similar glacial features are present in the other transverse troughs on the northern Baffin Island shelf.

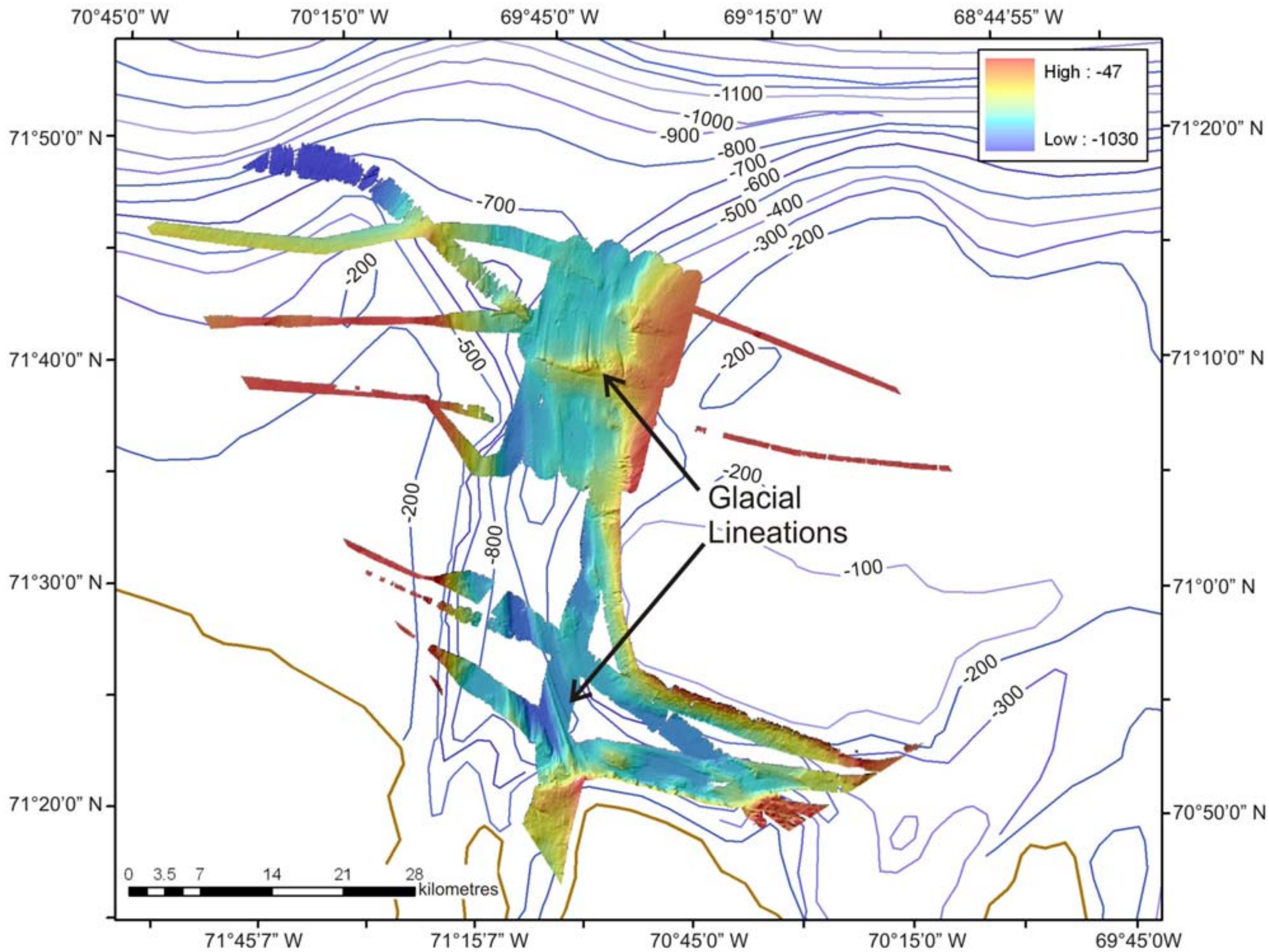

Figure 18: Seabed fluting on the floor of Scott Trough (Contours in metres; multibeam bathymetry data source: UNB-OMG).

Hydrocarbon venting features

A naturally occurring seabed hydrocarbon seep at Scott Inlet was first observed in 1976 (Loncarevic and Falconer 1977) by the discovery of an oil slick on the sea surface. Since then, the seep area has been studied with seismic reflection, side scan sonar, submersibles, multibeam bathymetry, satellite imaging of the sea surface, and other methods to determine the source and character of the hydrocarbons. Evidence collected by MacLean et al. (1981) suggested that the hydrocarbons were originating from the seabed along the south margin of outer Scott Trough (Figure 19). Praeg et al. (2007) also hypothesized that hydrocarbon seepage is mostly confined to the walls of Scott Trough where Quaternary sediment is thinnest. Submersible dives in 1981 and 1985 have observed white bacteria (genus *Beggiatoa*; Figure 20) covering the seabed in the area of the seep (MacLean et al., 1981; Grant et al., 1986). One submersible dive found that a carbonate crust on the sediment that was trapping oil beneath it (Grant et al., 1986; Figure 21). This sample was collected from a circular depression about 30 m wide and 2–3 m deep that may have been a pockmark (Grant et al., 1986). Gas has also been observed escaping from the seabed in ROV video footage collected onboard the CCGS Amundsen in 2009 (Jerosch, personal communication 2010).

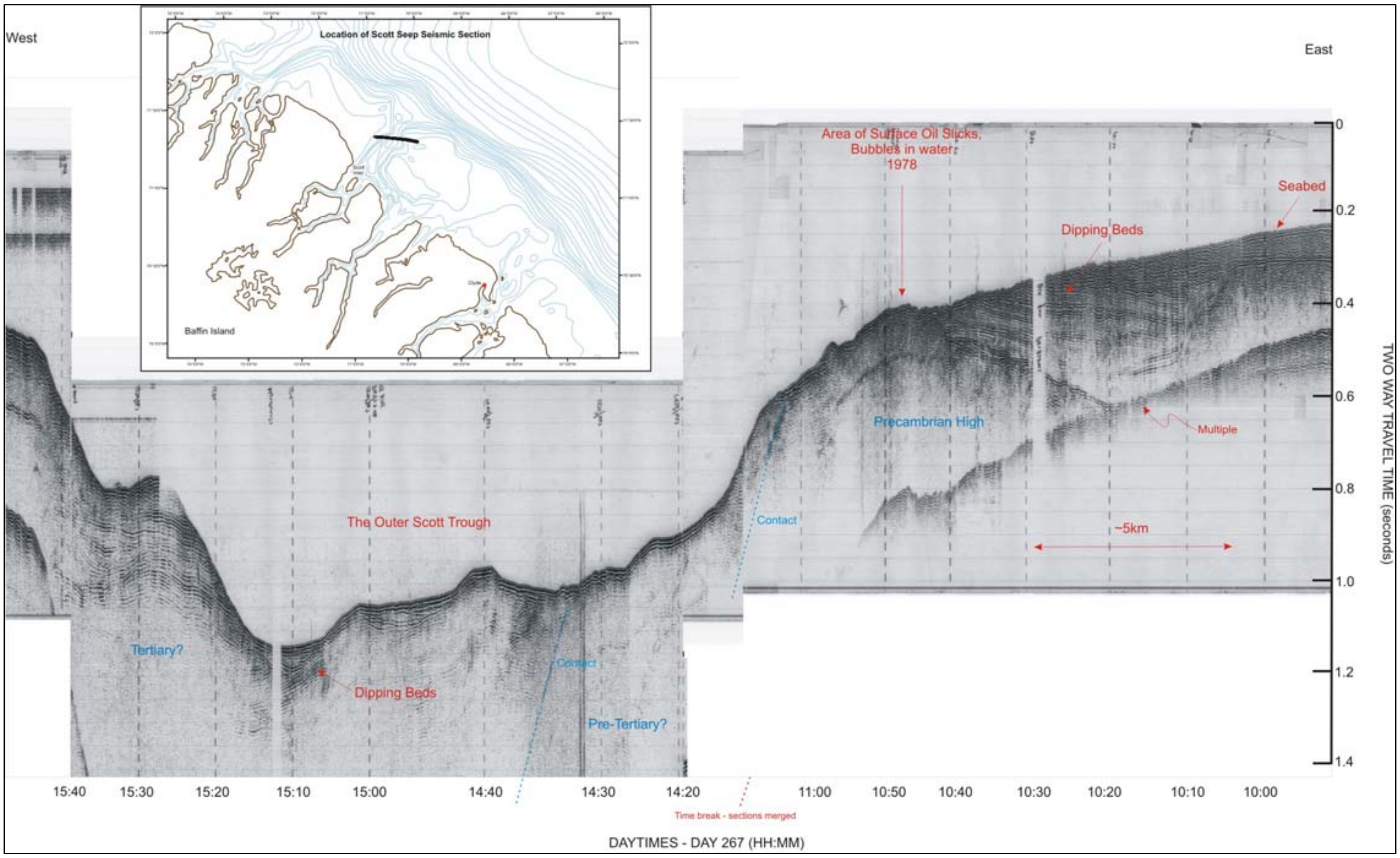

Figure 19: Seismic reflection profile across Scott Trough and the location where hydrocarbons were observed on the sea surface (from Blasco et al., 2010).

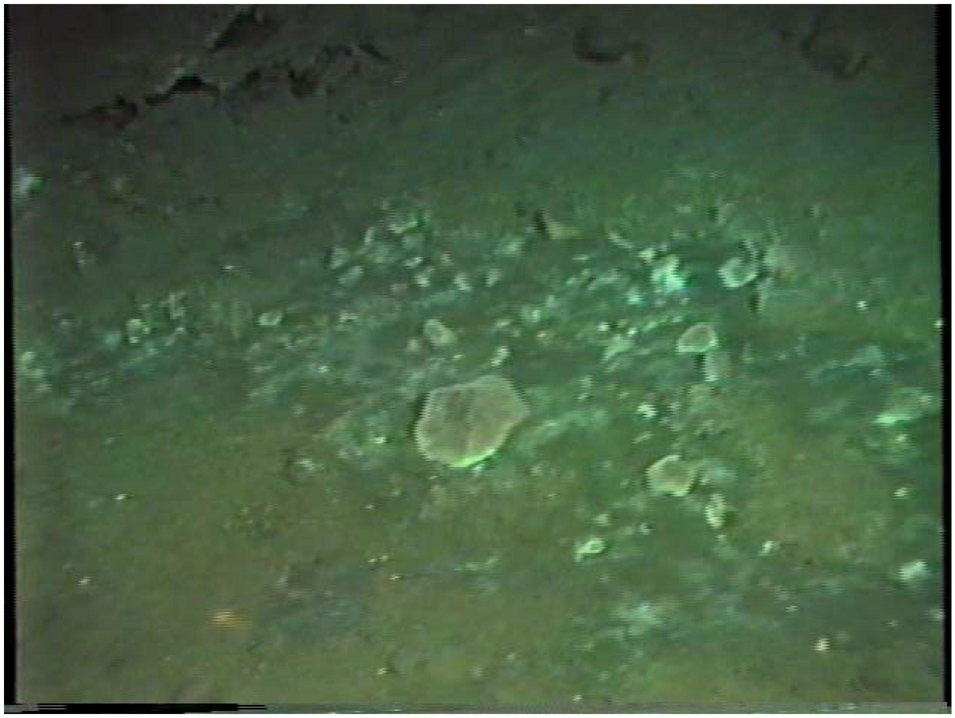

Figure 20: Seabed covered in white bacteria and carbonate crust observed during the Pisces IV 1984 submersible dive.

Figure 21: Sample of oil-coated carbonate crust collected during the Pisces IV 1984 submersible dive in Scott Trough (Photo by Al Grant).

Three pockmarks are observed in the multibeam echosounder data in Scott Trough (Figure 22). They are up to 130 m wide and 11 m deep (Figure 23). Due to the water depth and the resolution of the multibeam data, it is difficult to differentiate between pockmarks and artifacts inherent in the data set. Other pockmarks may be present in Scott Trough that are smaller than the 10 m horizontal resolution of the Kongsberg EM 302 multibeam system used to collect the data.

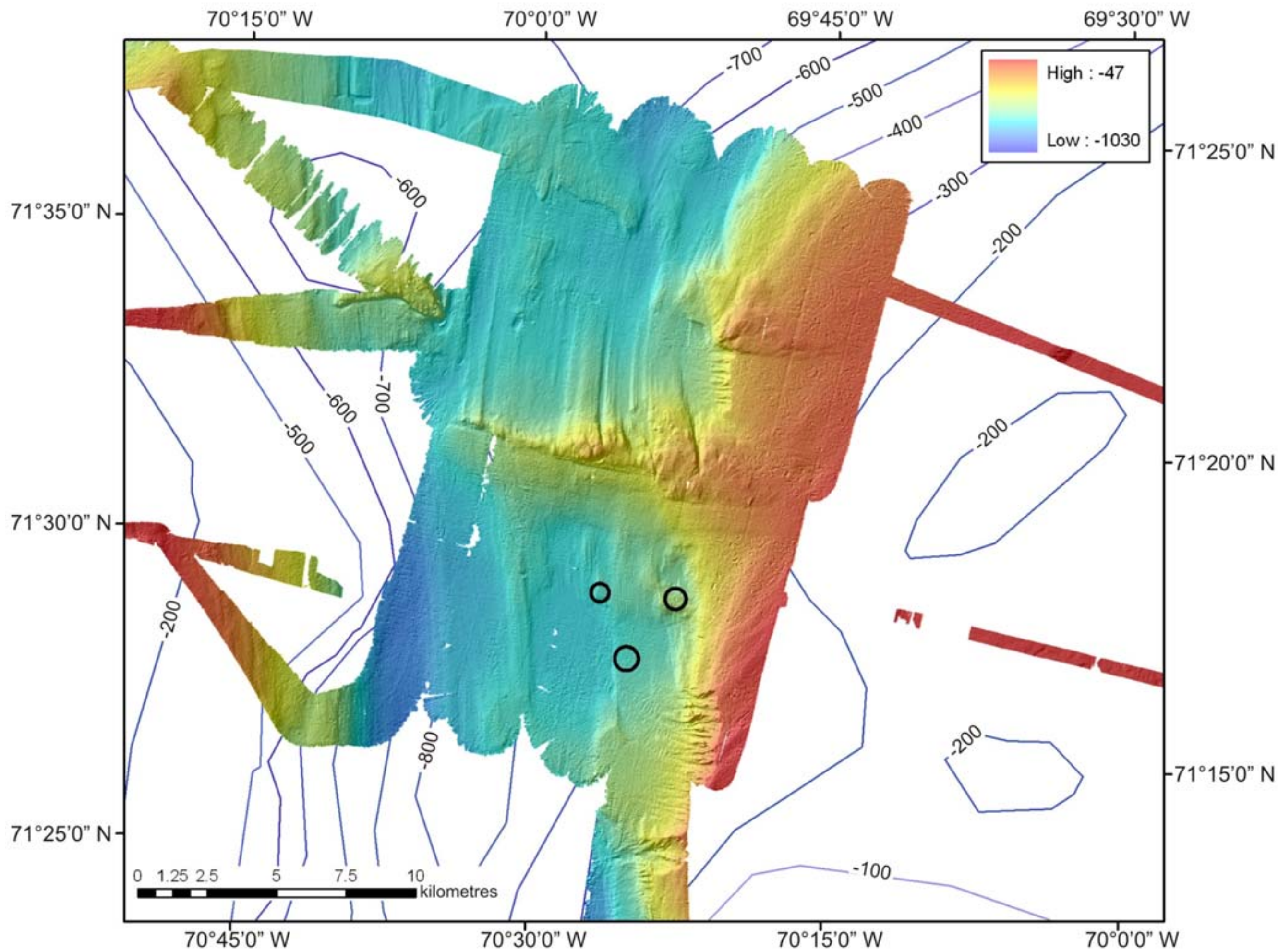

Figure 22: Pockmark distribution in Scott Trough (shown in circles outlined in black) (Contours in metres; multibeam bathymetry data source: UNB-OMG)

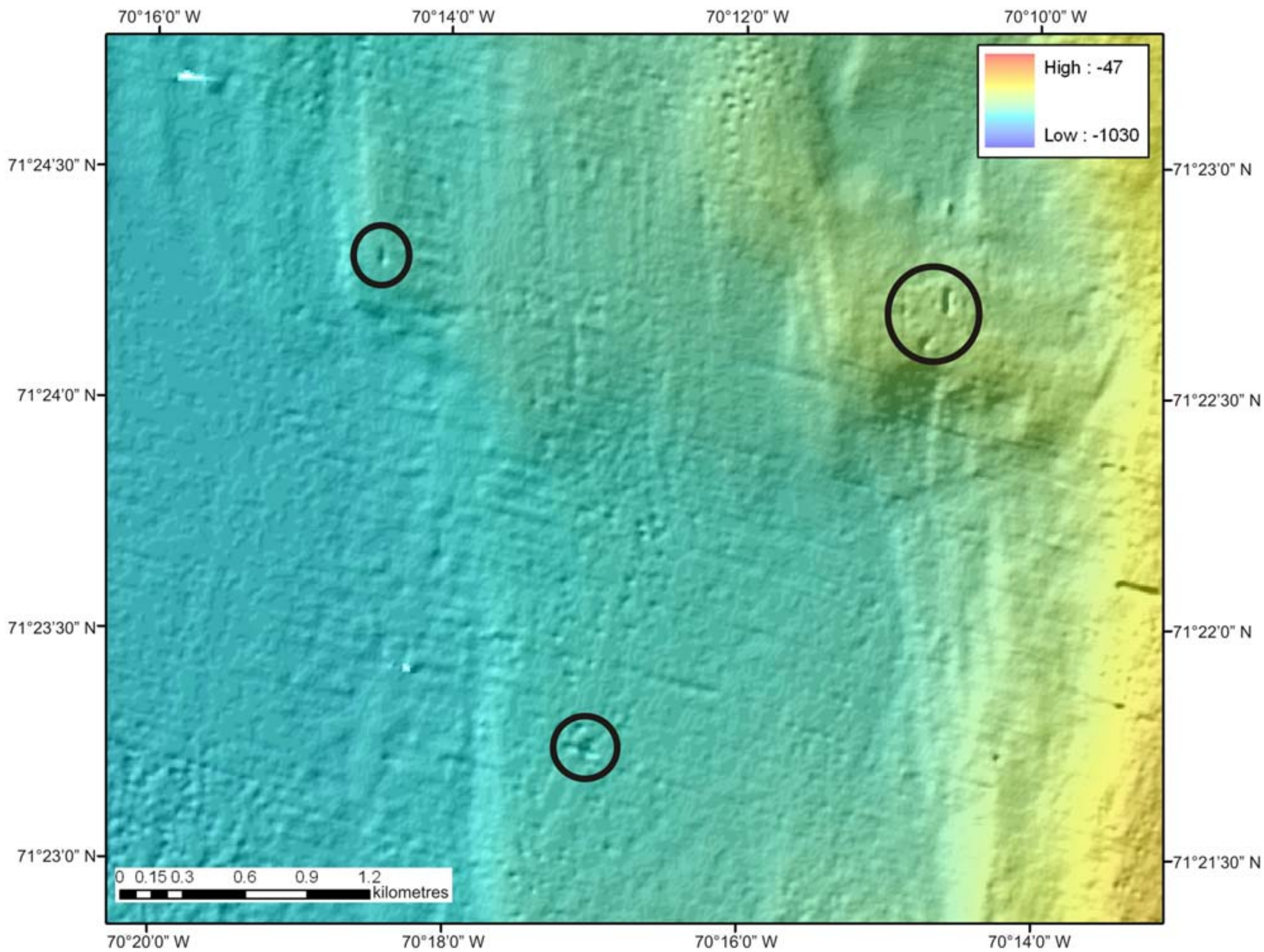

Figure 23: Multibeam data showing pockmarks in Scott Trough (shown in polygons outlined in black). Other small seabed depressions in this image other than the ones that are highlighted are interpreted to be multibeam data artifacts. (Contours in metres; multibeam bathymetry data source: UNB-OMG)

Other hydrocarbon seeps have been interpreted from satellite imagery offshore southern Baffin Island in Davis Strait to Northern Labrador Sea (Jauer and Budkewitsch, 2010) and northern Baffin Bay to Lancaster Sound (NPA Group & TREIC°Ltd, 2002). Due to the numerous hydrocarbon basins in Baffin Bay it is reasonable that other venting features will be encountered in the area.

Slope Failure of Transverse Trough Margins

Unstratified lobes are recognized in the shallow sub-surface (~1–2 m deep) of the Tiniktartuq Mud that are interpreted by Praeg et al. (2007) to represent slide compression toes of tensional failures along the steep sides of Scott Trough. Slope failures are triggered by many factors including oversteepened slopes, rapid sedimentation, seismic activity, glacial loading, weak geological layers, and high pore water pressure in slope sediments (Hampton and Locat, 1996). Sediment failure can also occur along trough margins during deglaciation when glacial ice retreats from a trough and remove support from margin sediments (Longva et al., 2008). Many of these factors have been present on the northern Baffin Island shelf but the specific trigger of the failures on the Scott Trough margin is not known.

A series of gullies are observed in multibeam data along the southern margin of Scott Trough extending from the bank tops and upper trough slopes in 230–350 m water depth to the bottom of the trough in 560–600 water depth (Figure 24). The gullies are clustered in three areas on the slope between the southern bank top and the bottom of Scott Trough (Figure 25). These gullies show similar morphology to ice margin gullies observed in Marguerite Bay, Antarctica (Dowdeswell, 2004) and on both sides of Flemish Pass (Stacey, 2011) which were formed by high rates of erosion and sedimentation at glacial ice margins.

Further down slope from the gullies in Scott Trough are sediment bedforms that are oriented perpendicular to the direction of the gullies (Figure 25). Similar features have been observed in the Bellingshausen Sea, Antarctica, that have been interpreted as being formed by the transport of turbidity flow-generated, fine-grained sediments by bottom currents (Nitsche, 2000). Strong currents have been observed along the inner wall of Scott Trough (Praeg et al., 2007) that could be responsible for the morphology of these bedforms.

Similar slope conditions are likely to exist in the other transverse troughs on the northern Baffin Island shelf, however additional data are required to confirm the presence of sediment failure and gullies. Data are also required to determine if the trough margin gullies are active conduits for sediment transport.

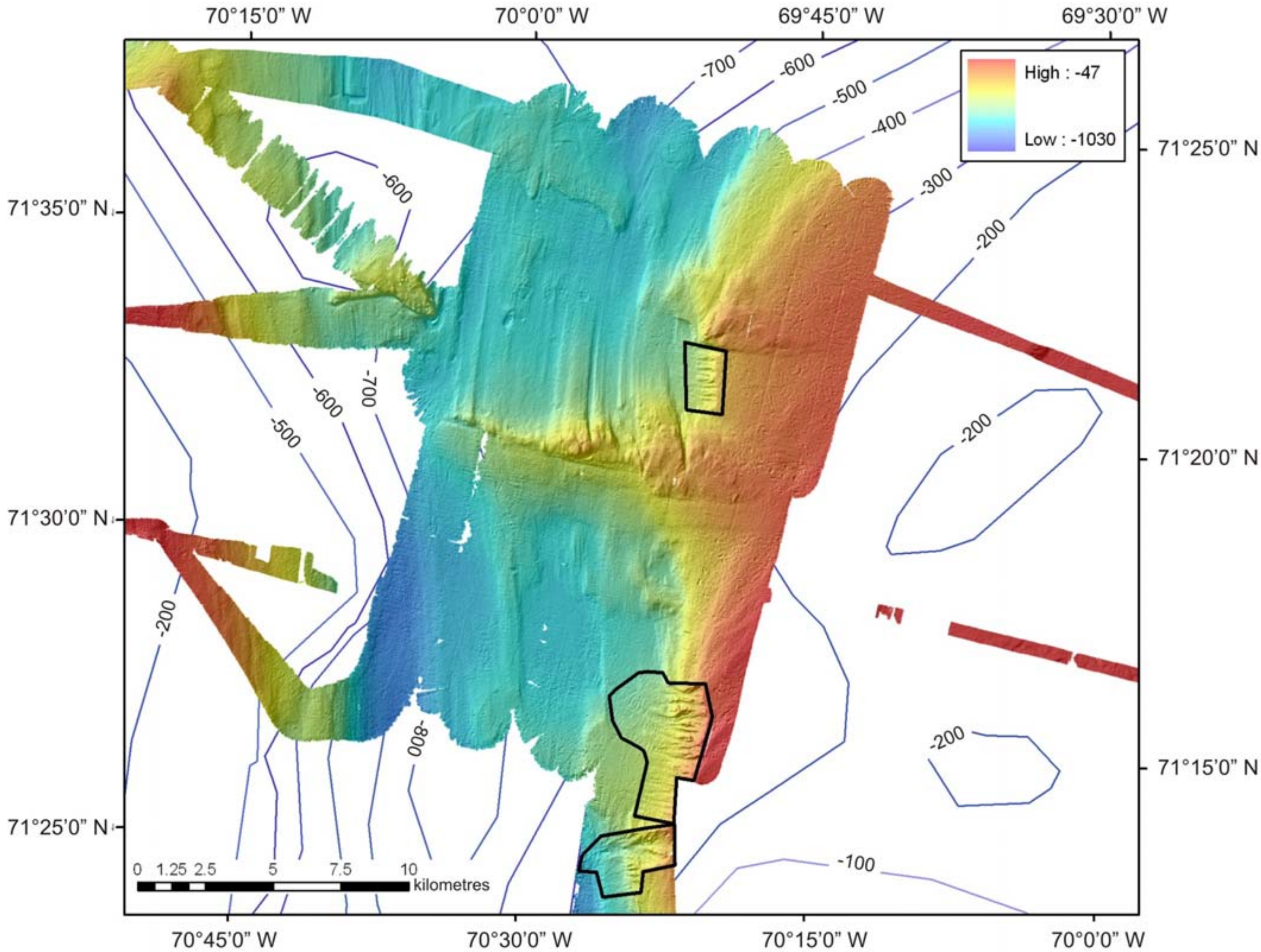

Figure 24: Distribution of gullies and sediment bedforms along the southern margin of Scott Trough (shown in polygons outlined in black) (Contours in metres; multibeam bathymetry data source: UNB-OMG).

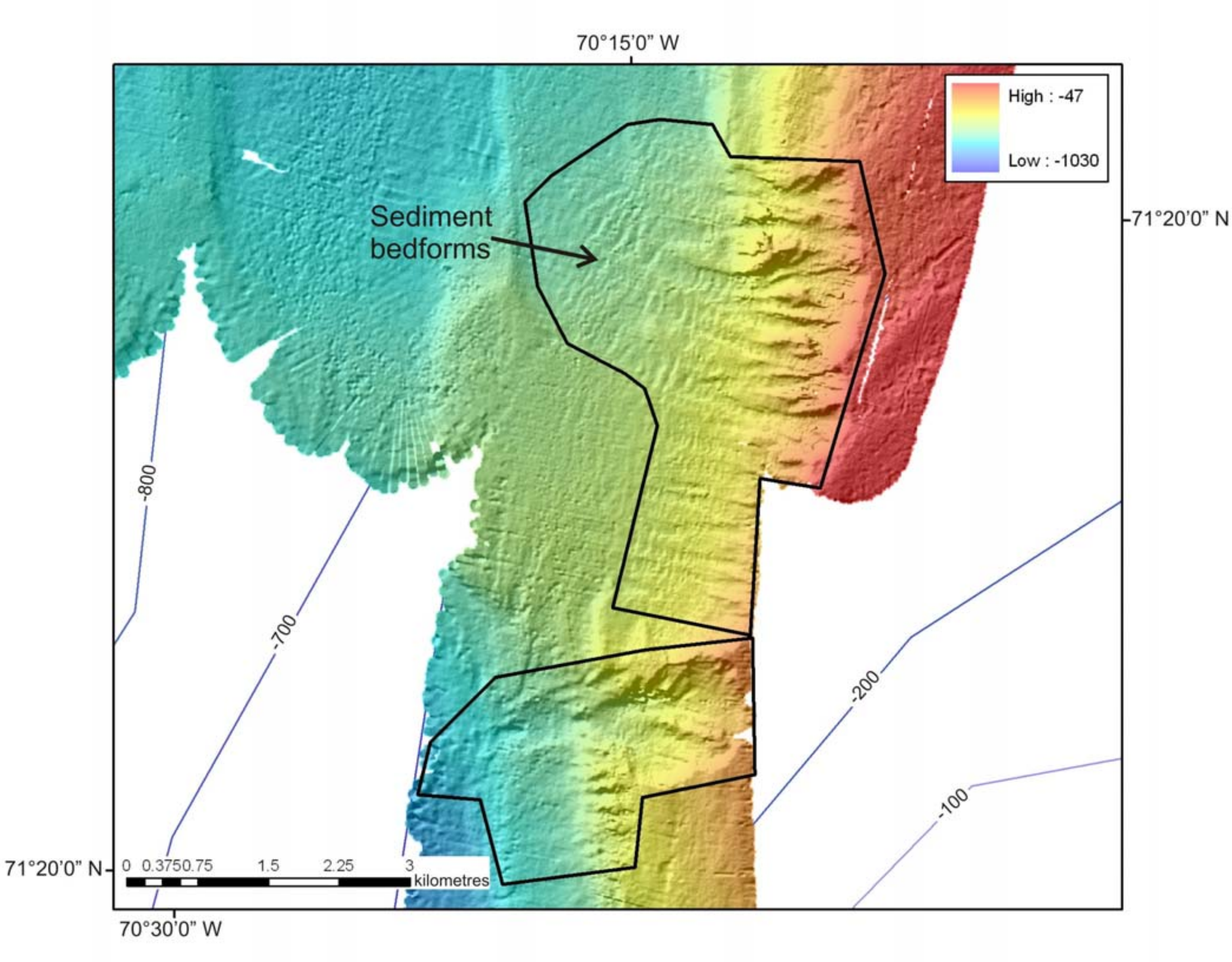

Figure 25: Gullies and sediment bedforms along the southern margin of Scott Trough (Contours in metres; multibeam bathymetry data source: UNB-OMG).

Seismicity

The Baffin margin is unique when compared to other passive margins of Canada because it is very seismically active. Canadian seismic hazard maps show that Baffin Bay has a level of hazard comparable to that of coastal British Columbia (Basham et al., 1997; Adams and Halchuk, 2003). A large number of seismic events (including the 1933 M = 7.3 event) have occurred in deep water on the Baffin Fan near the Eocene rift axis (Harrison et al. 2011; Figure 26). On the shelf, clusters of seismic events are located at Buchan Trough, Scott Trough, and Home Bay (Figure 26). Seismic events greater than M=6.0 may be able to trigger slope failures on the steep slopes along the margins of the transverse troughs but would not have much effect on the bank tops.

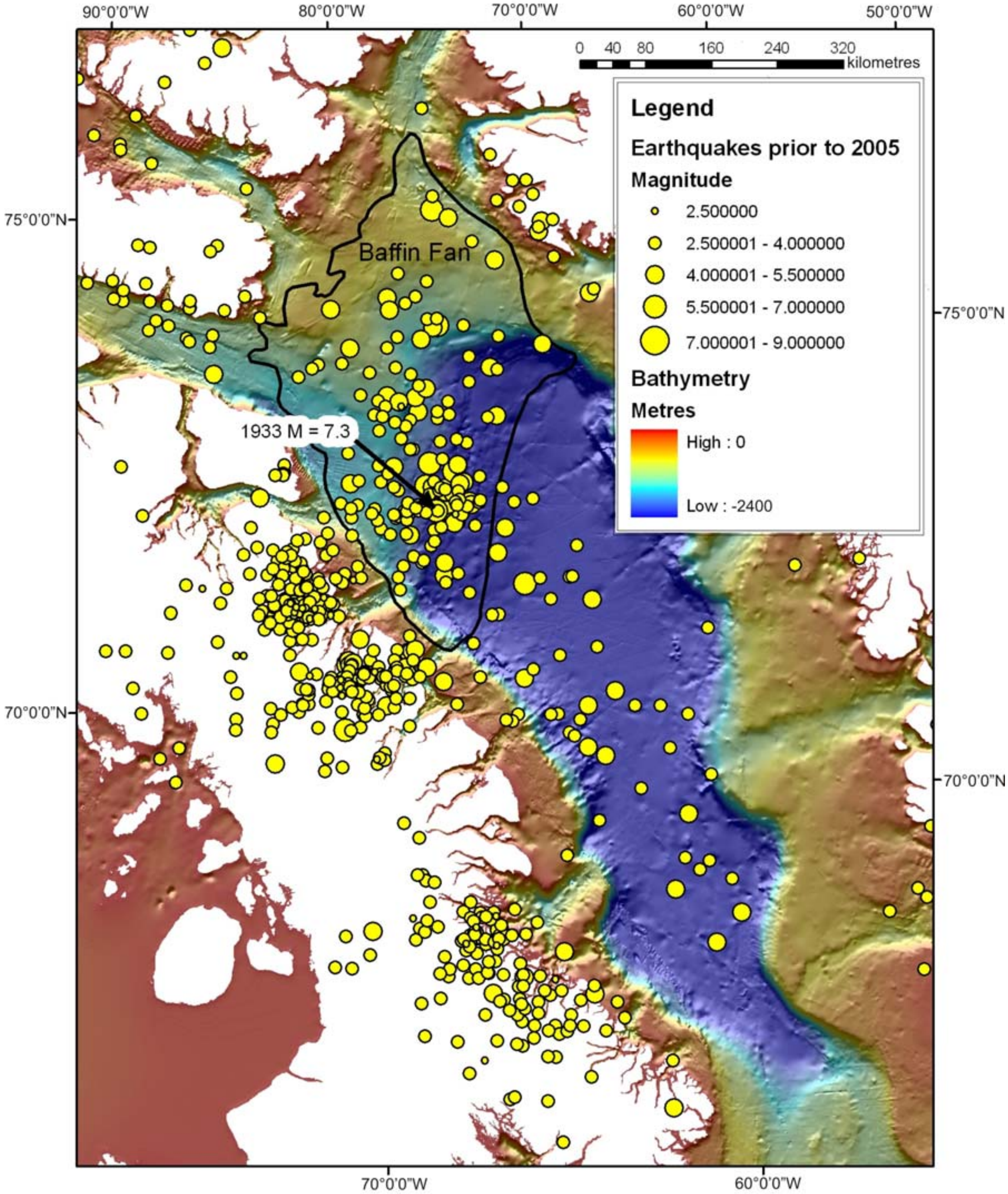

Figure 26: Seismic events prior to 2005 (Source of earthquakes data: www.earthquakescanada.nrcan.gc.ca; Bathymetry data from unpublished Canadian Hydrographic Service database, not for navigation purposes)

Issues and Gaps

Geohazards observed in Baffin Bay using existing data and reports include hydrocarbon venting features, uneven seabed caused by glacial seabed features, slope failures, ice scour and a high level of seismic activity. With the exception of high seismic activity, these hazards are typical of other glaciated continental margins. The frequency of seismic events combined with its high latitude is what makes Baffin Bay unique compared to other glaciated margins.

Knowledge of geohazards is required in Baffin Bay to support community, Nunavut government, and regulator decisions on the use of offshore areas and provide northern coastal communities with better knowledge for improving public safety. Improved understanding of geohazards in Baffin Bay would provide the following benefits:
1. Understanding seabed stability during earthquakes, the effect of global warming on that hazard, and consequent tsunami hazard
2. Removing economic and environmental barriers to potential hydrocarbon exploration and development
3. Understanding hazards that affect the routing and integrity of communication cables or other future seabed uses

Geohazards that require more research on the northern Baffin Island shelf include:
1. Iceberg scour: Modern icebergs scour to depths of at least 427 m. The rate of iceberg scouring is unknown. The impact of enhanced melt rates in Greenland is unknown.
2. Slope instability: Of particular concern for the area are events that are seismically triggered and preconditioned by hydrocarbon migration since northern Baffin Bay is seismically very active and there are known hydrocarbon seeps. Global warming may increase flux of hydrocarbons from gas hydrates. Baffin Island fjords probably have a similar failure hazard as the fjords of British Columbia.
3. Ocean currents and their erosive effects: The role of the Baffin Current in eroding the upper slope, remobilizing sediment and building sediment drifts is not known; sparse legacy data from Baffin slope shows severe seabed erosion comparable to the outer Grand Banks margin. The contribution of currents to upper slope instability is not understood.
4. Gravity driven currents, particularly in gullies and canyon: The possible role of cascading cold dense-water flows, sediment accumulation in gully and canyon heads, and remobilisation in storms in Baffin Bay is not well understood.
5. Sediment movement and scour in storms and by tidal currents: Significant sediment transport on the shelf could lead to scour around any seabed infrastructure.
6. Spatial distribution of foundation conditions: Any structures on the sea-floor, anchoring of rigs, and drilling the upper few hundred metres of sediment section require knowledge of rock or sediment type, strength, permeability and lateral continuity. These sediment properties are poorly understood in Baffin Bay.

Work on the geohazards of the northern Baffin Island shelf carried out to date, with the exception of a few days of ship time in 2008, has been on an opportunity basis and relies substantially on sparse legacy data. To resolve geohazard issues in a timely manner before any exploratory drilling requires a multi-year program with dedicated and targeted ship time. This program would address the following seven issues.

1. Conduct background work that is necessary to systematically answer questions about geohazards including:
(a) Sufficient multibeam bathymetry to understand the distribution of geohazards and of seabed morphology that is indicative of geohazards. The effectiveness of expensive shiptime for groundtruthing is more than doubled by the availability of multibeam bathymetry.
(b) A regional understanding of Quaternary stratigraphy, the age and geometry of Quaternary strata, and the regional changes in glacial and oceanographic processes in the Quaternary. These allow more site specific geohazard issues to be interpreted in a geological context and provide a basis for prediction of geohazards in areas of sparse data.
(c) A minimal level of monitoring of (a) interaction of oceanographic processes with the seabed, such as the drivers for along-slope currents and for gravity flows; and (b) changes in the rates at which hydrocarbons are escaping at the seabed.

2. Iceberg scour
(a) Determine the rate of seabed scouring from repeat multibeam or legacy side scan/modern multibeam surveys.
(b) Determine regional differences in scouring rate, notably Lancaster Sound, banks and troughs of Baffin Island shelf (latitudinal variation), upper slope (latitudinal variation).
(c) Determine the impact of scour on seabed properties of sediments (emphasise any differences from conditions on Labrador Shelf, Grand Banks, and the Beaufort Sea).

3. Slope instability
(a) Use fjords as a record of the frequency of failure-triggering earthquakes, changes through Holocene, and changes with latitude.
(b) Define style, age and frequency of failures in example areas on trough walls and continental slope.
(c) Measure geotechnical properties in relevant sediments related to failures.
(d) Use acoustic and sediment sampling techniques to determine the distribution of migrating hydrocarbons and if these hydrocarbons are preconditioning sediments for failure; use targeted seabed lander studies in areas of know hydrocarbon seepage to understand the rate of seepage.

4. Ocean currents and their erosive effects
(a) Groundtruth multibeam surveys of the continental slope with various resolutions of seismic and sediment cores in order to understand the distribution and timing of erosion by contour currents.
(b) The comparison on the Baffin margin with other margins that are better understood such as the Labrador and Grand Banks margins.

5. Gravity driven currents, particularly in gullies and canyons
(a) Use targeted seabed lander studies to understand the character of down-slope gravity flows on trough walls and on the upper slope.

6. Sediment movement and scour in storms and by tidal currents
(a) Opportunity-based (e.g. with fisheries research, military) collection of seafloor sediments (grabs, box cores, gravity cores) to define regional variation in surface grain size.
(b) Collaborate with DFO modellers to refine numeric models of sediment transport, both in oceanic currents and in storms.

7. Spatial distribution of foundation conditions
(a) Collect sufficient targeted long cores with geotechnical data (tied to high-resolution seismic profiles) to define gross characteristics of the upper few hundred metres of sediment.

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