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THE NEWFOUNDLAND ICE SHEET SHELF (NISS) SURVEY – RESEARCH CRUISE: BAY d'ESPOIR TO BURGEO, NEWFOUNDLAND

J.S. Organ, P. Dunlop[1], S. Benetti[1], J. Shaw[2], T. Bell[3]
Geochemistry, Geophysics and Terrain Sciences Section
[1]Quaternary Environmental Change Research Group, Ulster University, Coleraine, Northern Ireland
[2]Geological Survey of Canada, Dartmouth, NS
[3]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5

ABSTRACT

The Newfoundland Ice Sheet Shelf Survey (Cruise CE16010) was a 3.5-day marine survey along the south coast of Newfoundland, between Bay d'Espoir and Burgeo. The survey investigated the glacial record by collecting new multibeam, seismic-profile data, and sediment cores.

Over 100 nautical miles of multibeam, backscatter and seismic-profile data were collected; in addition, twenty-six sites were sampled and over 37 m of core were collected using both a vibro-corer and gravity corer; target sites were glacial sediments on submarine moraines. The objective of this work is to acquire new multibeam bathymetric, seismic data, and sediment cores on submarine moraines at the mouths of these southern fjords. This data will contribute to the Atlantic Seabed Mapping Initiative, and help to refine the timing and retreat of the Newfoundland Ice Cap during the Late Wisconsinan glaciation.

INTRODUCTION

In April 2016, the Geological Survey had a valuable opportunity to participate in the acquisition of new data on fjord-mouth submarine moraines, located along the south coast of Newfoundland (Figure 1). This was part of the research project 'Newfoundland Ice Sheet Shelf' (NISS) led by researchers from the Ulster University, in collaboration with the Marine Institute of Ireland, the Geological Survey of Canada and Memorial University. This paper describes the background, project rationale, the survey objectives and preliminary results.

BACKGROUND AND PROJECT RATIONALE

During the Late Wisconsinan glacial maximum, the Newfoundland Ice Cap (NIC) extended to the edge of the continental shelf, and coalesced with the Laurentide Ice Sheet (LIS) seaward of the modern west and southwest coastline of Newfoundland (Figure 2A; Grant, 1992; Dyke *et al.*, 2002; Shaw, 2003, 2006; Shaw *et al.*, 2006). Along the south coast of the Island, the glacial landform record onshore clearly demonstrates that ice streamed from the interior through deep marine channels into the Laurentide Channel (Shaw *et al.*, 2006; McHenry and Dunlop, 2015). Due to it being largely marine-based, the southern margin of the NIC

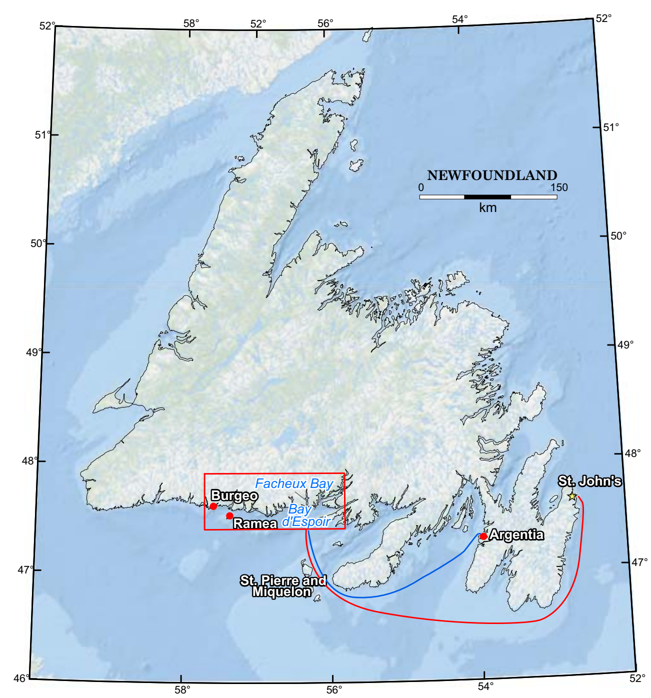


Figure 1. *Red box shows location of the NISS survey along Newfoundland's south coast. The red line shows the route sailed from St. John's to the study area; the blue line shows the route to Argentia where the survey ended.*

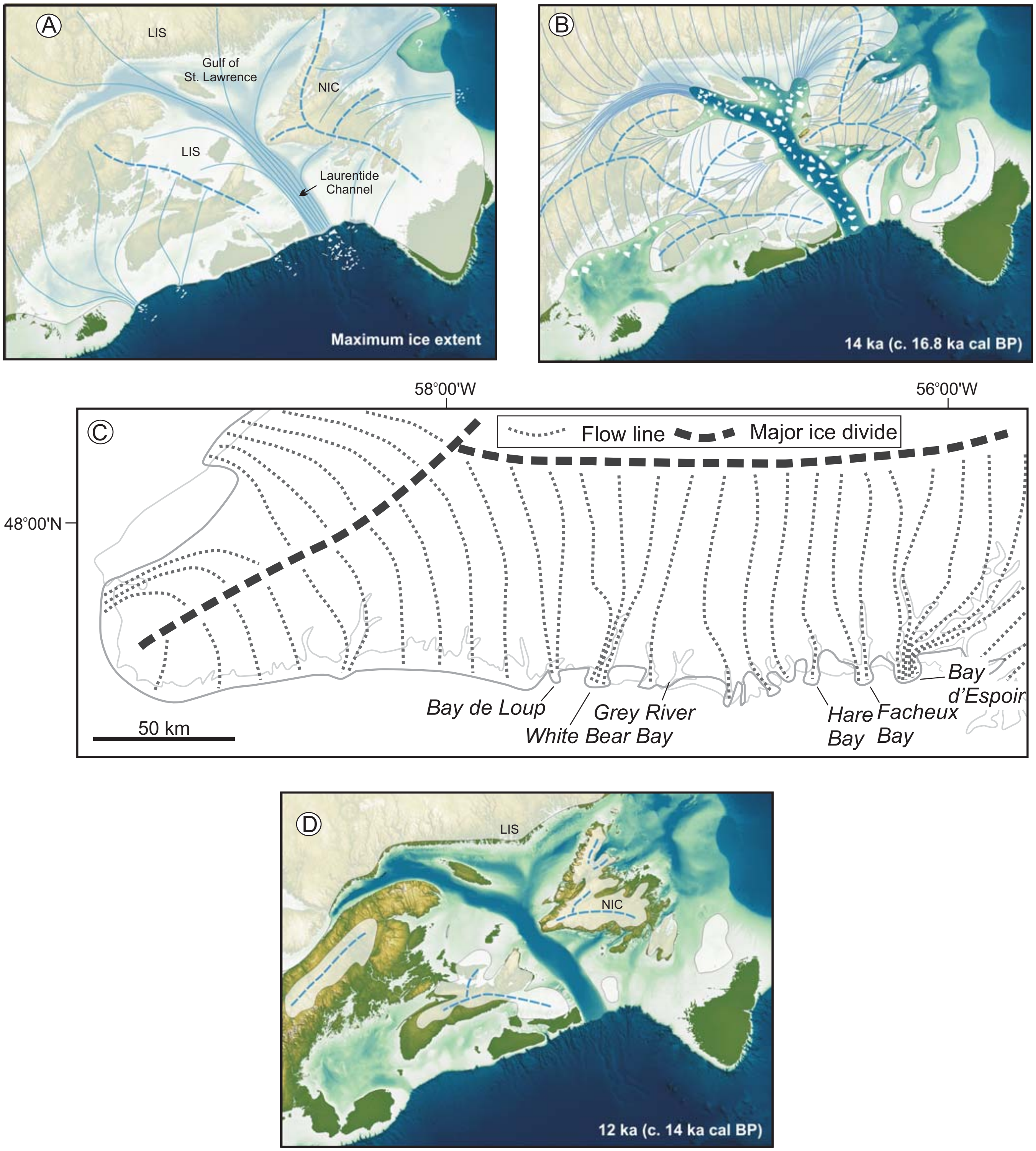


Figure 2. *A) Maximum ice extent during the Late Wisconsinan glaciation. Dashed blue lines are major ice divides and solid blue lines generalized flow lines. The Laurentide Ice Sheet (LIS) extended over mainland Canada and coalesced with the Newfoundland Ice Cap (NIC) over the Island of Newfoundland; B) Calving is believed to be responsible for a rapidly changing ice margin at 14 ka BP, resulting in ice being removed from the Gulf of St. Lawrence, and isolation of the Newfoundland Ice Cap; C) Ice margin 13.5 ka BP along the south coast of Newfoundland showing lobate ice margins in Bay de Loup, White Bear Bay, Hare Bay, Facheux Bay and Bay d'Espoir; D) Ice margins and major ice divides (dashed blue lines) at 12 ka BP. llustrations A, B and D are adapted from Shaw* et al. *(2006); illustration C is adapted from Shaw (2003).*

was susceptible to accelerated ice calving, and is believed to be responsible for the retreat of the ice stream into the Gulf of St. Lawrence by 14 ka BP (Figure 2B). By 13.5 ka BP, the ice margin, along the south coast of Newfoundland, was at, or close, to the mouths of the fjords (Figure 2C; Shaw, 2003). By 12 ka BP, the ice margins had retreated onshore, causing migrating ice centres within the NIC, as well as isolation from the LIS (Figure 2D; Shaw, 2003).

Shaw *et al.* (2000) examined the mouths of fjords along the south coast of Newfoundland using a Hunter (boomer) seismic reflection system, 3.5 kHz sounder and sidescan sonar along with a Simrad Em-1000 multibeam system. A number of linear to lobate submarine ridges were identified along the inner continental shelf at the fjord-mouths of Bay d'Espoir, Facheux Bay, Grey River, White Bear Bay, and Bay de Loup (Shaw *et al.*, 2000; Shaw, 2003). Seismic, multibeam data from these locations along with sediment cores from Facheux Bay and Grey River led Shaw (2003) to interpret these ridges as submarine moraines. The following is a brief description of the submarine ridges documented by Shaw *et al.* (2000) and Shaw (2003) from Bay d'Espoir and Facheux Bay.

Figure 3A from Shaw *et al.* (2000) is a multibeam image of an arcuate submarine ridge located at the mouth of Bay d'Espoir. It comprises two prominent seaward lobate ramps and steep seaward sides, separated by a ridge, oriented perpendicular to the ramps (Shaw *et al.*, 2000; Shaw, 2003). The landward part of the ramp displays grooves and drumlin-like forms indicative of basal sliding. The morainal ridge has been described and interpreted by Shaw *et al.* (2000) to be composed of ice-contact sediment, and stratified glaciomarine sediments on the landward part of the ramp (Figure 3B).

The submarine moraine off Facheux Bay shown in Figure 4A is made up of convex seaward ramps and landward-projecting cusps (Shaw *et al.*, 2000; Shaw, 2003). High backscatter-intensity images of seismic profiles (Shaw *et al.*, 2000) suggest that the moraine is covered with boulder gravel, and the ridge composed of ice-contact sediment, up to 120 m thick, that passes laterally into glaciomarine mud (Figure 4B).

The submarine moraines mapped by Shaw *et al.* (2000) and Shaw (2003) provide strong evidence that the NIC extended offshore; however, recent onshore glacial mapping by McHenry and Dunlop (2015) suggests that ice from the interior streamed into fjords that have not been previously studied. It is postulated that mouths of these fjords may also contain fjord-mouth submarine moraines, similar to those identified by Shaw *et al.* (2000).

SURVEY OBJECTIVES

The two main geoscientific objectives of the NISS project arise from previous studies of fjord-mouth moraines (Shaw *et al.*, 2000; Shaw 2003), these objectives include:

1) To acquire multibeam bathymetric and seismic data across fjord-mouth submarine moraines new (Hare Bay) and previously identified (Grey River, Bay de Loup and White Bear Bay) on Newfoundland's south coast. In addition this data will contribute to the background knowledge about the Atlantic Ocean under the Atlantic Ocean Research Alliance umbrella and will provide bathymetric data for the Atlantic Seabed Mapping Initiative.

2) To collect sediment cores from fjord-mouth submarine moraines along the inner shelf for sedimentological and geochronological analyses to constrain the timing and pattern of deglaciation on the south coast of Newfoundland. A better understanding of the processes that initiate and sustain deglaciation in the marine-based Newfoundland Ice Cap may provide a useful analogue to understanding contemporary marine-influenced ice sheets such as Greenland and Antarctic and their response to future climate change.

METHODS

Data were collected using a Kongsberg Maritime EM2040 (200–400 kHz) multibeam system. New sub-bottom data were acquired using an IXBlue Echoes 3500 T7 Sub Bottom Profiler (1.7–5.5 kHz) (Figure 5). Seismic-profile data were collected along the same transects using a towed GeoMarine Survey System Geo-Source 200 (100–1000J power range), which has a vertical resolution up to 10–30 cm and normally a penetration of up to 100–200 m below the seabed in glacial sediments.

Coring sites were selected using earlier seismic and multibeam data available from the Natural Resources Canada marine-data holdings, and new marine-geophysical data acquired as part of the NISS cruise. This allowed for the optimal selection of coring sites by taking into consideration the type of substrate. To retrieve the targeted glacial sediment, locations on the seabed were selected with the least amount of glaciomarine mud, and a relatively flat surface, to accommodate the footprint of the vibro-corer. The mouths and surrounding seabed of eight fjords were selected for investigation: Bay d'Espoir, Facheux Bay, Hare Bay, Rencontre Bay, Grey River, Bay de Vieux, White Bear Bay, and Bay de Loup (Figure 6).

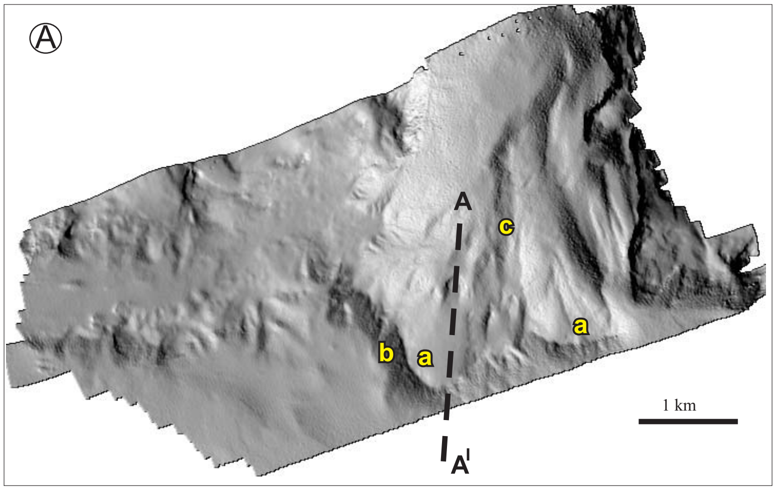
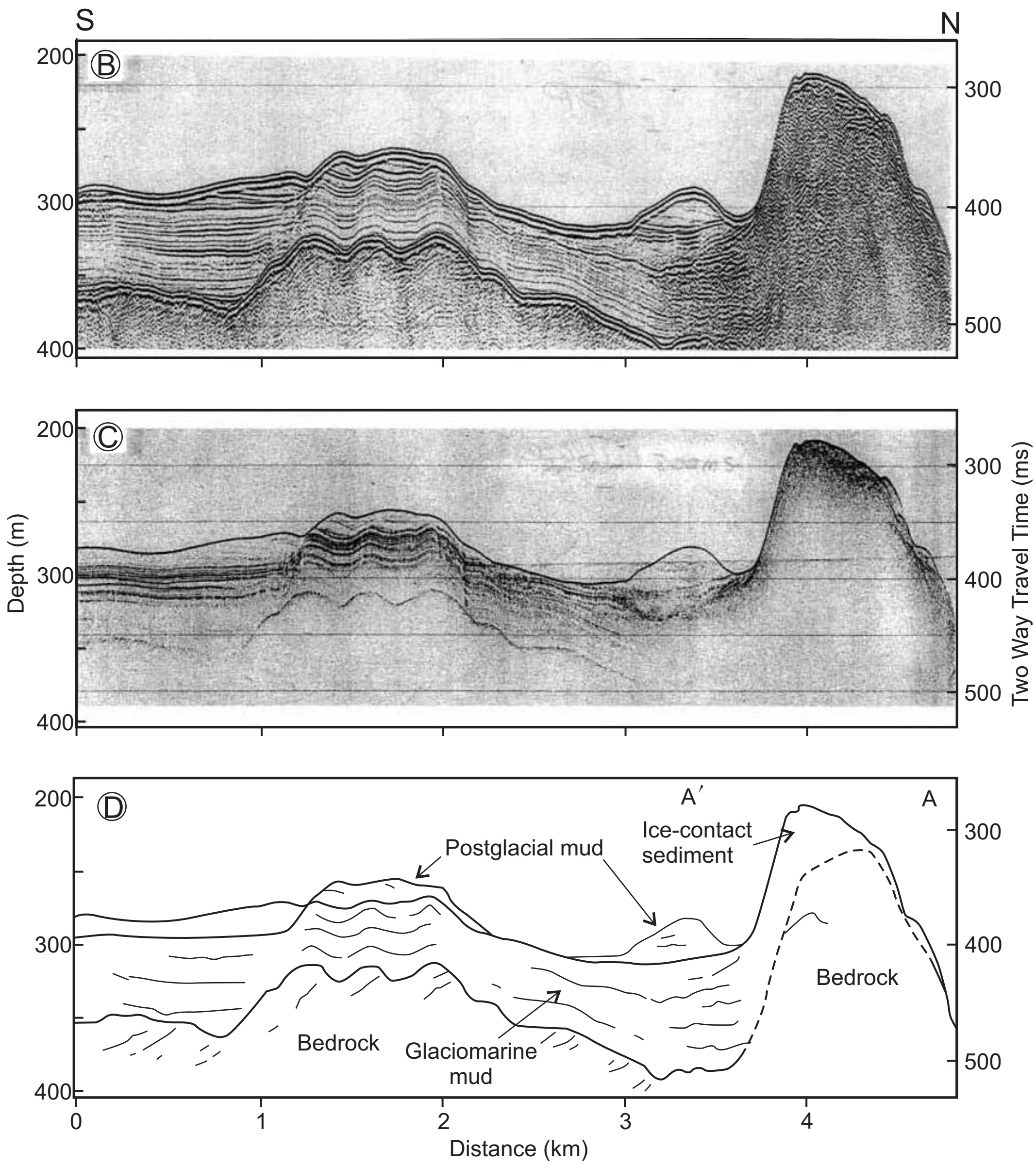


Figure 3. *A) Shaded-relief multibeam image of arcuate submarine ridge at the mouth of Bay d'Espoir. It is composed of two lobate ramps (a), separated by a ridge (b), the distal part of the ramps have grooves and drumlin-like forms (c); A-A' is the location of sleeve-gun record, seismic profile and interpretation shown in 3B–D; B) The sleeve-gun record; C) The 3.5 kHz record; D) The interpretation of these records identifying locations of ice-contact sediment, glaciomarine mud and post-glacial mud. All illustrations adapted from Shaw* et al. *(2000).*



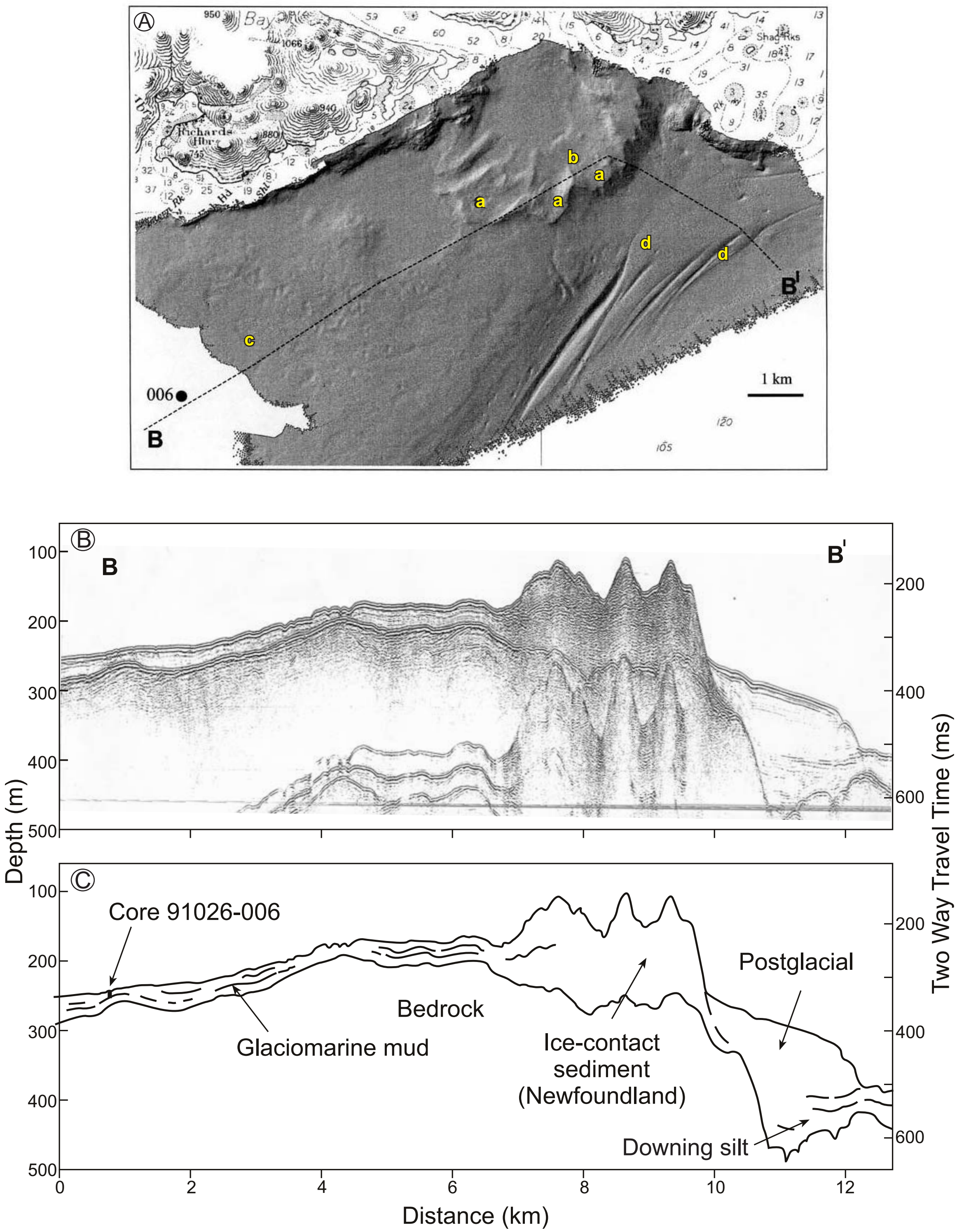


Figure 4. *A) Shaded-relief multibeam image of the submarine moraine off Facheux Bay, which has convex-seaward ramps (a) and prominent landward cusps (b), iceberg furrows and pits (c) and long, deep arcuate iceberg furrows (d). B-B' is line of the sleeve-gun record taken over the moraine; B) Sleeve-gun record across the submarine ridge off Facheux Bay; C) Interpretation showing the location of the ice-contact sediment. All illustrations taken from Shaw* et al. *(2000).*

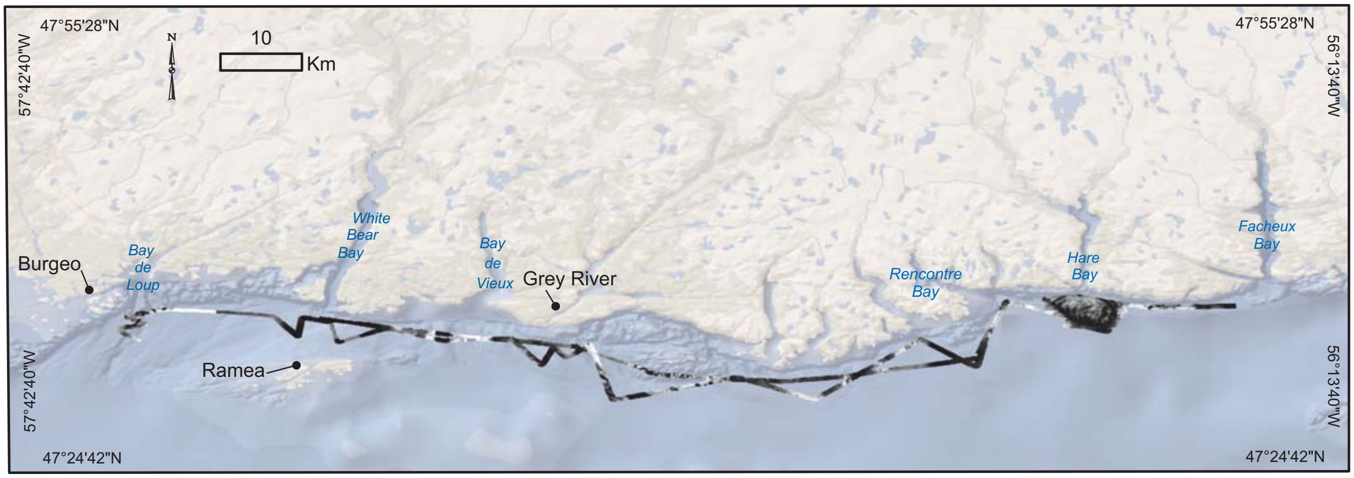


Figure 5. *Location of multibeam and seismic data collected between Facheux Bay and Bay de Loup.*

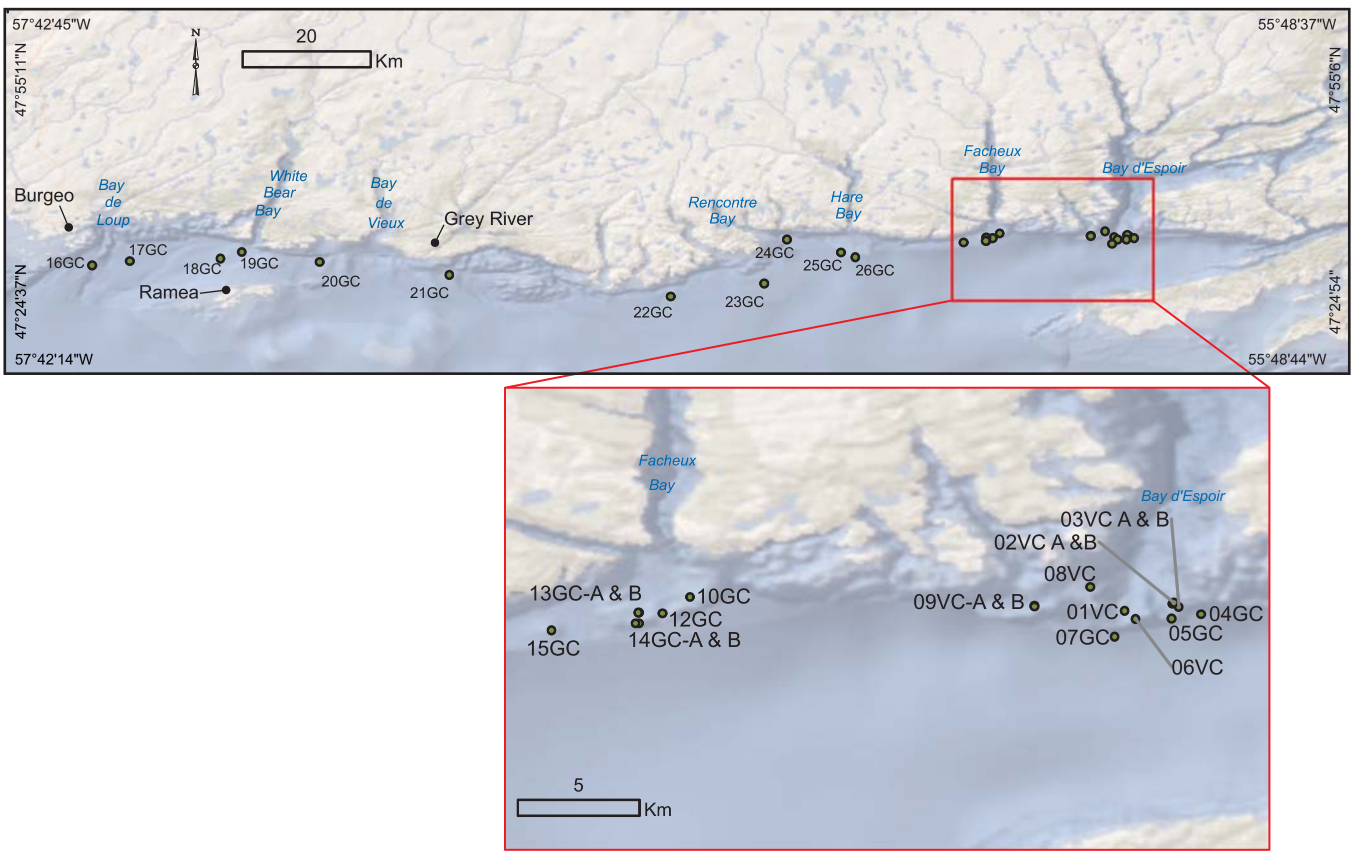


Figure 6. *Location of coring stations between Bay d'Espoir and Burgeo. Black dots show locations of neighbouring communities. Inset shows enlarged area of Facheux Bay and Bay d'Espoir. The letters after the site numbers refer to the type of corer used: GC – gravity corer; VC – vibro-corer.*

Sediment cores were retrieved using both a vibro-corer and a gravity corer. A Geo-Vibro Corer 3000 + 6000 is a high-frequency (28 Hz) electrically driven vibro-coring system (Plate 1). It uses 6 m lengths of standard PVC liner, with an internal diameter of 10 cm. The penetration force can be adjusted by varying the deadweights on the vibrator head. It has a successful record in coring submarine glacial landforms, composed of compact, clast-rich glacial diamictons, on the continental shelf offshore of western Ireland (Peters *et al.*, 2015). A limiting factor of the corer is that it requires a relatively flat surface, at least 5 m in diameter, to provide sufficient stability to operate effectively. The gravity corer is a simpler, robust coring system in which the weighted top of the coring barrel works with gravity to penetrate the seafloor (Plate 2). It is a smaller device than the vibro-corer, with a maximum recovery length of 3 m and a diameter of 7 cm. Whereas it is relatively straightforward to deploy, it typically does not have enough force to penetrate compact glacial diamicton and is more often used to collect glaciomarine mud.

Plate 1. *Vibro-corer used during the NISS survey. The vibrator head (yellow) is located toward the base of the corer whereas the grey core barrel extends from the corer toward the bottom right for retrieval of core. The vibrating head moves to the top of the corer once the core barrel is brought to an upright position.*

Once retrieved, cores were cut into 1 m segments and labelled for storage (Plates 3 and 4). The tops and bottoms of the cut cores were described for texture, clast content, angularity of clasts, and presence of shells or bioturbation before being capped. All cores were labelled in the dry lab before being stored for transport in a refrigerated container.

Plate 2. *Gravity corer used during the NISS survey.*

Plate 3. *Core liner was measured into 1 m segments and cut with a handsaw. Caps were placed on the ends of the core after cutting.*

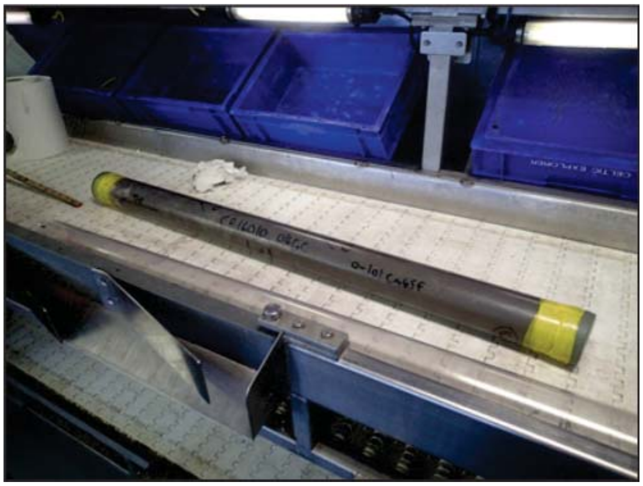


Plate 4. *Core was labelled with site number, length, number of segments in core and top direction. Archival and working halves were marked accordingly.*

Plate 5. *Grey mud inside a section of core liner recovered using the vibro-corer in Bay d'Espoir.*

SURVEY RESULTS

Cruise CE16010 left St John's and traversed to the first coring location at Bay d'Espoir (Figure 1). An undated arcuate fjord-mouth submarine moraine was identified and described by Shaw *et al.* (2000) and Shaw (2003) at the entrance to Bay d'Espoir. Cores retrieved from the moraine would allow study of its depositional environment and to constrain its depositional history on the shelf; nine sites were selected. A total of 16.4 m of core was recovered from five of nine stations at the entrance of Bay d'Espoir (Figure 6; Table 1; Plate 5). At three stations a second attempt was made; this only proved successful at station CE16010_09VC-B (Table 1). Preliminary interpretation of exposed core sediments (based on an assessment from the top and bottom of the 1-m core segments) indicates that the targeted sediment of glacial diamicton was collected at sites 1VC and 6VC.

At station CE16010_02VC-B in Bay d'Espoir (Figure 6; Table 1) in 234 m of water, the vibro-corer developed an electrical fault; coring switched to using the 3-m gravity corer (Plate 2); this produced mixed results at three sites in Bay d'Espoir. There was no recovery of sediment at station CE16010_05GC; two cores were retrieved from station CE16010_07GC (2m) and station CE16010_04GC (3 m) (Figure 6; Table 1).

The next coring location was the Facheux Bay fjord-mouth submarine moraine located approximately 4.5 nautical miles west of the Bay d'Espoir site (Figure 6). Five cores were collected from the moraine located at the mouth of this fjord. At station CE16010_10GC in a water depth of 141 m, a 1.17 m core was retrieved that contained grey mud with gravels. Again, there were mixed results with the gravity corer; however, all but one station (CE16010_14GC-B) produced a sample. The shortest core interval retrieved (20 cm) at station CE16010_13GC-A contained brown silt and mud and angular clasts up to 2 cm in diameter (Figure 6; Table 1). Shells were identified in the top of a short 30 cm core that contained a grey matrix of clay to sand at station CE16010_14GC-A. The longest core (2.5 m) was retrieved at location CE16010_15GC (Figure 6) and it contained very compact grey mud and small (less than 1 cm) angular clasts (Table 1).

After Facheux Bay, the survey switched to a different data acquisition phase, which focused on collecting geophysical lines of the inshore region between Facheux Bay and Bay de Loup (Figure 5). On this leg, seismic (Spot profiler) and multibeam (EM2040) data were acquired (Figure 5). Fjord entrances traversed between Facheux Bay and Bay de Loup may have similar fjord-mouth submarine moraines, and the geophysical lines could identify them. As these fjords had never been imaged, a survey close to the entrances would provide the best opportunity of recording them. Conditions were excellent for this leg of the survey, which produced ideal conditions for collecting the geophysical data.

High-quality data were collected continuously throughout the entire geophysical leg of the survey. The seismic data captured the sedimentary and bedrock architecture of the sub-seafloor (Plate 6). Several moraines were also imaged using the multibeam system. This included new mapping on three previously identified moraines at Grey River, Bay de Loup and White Bear Bay (Shaw *et al.*, 2000; Shaw, 2003)

Table 1. *Core locations and preliminary descriptions based on observations made on deck. Within the Station Number label, VC refers to vibro-corer, GC refers to gravity corer, and A and B are the first and second attempt at coring the same station. Latitude and Longitude are given in decimal degrees. WD – water depth, AP – apparent penetration, CC – core catcher*

Location	Station No. (CE16010_)	Day of Year	Latitude (N)	Longitude (W)	WD (m)	AP (m)	Length (m)	CC	Description
Bay d'Espoir	09VC-A	22/04/2016	47.6038	56.1812	170	5	0.51	Empty	Grey silt mud
	09VC-B	22/04/2016	47.6035	56.1812	170	4.5	4.5	Grey mud	Stiff grey mud, grey silty mud, silty sand pebbles (0.5-2 cm), semi-rounded to rounded
	08VC	22/04/2016	47.6107	56.1605	180	0	0	Empty	
	01VC	23/04/2016	47.6020	56.1477	226	3.5	4.75	6 cm diameter clast	Sand to silt, fine med sand-silt matrix, pebble (5 cm)
	06VC	23/04/2016	47.5990	56.1437	190	3.5	3.63	Empty	Grey silty mud, fine sand, dark grey mud, some pebbles (2-3 cm appear striated)
	02VC-A	23/04/2016	47.6045	56.1300	246	0	0	Empty	
	02VC-B	23/04/2016	47.6050	56.1295	234	0	0	Empty	
	03VC-A	23/04/2016	47.6033	56.1277	279	0	0	Empty	
	03VC-B	23/04/2016	47.6033	56.1277	279	0	0	Empty	
	04GC	23/04/2016	47.6007	56.1195	330	3	3.02	Fine grained grey/black mud, some isolated coarse fragments	
	05GC	23/04/2016	47.5992	56.1303	234	0	0	Empty	
	07GC	23/04/2016	47.5923	56.1513	284	2	2.04	Empty	Uniform grey and tan mud/silt, stiff grey uniform packed mud upper part pebbles visible, 1 granitoid/triangle shaped
Facheux Bay	10GC	23/04/2016	47.6070	56.3084	141	0.5	1.17	Grey/brown mud on core and end of core, approx. 30 grams of material	Compact grey mud, gravel on top
	12GC	23/04/2016	47.6009	56.3188	143	3	2.07	Grey compact mud, approx. 60 grams of material	Compact uniform grey mud, large (2 cm) triangle shaped pebbles towards the top
	13GC-A	23/04/2016	47.6012	56.3275	140	2	0.2	Brown mixed gravel and mud	Brown/grey waterlogged mud and triangular gravel clasts, approx. 10% gravel and 10% sand
	13GC-B	23/04/2016	47.6012	56.3277	139	0.2	0.49	Approx. 20 grams of brown silt/mud matrix with rough angular clasts	Mixed brown silt and clay with larger clasts (up to 2cm), clasts are a sub-angular-subrounded triangular shape
	14GC-A	23/04/2016	47.5973	56.3275	141	0.2	0.3	Grey silt/sand/clay/gravel	Grey matrix with silt, clay, sand and large gravel (angular clasts), abundant shells on top, clasts up to 4 cm in diameter
	14GC-B	23/04/2016	47.5972	56.3285	135	0	0	Empty	
	15GC	23/04/2016	47.5947	56.3596	142	3	2.51	Thick compacted grey mud and a little grit, triangular pebbles (subangular)	Very compacted grey mud, some grit and pebbles
Bay de Loup	16GC	24/04/2016	47.5628	57.5828	230	3	3.02	Grey stiff mud with some clasts	Stiff grey mud with clasts, slightly gritty with some silt content
	17GC	24/04/2016	42.5683	57.5300	230	1	2.2	Grey silty mud, slightly gritty	Grey silty mud, slightly gritty with higher sand content and larger clasts towards the top
White Bear Bay	18GC	24/04/2016	47.5723	57.4027	184	3	1.48	Grey mud	Grey/brown sandy mud
	19GC	24/04/2016	47.5812	57.3728	146	1	0	Empty	
Bay de Vieux	20GC	24/04/2016	47.5670	57.2635	209	0.5	1.41	Grey/brown mud, slightly gritty	Grey/brown mud, slightly gritty
Grey River	21GC	24/04/2016	47.5492	57.0813	160	0	0	Empty	
	22GC	24/04/2016	47.5187	56.7705	158	3	0.88	Gritty, silty mud	Sandy clay, with some smaller clasts (up to 2 mm), coarser towards the top, with some triangular shaped clasts
	23GC	24/04/2016	47.5372	56.6393	175	0	0.18	Coarse brown/mud with clasts component-angular, with lots of sand	Mixed clay, sand and clasts (>2 mm)
Rencontre Bay	24GC	24/04/2016	47.599	56.6077	217	3	3.01	Silty grey clay, some clasts	Homogeneous grey mud, gritty tan silty clay
Hare Bay	25GC	24/04/2016	47.5802	56.5315	129	1	0.4	Very hard grey mud with 1 mm clasts visible in matrix, 2 cm pebble (angular) and shell fragments, bullet shaped 3.5 cm clast	Similar to core catcher
	26GC	24/04/2016	47.574	56.5113	158	0	0	Empty	

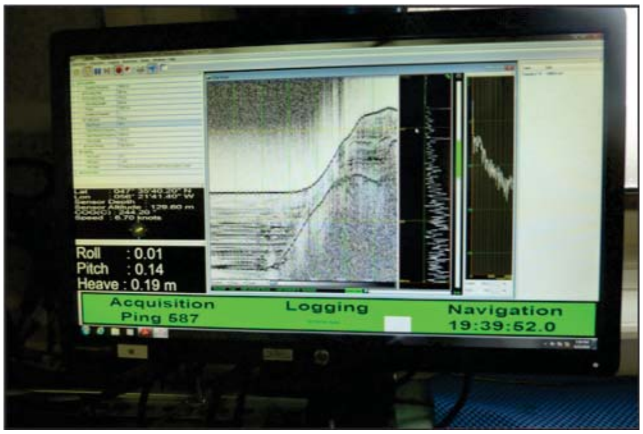


Plate 6. *Screen shot of a seismic profile showing the quality of the data. Note the various horizons that capture the sedimentary architecture of the seabed along the survey path.*

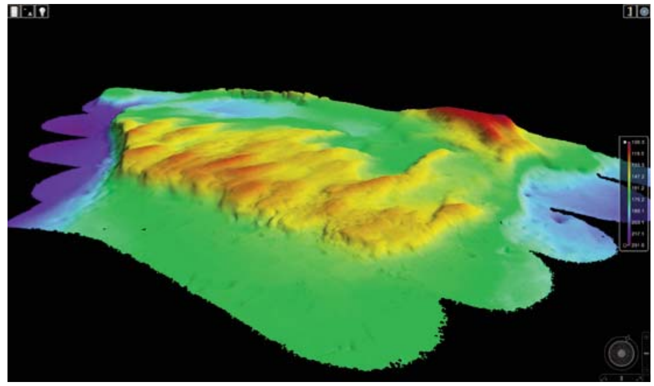


Figure 7. *New multibeam imagery acquired at the entrance of Hare Bay. Looking northwest across the moraine. This moraine is similar in morphology and dimension to the Facheux Bay and Bay d'Espoir moraine systems to the east.*

and one previously unidentified fjord-mouth submarine moraine at the head of Hare Bay (Figure 7).

The geophysical leg of the survey terminated at Bay de Loup (Figure 5); the main focus of the final leg was to acquire core at new locations using a combination of earlier seismic data, and new seismic and mulitibeam data acquired. Coring was conducted using the 3-m gravity corer. At the first station (CE16010_16GC), 3 m of core containing stiff grey mud with clasts was retrieved. Ten more locations were targeted between Bay de Loup and Hare Bay (Figure 6) including the previously undated Bay de Loup, White Bear Bay, Grey River and Hare Bay fjord-mouths moraines (Shaw *et al.*, 2000; Shaw, 2003). Of the 11 sites, only 3 sites had no recovery (Table 1). The remainder had some recovery including three short core segments containing 18, 40 and 88 cm of sediment, and others ranging in between 1.5 and 3 m. A 40 cm core at station CE16010-25GC was located on the newly identified Hare Bay fjord-mouth submarine moraine. The bottom of this core contained very hard grey mud and granule to pebble-sized clasts along with unidentified shell fragments.

Detailed core logging of the sediments acquired during the cruise will determine if coring was successful in collecting glacial diamicton from the fjord-mouth submarine moraines. In addition, radiocarbon dating of any shells identified including those at stations CE16010_14-A and CE16010-25GC could provide the timing, and deglacial retreat pattern of the Newfoundland Ice Cap.

The final portion of the survey (from Hare Bay to Argentia), involved packing, documenting and storing the core samples and organizing and managing data collected from the trip. Demobilization took place in Argentia port where the cruise officially ended.

CONCLUSIONS

The NISS survey successfully collected over 100 nautical miles of multibeam seabed bathymetry, backscatter and seismic data along Newfoundland's south coast from Bay d'Espoir to Burgeo, and 37 m of sediment cores from targeted glacial sediments and fjord-mouth moraines. These data will form the basis of new investigations on the glacial and postglacial development of the southern Newfoundland continental shelf, as well as the timing and pattern of retreat of the Newfoundland Ice Cap.

In addition to providing new data to better understand the glacial history of the Newfoundland shelf, data from the NISS project contributes to Atlantic Seabed Mapping Initiative as part of the Atlantic Ocean Research Alliance.

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