

ICE-FLOW HISTORY OF PLACENTIA BAY, NEWFOUNDLAND: MULTIBEAM SEABED MAPPING

D. Brushett, T. Bell, M.J. Batterson¹ and J. Shaw²

Department of Geography, Memorial University, St. John's, NL, A1E 3X5

¹ Geological Survey, Newfoundland and Labrador Department of Natural Resources, St. John's, NL, A1B 4J6

² Geological Survey of Canada, Natural Resources Canada, Dartmouth, NS, B2Y 4A2

ABSTRACT

This paper reports recent progress made on ice-flow mapping in Placentia Bay, Newfoundland, using multibeam sonar imagery. Flow-parallel features identified on the imagery include drumlins, flutes, mega-lineations, and crag-and-tail landforms. These features show a general trend of convergent ice flow, which is interpreted to represent fast-flowing ice (an ice stream) down the axis of Placentia Bay. Drumlins and fluted terrain onshore demonstrate that the convergent ice flow can be traced up-ice to regional dispersal centres. Flow-transverse features interpreted as deGeer moraines occur in water depths of 100 to 350 m, and were likely deposited during the deglaciation of the bay as tidewater margins became grounded in shallow water. Ice-flow mapping of Placentia Bay also demonstrated that the largely depositional record preserved on the seabed is incomplete, with the apparent absence of a strong westward flow onto the Burin Peninsula. The mostly erosional ice-flow record on land also appears incomplete because there is no evidence, to date, for a southwestward ice flow that is recorded by a fluting field on the seabed of southwestern Placentia Bay. The integration of onshore and offshore glacial records in Newfoundland represents an important development in mapping palaeo ice-flows and the understanding of ice-sheet behaviour during the transition from largely marine-based to land-based glacial conditions.

INTRODUCTION

Traditionally, palaeo ice-flow mapping in Newfoundland and Labrador has had a terrestrial focus, combining surficial geology, striation direction data and clast provenance studies. Recent technological advances in both terrestrial (Shuttle Radar Topography Mission (SRTM)) and marine (multibeam bathymetric sonar) mapping have generated landscape and seabed imagery that permit a broader interpretation of glacial geomorphology and palaeo ice dynamics (e.g., Liverman *et al.*, 2006; Shaw *et al.*, 2006a).

This paper discusses the recent progress made on ice-flow mapping in Placentia Bay, Newfoundland, using seabed sonar imagery and subbottom acoustic profiles, acquired as part of the Geological Survey of Canada's *Geoscience for Ocean Management Program*. Seabed mapping surveys were carried out in 2004 and 2005, building upon earlier surveys in 1995 and 1999. Follow-up activities, including subbottom profiling (Huntec DTS), sidescan sonar imaging, bottom photography, grab sampling and piston coring, were carried out in two subsequent cruises (CCGS Matthew #2005-51 and CCGS Hudson #2006-39). Together, these data will be used to produce maps of bathymetry, acoustic backscatter and surficial geology for

Placentia Bay, similar to those recently published for St. George's Bay, southwest Newfoundland (Shaw *et al.*, 2006b).

This project represents a further development in the integration of onshore and offshore glacial records in Newfoundland, in that it attempts to directly trace surface features and palaeo ice-flows mapped on land onto the adjacent seabed. Previous studies relied on stratigraphic correlations of terrestrial and marine glaciogenic units, together with inferences about glaciological behaviour of palaeo ice sheets (e.g., Bell *et al.*, 1999). It is anticipated that based on similar nearshore studies (e.g., Bedford and Halifax basins, Nova Scotia; see Miller and Fader, 1995) and the preliminary analysis of the present dataset (Batterson *et al.*, 2006), the Placentia Bay seabed preserves a geomorphologic record of former ice flow of equal or higher resolution than that of the adjacent terrestrial landscape.

In a broader context, the tracing of palaeo ice-flows from terrestrial to marine environments provides an opportunity to test our understanding of ice-sheet behaviour across the transition from largely marine-based to land-based glacial conditions. For example, abrupt temporal and spatial shifts in ice-bed interactions of a marine-based ice

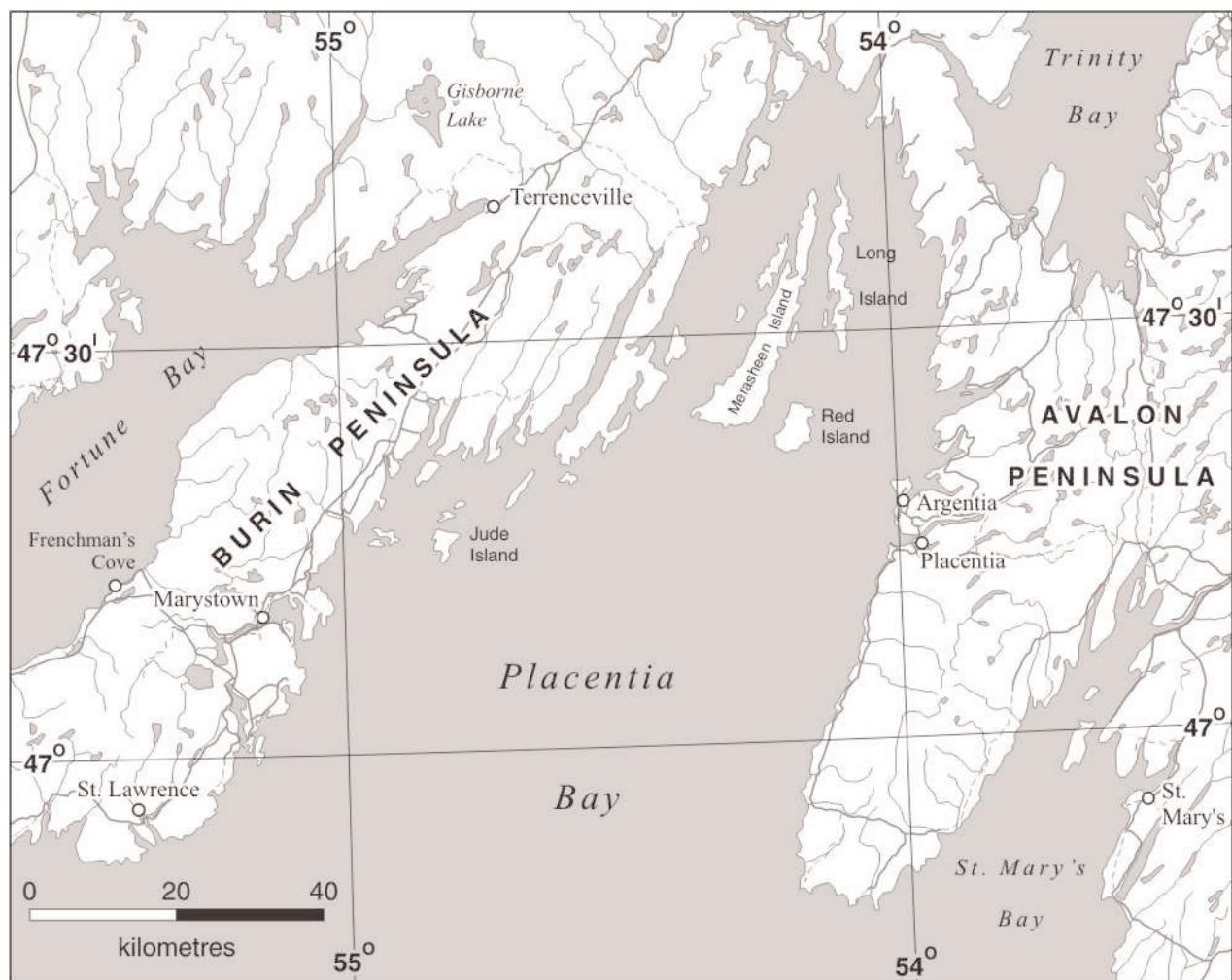


Figure 1. Location map of study area.

sheet may produce a broad assemblage of subglacial landforms reflecting conditions ranging from sustained fast flow to rapid disintegration and ice-marginal retreat. Reconstruction of past glacial dynamics in Placentia Bay will provide insights into possible deglacial scenarios for other bays and inlets around Newfoundland.

In this paper, the ice-flow data interpreted from the multibeam survey of Placentia Bay are compared with the ice-flow record onshore, to address questions related to the origin, pathways and relative chronology of local glaciation (Batterson *et al.*, 2006; Batterson and Taylor, 2006; Shaw *et al.*, 1999, 2006a, c; Taylor, 2001).

STUDY AREA

Placentia Bay, in eastern Newfoundland, is a glacially modified basin having a surface area of over 5000 km² (Figure 1). It is bordered by the Burin Peninsula to the west, the Avalon Peninsula to the east, and the Isthmus of Avalon to

the north. The bathymetry exceeds the surrounding terrestrial relief in many places, reaching depths greater than 400 m, and is generally associated with northeast-southwest-trending structural depressions. The bedrock geology of Placentia Bay, interpreted from shallow seismic records, appears consistent with local Avalon Zone stratigraphy, as mapped by Colman-Sadd *et al.* (1990). In summary, the bedrock consists of Late Proterozoic submarine and non-marine volcanic and sedimentary rocks, overlain by Late Proterozoic and early Paleozoic shallow-marine rock types.

ICE-FLOW HISTORY

Placentia Bay has a complex palaeo ice-flow history, draining ice from the surrounding Burin and Avalon peninsulas, both of which also maintain a complex record of glacial movements. For the most part, the ice-flow history of the Avalon Peninsula, like that of the Burin Peninsula, is based on the crosscutting relationships of striations (Henderson, 1972; Catto, 1998; Catto and Taylor, 1998). At its

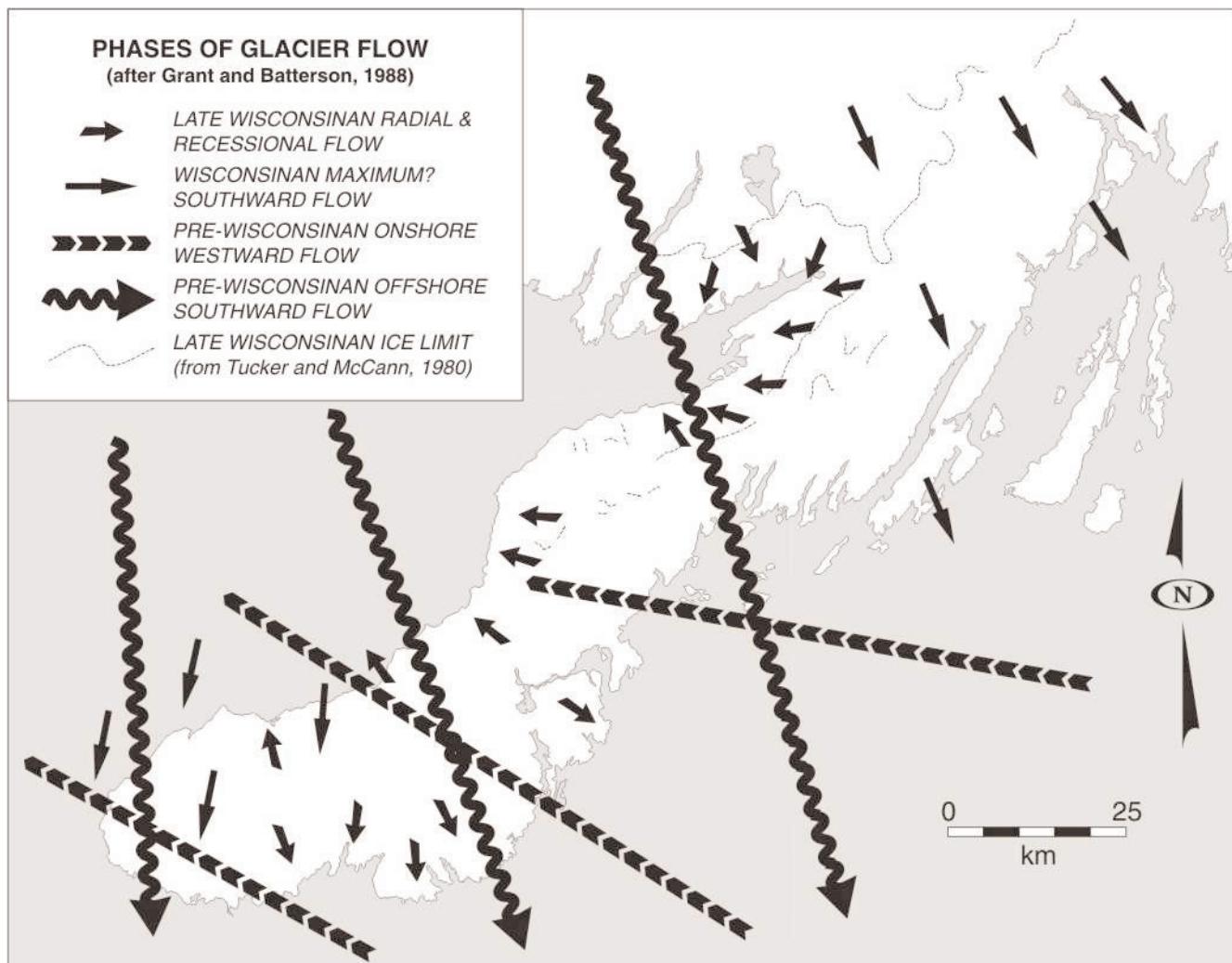


Figure 2. Glacial flow phases on the Burin Peninsula, as published in the 1980s (from Batterson et al., 2006, after Grant and Batterson, 1988; Tucker and McCann, 1980).

maximum extent, the Avalon ice cap was characterized by radial expansion and coalescence of local dispersal centres. Catto (1998) suggested that the westward-flowing ice from the Avalon Peninsula and the Isthmus was confluent with Newfoundland ice, flowing northward into Trinity Bay and southward down into Placentia Bay. Specific research questions that relate to onshore–offshore correlations however, will focus on the ice-flow history of the western side of Placentia Bay because of the availability of recent data in this area.

Previous Work

Grant (1975) defined 4 main phases of glacial flow in the Burin Peninsula based on crosscutting striations and the weathering of older striation sets. A regionally extensive southward flow extending across the northern part of the

Burin Peninsula in the area south of Terrenceville, followed by a northwestward flow originating from an offshore source (both of these flows were assigned a pre-Wisconsinan age); a southward, late Wisconsinan ice flow across much of the northern Burin Peninsula; and a late Wisconsinan radial flow from an ice-divide extending along the length of the peninsula (Figure 2).

Subsequent work by Tucker (1979) and Tucker and McCann (1980), generally supported Grant's sequence of events but argued for more restrictive late Wisconsinan ice, based on an extensive end moraine along the Gisborne Lake Basin, identified by Jenness (1960). This interpretation had limited local ice in the centre of the upper Burin Peninsula with the remainder of the peninsula ice-free during the late Wisconsinan.

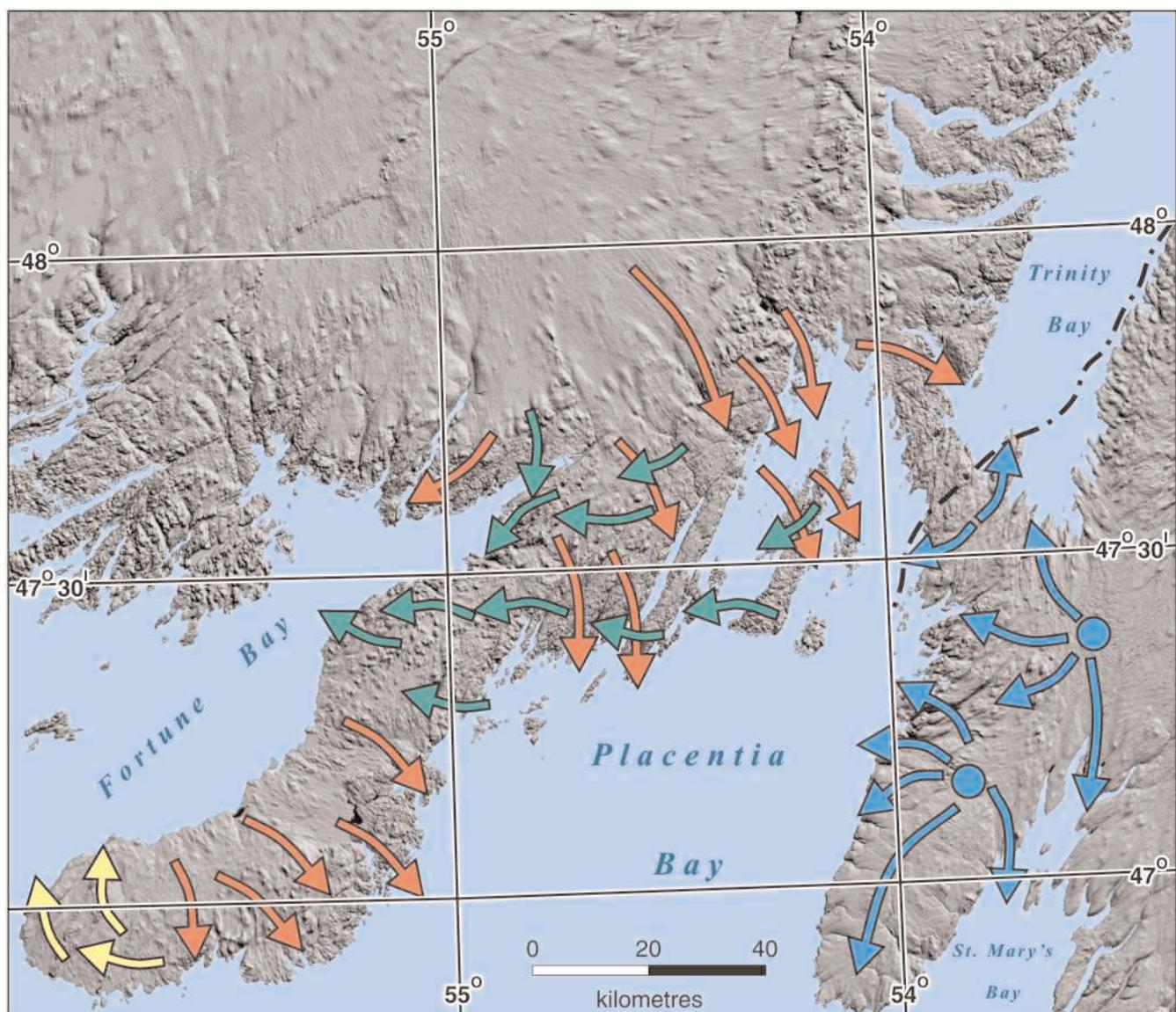


Figure 3. Ice-flow patterns on the Burin Peninsula interpreted from recent mapping superimposed on the SRTM image. All flow phases are interpreted as late Wisconsinan. Red arrows represent regionally extensive southeastward flow originating from Newfoundland-centred ice. Green and yellow arrows represent westward flow(s) recorded in the striation record on the Burin Peninsula. The dotted line marks the limit of Newfoundland ice. The blue arrows represent part of the series of local ice-dispersal centres on the Avalon Peninsula (modified from Batterson *et al.*, 2006; Catto, 1998).

In contrast to previous interpretations, Batterson *et al.* (2006) proposed that all the ice-flow events observed on the Burin Peninsula were late Wisconsinan. This interpretation was based on the fresh and unweathered appearance of striations, and the consistency of flow patterns observed on both the Burin Peninsula and the main part of Newfoundland where flow patterns have been interpreted as late Wisconsinan.

Batterson *et al.* (2006) suggested there were up to three phases of glacial flow on the Burin Peninsula, summarized

in Figure 3. The earliest flow was a regionally extensive, south-southeastward flow, indicated by the orientation of fluted terrain and striations. Large-scale streamlined landforms identified from SRTM imagery parallel the striation pattern (Batterson and Taylor, *this volume*). The direction of movement is generally consistent across the northern part of the peninsula but trends more southward across Merasheen Island and Long Island into Placentia Bay. The distribution of Ackley Granite clasts, originating from bedrock sources to the north, also supports this southward flow (Batterson *et al.*, *op. cit.*).

The second flow phase covered an area near the head of Fortune Bay, south to a line extending between Marystown and Frenchman's Cove, trending southwestward in the north to northwestward in the south. Westward striations are also found on Merasheen Island and Jude Island in Placentia Bay. The westward onshore flow is well developed on bedrock surfaces and commonly removed evidence of the earlier southeastward flow from west-facing bedrock surfaces. This westward event appeared to have little influence on sediment dispersal and is not apparent on the SRTM imagery (Batterson and Taylor, *this volume*). Striations found on the tip of the Burin Peninsula indicate a third, north-northwestward ice flow, from a possible offshore source.

METHODS

MULTIBEAM SONAR

Multibeam bathymetric systems offer new opportunities for recognition and interpretation of seafloor features and have become the tool of choice for ocean mapping by navies, hydrographers, and research scientists (Courtney and Shaw, 2000). In Atlantic Canada, the use of multibeam sonar systems began when the Canadian Hydrographic Service invested in high resolution multibeam sonar for surveying the continental shelf in the late 1980s (Courtney and Shaw, *op. cit.*). This work started by mapping the marine geology and geomorphology of the offshore banks on the inner Scotian Shelf (e.g., Todd *et al.*, 1999) and has expanded to cover shallower coastal areas, including fjords and bays in Newfoundland (e.g., Shaw, 2003).

The basic principles behind multibeam echo sounders are similar to other sonar systems, in that they send out beams of sound that contact a target and are reflected back to a receiver. Unlike other sonar devices (e.g., single beam, normal incidence sonar) multibeam echo sounders emit many beams of sound from an array of transducers mounted on the hull of the survey ship. These beams span a fan-shaped arc below and to the sides of the vessel. Each of these beams contacts the seabed at a slightly different angle creating a cone of sound that covers a swath of the seabed. The width of the beam on the seafloor – the footprint of the system – expands with the distance between the transducer and seabed. As water depth increases the area of the seafloor covered by the sonar swath increases and the resolution decreases (Shaw and Courtney, 1997).

MULTIBEAM BATHYMETRY DATA

Two kinds of data are provided by multibeam sonar: bathymetry and backscatter intensity data. For this paper,

only the multibeam bathymetry data will be considered. Multibeam echo sounders record the two-way travel time of the emitted sound through the water column to the target (seabed) and back to the transducer array. Using this two-way travel time and measurements of acoustic velocity variations in the water column, the water depth is calculated. The system also records the angle from which the return signal arrives, which gives the location of the beam across the survey track. Water depth is calculated for each beam and combined to give a continuous record of water depth so that when the data are mapped, topographic features can be observed because of changes in water depth, and hence elevation, across the seabed (Shaw and Courtney, 1997).

MULTIBEAM DATA ANALYSIS

Glacial features preserved on the seafloor of Placentia Bay were mapped and interpreted using the multibeam bathymetric data compiled from various survey cruises (Shaw *et al.*, 1999, 2006a, c). Where applicable, data from acoustic subbottom profiles, sidescan sonar imagery and grab samples were used to support sediment and feature interpretations.

Processed multibeam imagery (gridded at 5 m horizontal resolution) was imported into *ARCMAP* 9.1 in geotiff format (projected in UTM Zone 21 using the NAD 1983 datum). The recognition of seabed features depends on the sun illumination angle chosen to view the bathymetric image. Typically, the optimal angle is one perpendicular to the seabed feature. Two illumination angles at 90° to each other (45° and 315°) were chosen for this analysis to be consistent with the SRTM landscape imagery (Liverman *et al.*, 2006). Features were mapped separately for each of the two illumination angles and then combined into a single database. These data were then viewed in combination with the digital landform database from adjacent land areas (Bell *et al.*, 2005) and recent field mapping carried out by Batterson and Taylor (2006, *this volume*).

Figure 4 shows the multibeam shaded-relief image covering Placentia Bay and the SRTM imagery of the surrounding land areas. This figure and all subsequent multibeam images are shown sun-illuminated with an azimuth of 315° at an elevation above the horizon of 45° and a vertical exaggeration of 10 times.

OBSERVATIONS

FLOW-PARALLEL FEATURES

Flow-parallel features evident from the multibeam imagery include drumlins, flutes, mega-lineations, and crag-

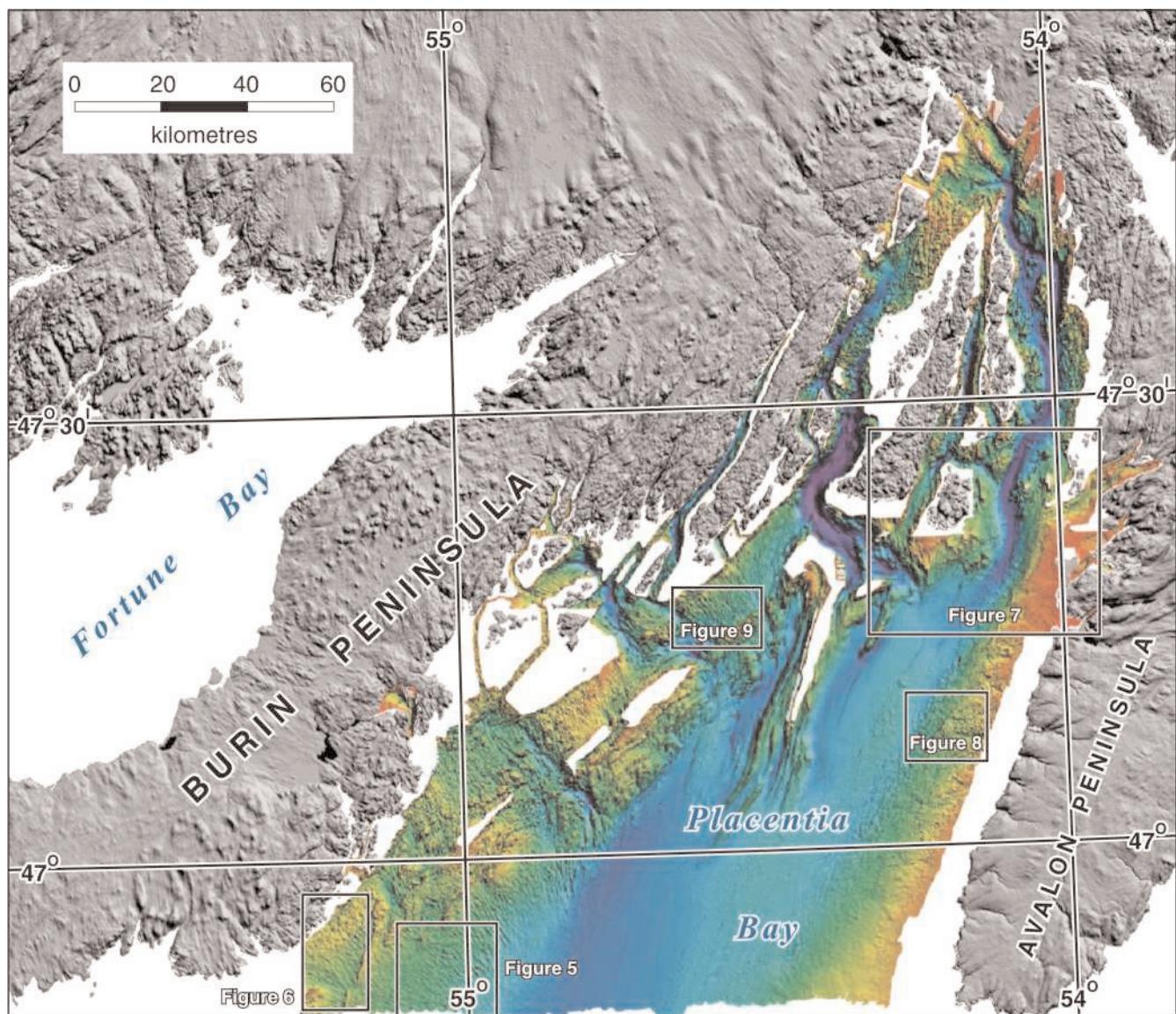


Figure 4. Shaded-relief images showing multibeam coverage of Placentia Bay and SRTM imagery of the surrounding landscape. Locations of subsequent figures are outlined by boxes. Image is sun-illuminated from the northwest (315°) at an azimuth of 45° with a vertical exaggeration of 10 times and horizontal resolution of 5 m. Water depths are indicated by colour ranging from shallow (red) to deep (blue). White represents areas where there is no multibeam data. The SRTM image is sun-illuminated from the northwest (315°) at an azimuth of 45° .

and-tail landforms. These seabed features were identified on the basis of their morphological and sedimentological characteristics as classified in Benn and Evans (1998).

The western side of Placentia Bay has the most extensive field of drumlins observed in offshore Atlantic Canada (Shaw *et al.*, 2006d; Figure 5). A typical long axis drumlin profile shows a steep, blunt stoss side and a gentle lee side, pointed in the direction of ice flow, which is southeast into the centre of the bay. In moderate water depths (more than 100 m), drumlins average 200 m wide and have elevations up to 20 m above the seafloor and 1200 m long, but are more

elongated at greater depths, where they grade into mega-linacations (up to 150 m wide, 20 m high and 2500 m long). Some drumlin forms appear more subdued and less elongated (averaging 250 m wide and 600–800 m long), but independent evidence presented later in this manuscript suggests that they may have experienced post-depositional reworking (*see below*).

Acoustically incoherent material observed in subbottom profiles suggests that the drumlins in Placentia Bay are composed of ice-contact sediment (*i.e.*, till). They may be draped by varying thicknesses of either acoustically strati-

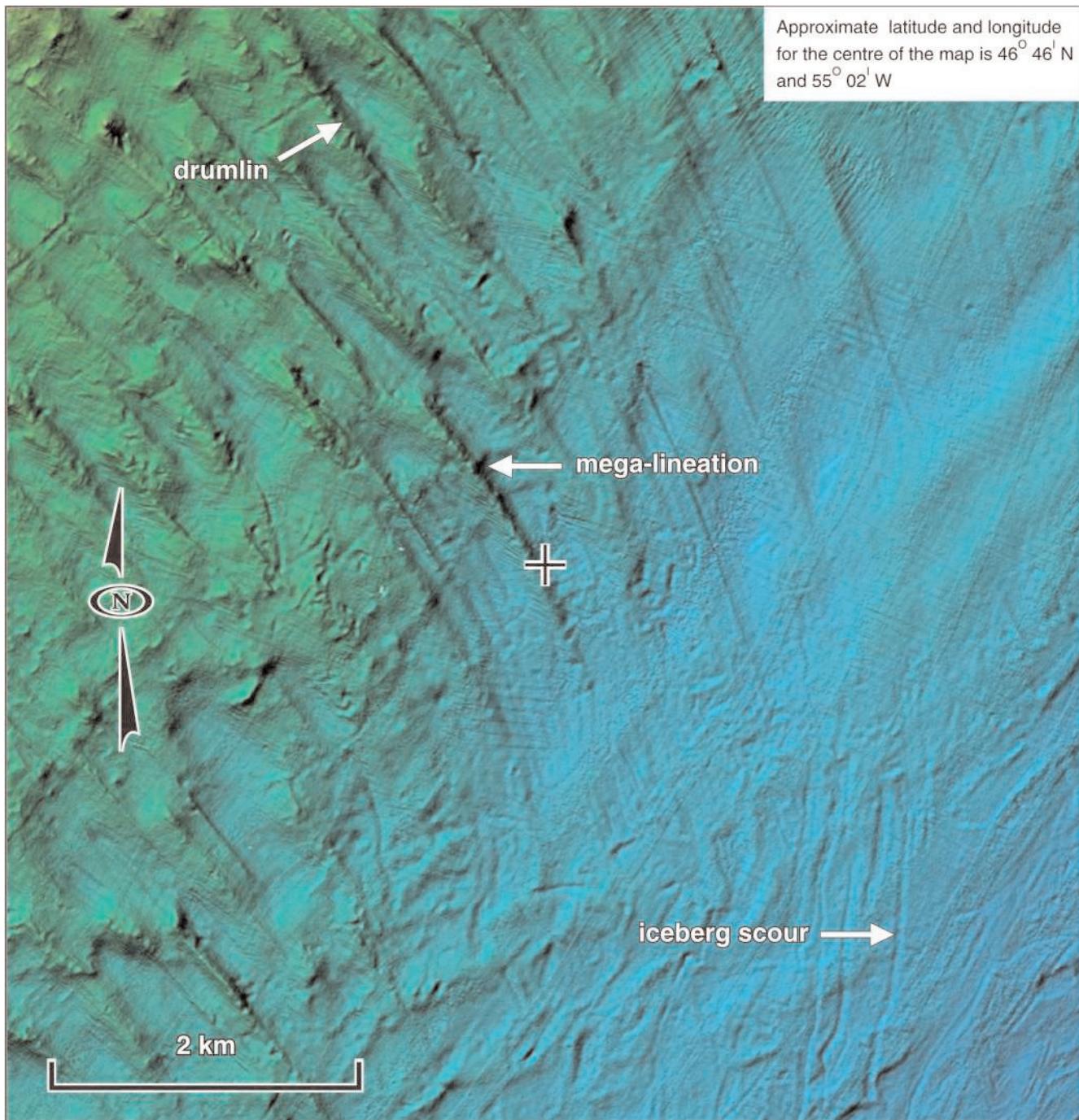


Figure 5. Multibeam shaded-relief image of drumlinized terrain and mega-lineations in southwestern Placentia Bay. Image is sun-illuminated from the northwest (315°) at an azimuth of 45° with a vertical exaggeration of 10 times and horizontal resolution of 5 m. Note the extensive iceberg scouring that becomes more prominent to the east. See Figure 4 for location.

fied sediments or acoustically transparent sediments, which are likely to be glaciomarine gravelly sand and silt and post-glacial mud, respectively (Shaw *et al.*, 2006a).

Two types of ridges may be superimposed on drumlin crests: i) short ridges (~ 500 m long by ~ 85 m wide) at right

angles to drumlin crests (Figure 6); and ii) more continuous ridges oblique to drumlin crests (Figure 6). The former are interpreted as flutes and occur in a field of parallel forms, trending southwest (Figure 6). The latter also occur in fields but are smaller, subparallel, and tend to follow the bathymetric contours; they are interpreted as deGeer moraines.

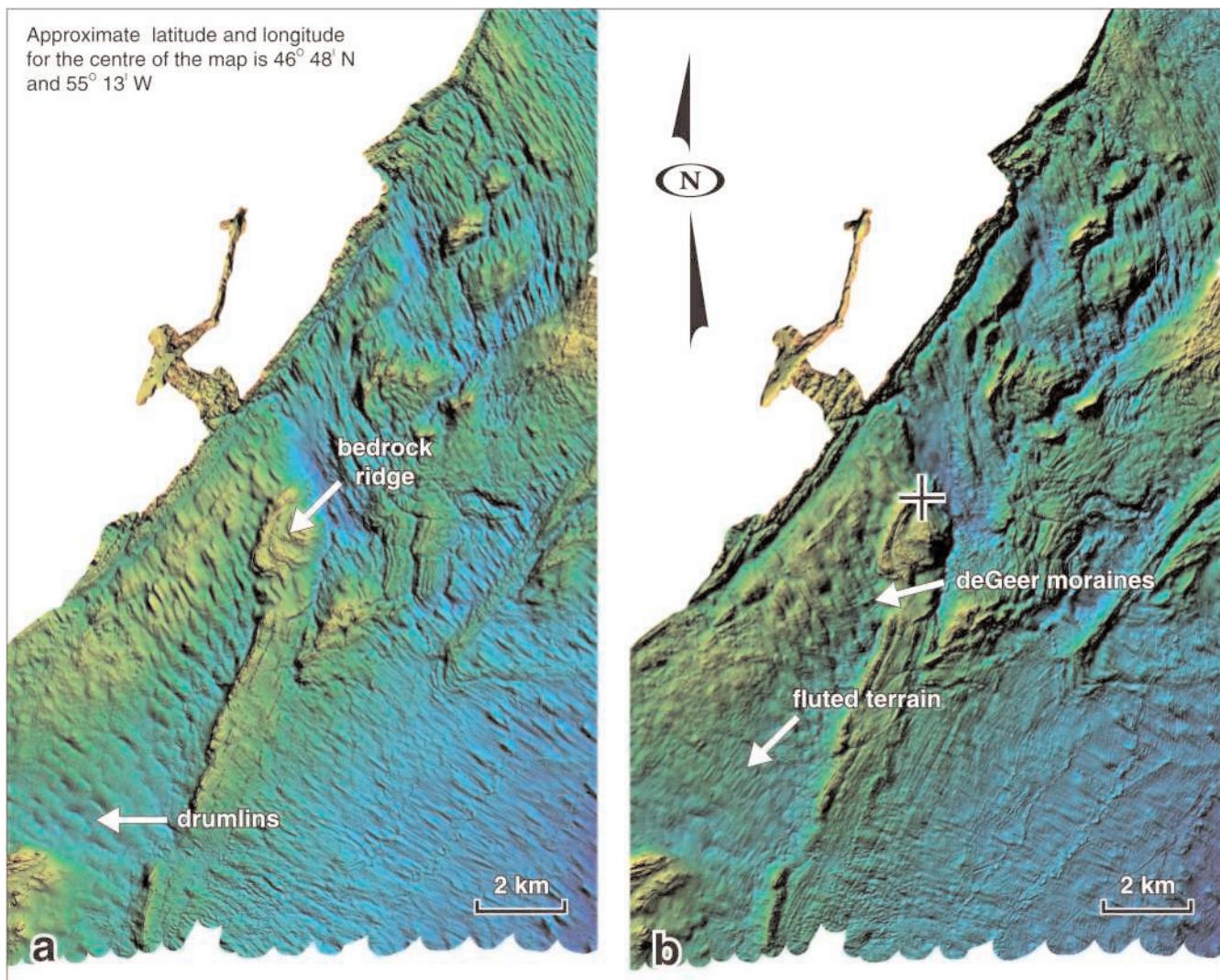


Figure 6. Two shaded-relief images of the same area in southwestern Placentia Bay using different illumination angles. Drumlins in the southwestern most part of the image, shown illuminated from the northeast (6a), display a more subdued morphology than those elsewhere in the bay (e.g., drumlins shown in Figure 5). The same area illuminated from the northwest (6b) displays a series of small transverse flutes superimposed on drumlin surfaces. Note in places the presence of ridges interpreted as deGeer moraines overlying drumlin surfaces. See Figure 4 for location.

On the eastern side of Placentia Bay, seabed features are composed of elongated spindle-shaped ridges that average 20 m high, 300 m wide and up to 2.5 km long. Farther southwest, in deeper water, these ridges attenuate into low, long ridges (commonly 5 m high by 3 km long). Together, this suite of landforms is interpreted to represent the gradation from drumlins to mega flutes to mega-lineations with increasing water depth. Streamlined bedrock and crag-and-tail forms occur south of Red Island. Together with drumlins, these features indicate a southwest-trending ice flow (Figure 7).

South of Red Island, there is generally fewer ice-parallel features (apparent on the imagery). Instead, there is a

wide area of generally hummocky terrain in 80 to 210 m water depth (Figure 8). Subbottom profiles indicate acoustically incoherent sediment overlying bedrock.

FLOW-TRANSVERSE FEATURES

There are several fields of ridges oriented transverse to the interpreted ice-flow direction that generally occur in water depths of 100 to 350 m and may be superimposed on drumlins (Figure 9). In deep water they tend to be more subdued or buried by Holocene marine sediments. These ridges are typically 2 to 6 m high, 40 to 130 m wide, spaced 50 to 80 m apart, and have variable lengths.

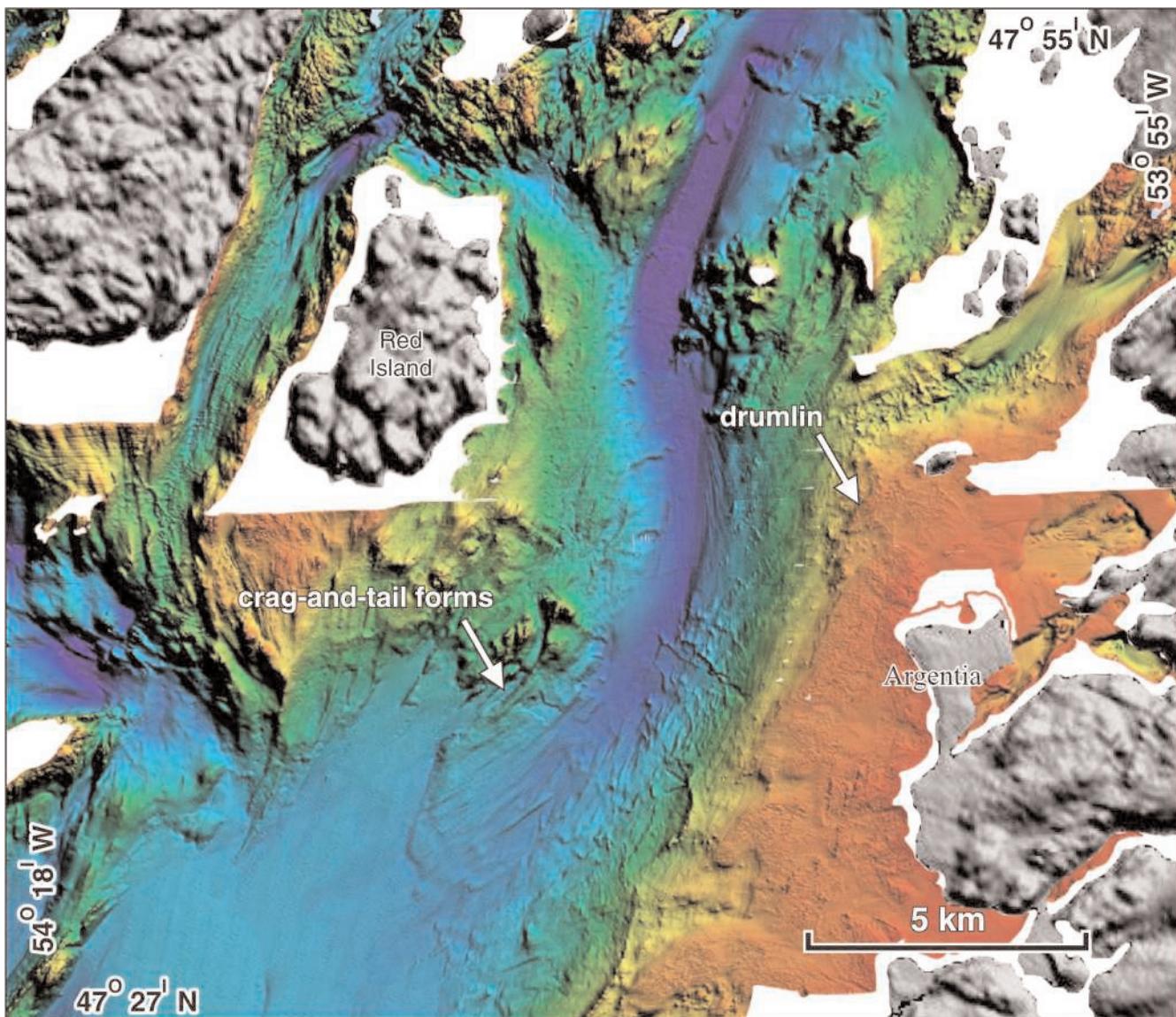


Figure 7. Multibeam shaded-relief image from east-central Placentia Bay showing flow features that include elongated drumlins and streamlined bedrock forms interpreted as crag-and-tail forms. These flow features show a converging southwest-trending pattern down the axis of Placentia Bay. Image is sun-illuminated from the northwest (315°) at an azimuth of 45° with a vertical exaggeration of 10 times and horizontal resolution of 5 m. White represents areas where there is no multibeam data. See Figure 4 for location.

These flow-transverse ridges are interpreted as deGeer moraines, deposited at, or just behind, a retreating tidewater ice margin. Todd *et al.* (*in press*) interpret similar ridges on German Bank as being the product of sediment deposited or pushed up during brief stillstands or minor readvances of the ice margin. These ridges show a generally regular horizontal spacing that suggests that the rate of ice-front retreat was consistent from one cycle of formation to the next.

Other possible depositional processes include the squeezing of substrate into basal crevasses behind the ice margin (Todd *et al.*, *in press*). However, this basal crevasse

model of formation requires several specific conditions including isolated water-filled crevasses that penetrate to the base of the ice, where the ice is less than 22 m thick, or where basal water pressure is higher than the ice overburden pressure. Given these conditions, material could squeeze into crevasses from below. Such ridges would display a different morphology from those described above and would have a more randomly oriented criss-cross pattern. The preservation of these ridges would require that ice either melted *in-situ* or lifted off the seafloor with no ice flow occurring once the crevasse fills formed (Todd *et al.*, *in press*).

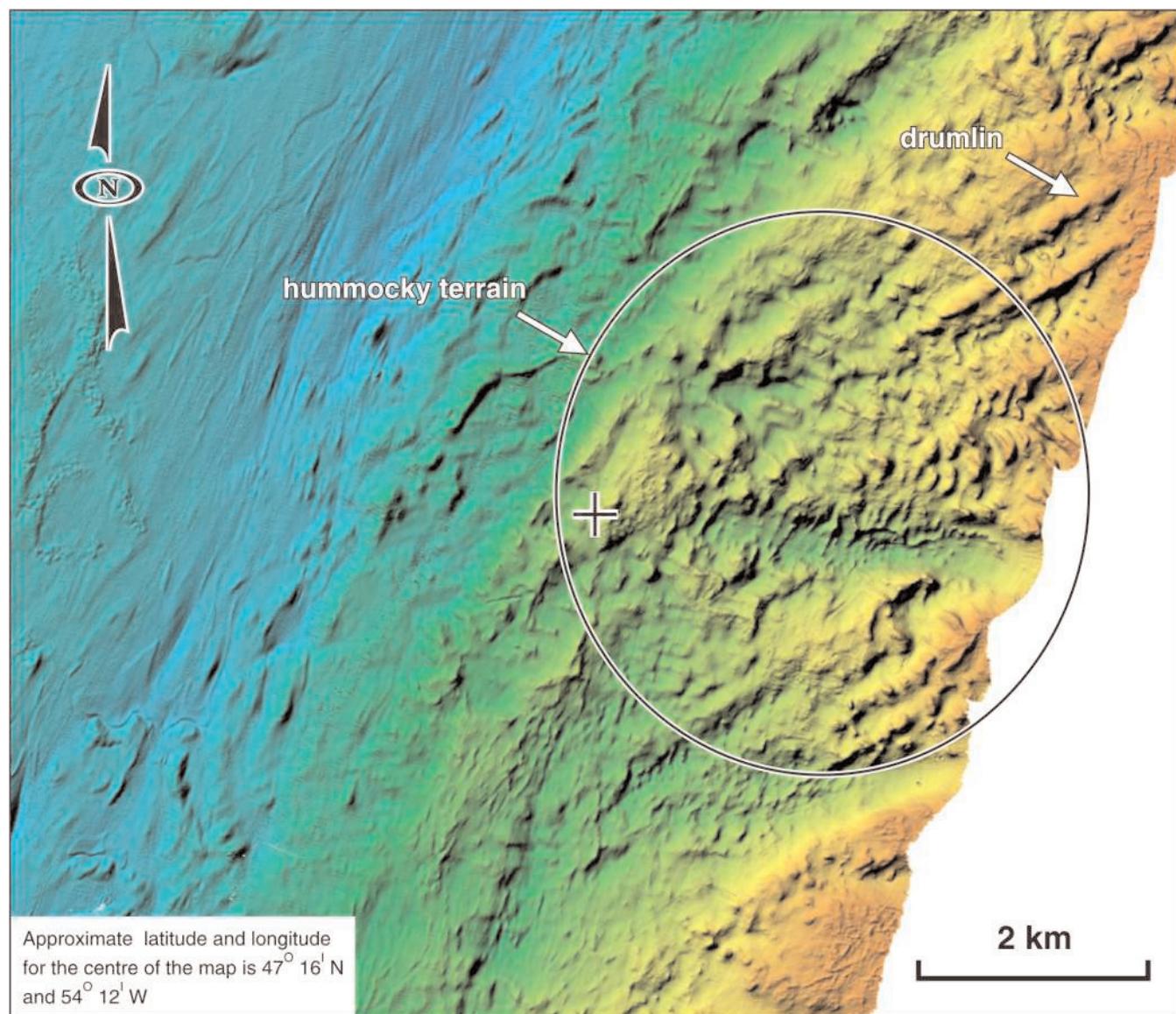


Figure 8. Multibeam shaded-relief image from eastern Placentia Bay showing flow-parallel features interpreted as drumlins that are either overlain or surrounded by hummocky terrain. Image is sun-illuminated from the northwest (315°) at an azimuth of 45° with a vertical exaggeration of 10 times and horizontal resolution of 5 m. White represents areas where there is no multibeam data. See Figure 4 for location.

DISCUSSION

OFFSHORE ICE FLOW AND RETREAT

The flow-parallel features from both sides of Placentia Bay show a general trend of convergent flow down the bay (Figure 10). Evidence for this convergence comes from the extensive field of southeast-trending drumlins and mega-linacations on the western side of the bay and from southwest-trending converging drumlins and crag-and-tail features on the eastern side of the bay. These landforms are interpreted as constituting a single flow set that was formed by conver-

gence of fast-flowing ice (an ice stream) down the axis of Placentia Bay. This concept of an ice stream was proposed in Shaw *et al.* (2006d) and the landforms in Placentia Bay are typical of those associated with former ice streams (*cf.*, Stokes and Clark, 1999, 2001), including the down-flow attenuation of drumlins into till ridges (O'Cofaigh *et al.*, 2001).

Drumlins and fluted terrain on both adjacent peninsulas demonstrate that the convergent ice flow can be traced up-ice to regional dispersal centres (Henderson, 1972; Catto, 1998; Catto and Taylor, 1998).

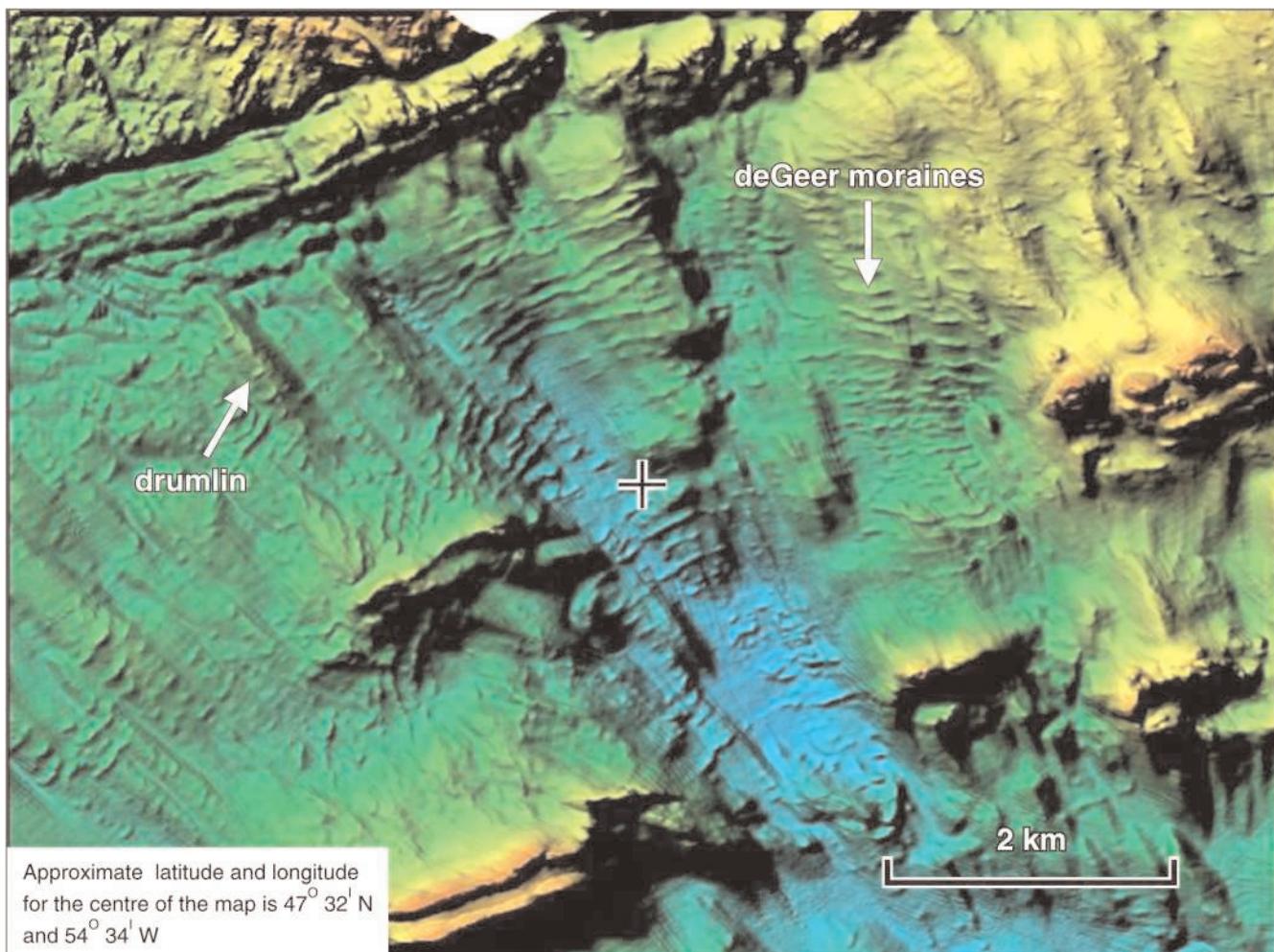


Figure 9. Multibeam shaded-relief image of a field of ridges that have been interpreted as deGeer moraines, from western Placentia Bay. These ridges are transverse to drumlins in this area and are commonly found superimposed on their surfaces. They appear to follow bathymetric contours within the bay. In seabed lows, these moraines are more subdued or absent likely because of post-depositional burial by Holocene marine sediments. Image is sun-illuminated from the northwest (315°) at an azimuth of 45° with a vertical exaggeration of 10 times and horizontal resolution of 5 m. See Figure 4 for location.

The deGeer moraines along the western side of Placentia Bay were likely deposited parallel to the ice front and record the north-northeastward retreat of a tidewater ice margin that became grounded in shallow water. In contrast, the hummocky terrain on the east side of the bay is likely derived from stagnation of ice from the Avalon dispersal centre and may reflect a thinner, less active ice centre compared to the western side of the bay. Similar hummocky terrain can be traced onshore on the Avalon Peninsula (Catto and Taylor, 1998; Catto, 1998).

ONSHORE-OFFSHORE CORRELATIONS

The multibeam imagery displays the continuation of the strong southeastward and southwestward flows observed on the Burin and Avalon peninsulas, respectively, and demon-

strates that these flows did indeed converge along the central axis of Placentia Bay. Although the data do not unequivocally confirm the contemporaneity of these two flows, it is unlikely that each flow would veer down the bay without the adjacent flow to help steer it. Non-contemporaneous ice flows would typically show splaying in all directions as the ice flowed into deeper water, unhindered.

With the exception of crag-and-tail features, most of the landforms preserved on the seabed of Placentia Bay are depositional in origin. It may not be surprising, therefore, that evidence for the westward ice flows documented by Batterson *et al.* (2006) on the Burin Peninsula are not observed on the adjacent seabed, as these flows are solely recorded as erosional marks (striations) on bedrock and, to date, are not associated with depositional features on land.

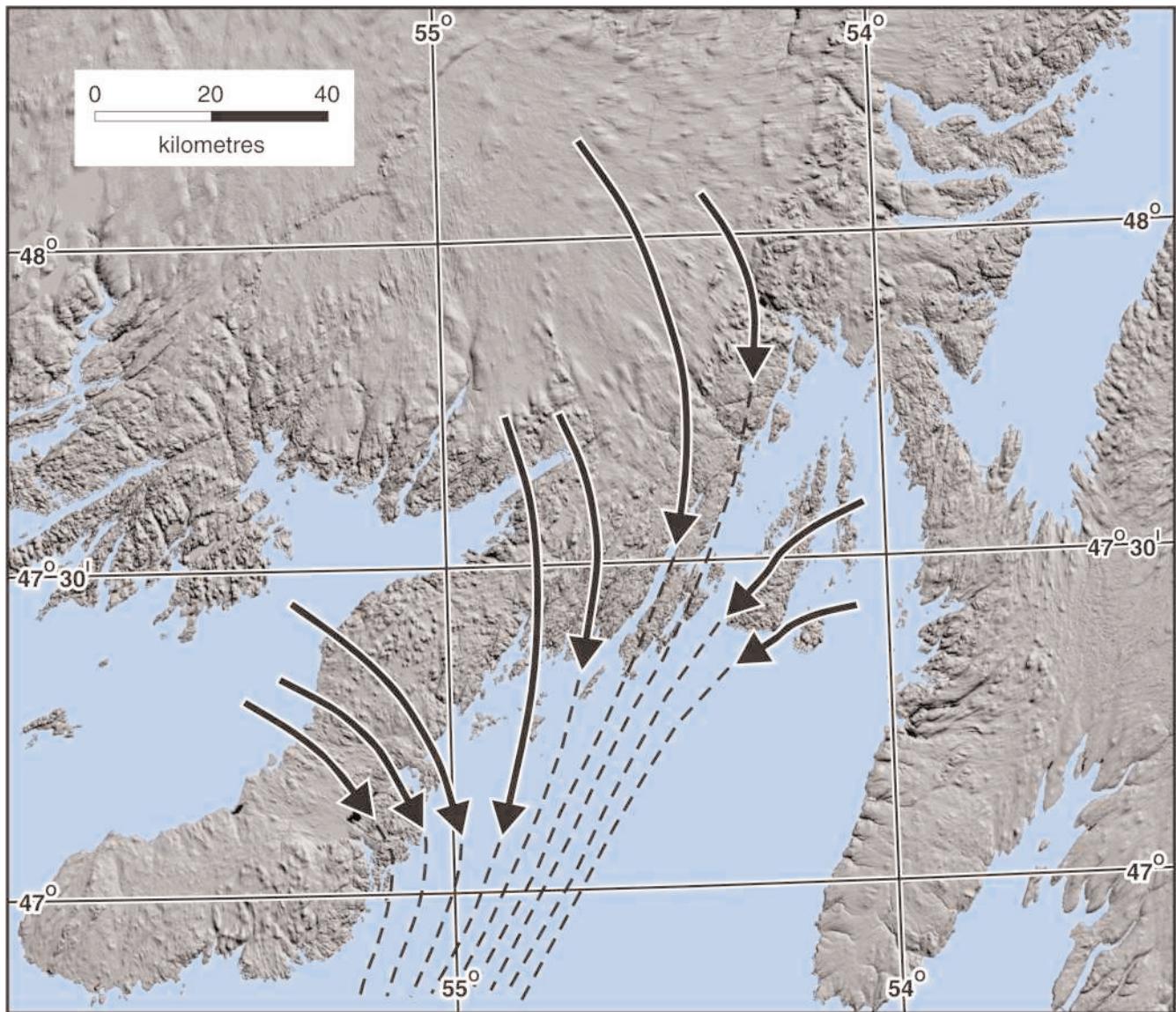


Figure 10. Pattern of ice flow interpreted from flow features on the seabed of Placentia Bay and from surrounding land (shown by solid arrows) showing a general trend of converging ice down the bay (shown by dashed lines).

These westward flows are younger than the regionally extensive southeastward flow that is preserved both onshore and offshore (Batterson *et al.*, 2006; Batterson and Taylor, *this volume*). It is reasonable to expect that some record of the westward ice flow should be observed superimposed on the older flow features or be represented through a modification of these features. Apparently neither is the case, even though this flow extended across the entire Burin Peninsula, necessitating ice thicknesses of at least 300 to 400 m.

The style of crosscutting features that might be expected from multiple ice flows in the offshore record is illustrated by the seabed record from southwestern Placentia Bay. Here, a fluting field is superimposed at right angles on top of subdued (modified?) drumlins. The drumlins are consid-

ered to be part of the regional southeastward flow, whereas the flutes represent a later coast-parallel, southwestward flow. Interestingly, the evidence for the later flow is quite spatially restricted with no sign of reworking or superimposition of landforms either on the seabed or on land, adjacent to this area. This suggests that basal conditions may have been quite variable even on small spatial scales and that clear evidence for the later flow is not pervasive.

FUTURE WORK

Future work includes examination of marine piston cores collected during CCGS Hudson cruise #2006-039. It is expected that these cores will generate more data on stratig-

raphy and chronology of ice-flow events that will help constrain the glacial history of the surveyed area. Additional chronological constraints may come from boulders from the Burin Peninsula that are currently being dated using cosmogenic exposure techniques (at Dalhousie University). These boulders all came from the Terrenceville area in the northern part of the Burin Peninsula and are expected to provide ages for the deglaciation in this region.

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