*Current Research (2010) Newfoundland and Labrador Department of Natural Resources*
*Geological Survey, Report 10-1, pages 143-157*

# ICE STREAMING IN THE NEWFOUNDLAND ICE CAP: IMPLICATIONS FOR THE RECONSTRUCTION OF ICE FLOW AND DRIFT PROSPECTING

P. Blundon, T. Bell and M. Batterson[1]
Department of Geography, Memorial University, St. John's, NL, A1B 3X5
[1]Geological Survey, Newfoundland and Labrador Department of Natural Resources,
St. John's, NL, A1B 4J6

## ABSTRACT

*A recent conceptual model of the late Wisconsinan Atlantic Canadian ice complex proposed that ice streams played a significant role in the deglaciation of the region. Within the Newfoundland portion of the ice complex, numerous topographically controlled ice streams were depicted; however, this model remains conceptual and up until recently there were few empirical tests to support this proposal.*

*This study uses a multi-scale mapping approach to explore the potential for ice streaming in the Newfoundland Ice Cap. Initially, seven potential ice-stream signatures were identified and the geomorphology of their beds characterized. A case study of the Exploits Ice Stream is presented to confirm ice-stream operation and to highlight the detailed characteristic geomorphology of late Wisconsinan ice streaming in the Newfoundland Ice Cap. This work has implications on how ice-flow histories are reconstructed in the Newfoundland Ice Cap, highlighting the need to incorporate new evidence of ice streaming and possibly re-evaluate previous reconstructions of ice flow. Because drift prospecting relies heavily on ice-flow reconstructions to trace indicators of economic mineralization, any re-assessment of ice-flow histories requires further re-evaluation of traditional approaches to drift prospecting.*

## INTRODUCTION

Drift prospecting is based on the idea that indicators of (economic) mineralization can be traced in glacial deposits back to their source and therefore relies heavily on ice-sheet models as the basis for the reconstruction of ice-flow history (Klassen, 2001). Ice-sheet research, over the last several decades, has led to the realization that ice sheets are highly dynamic, where ice streams drive most of this dynamic behaviour (Boulton and Clark, 1990; Kleman and Hattestrand, 1999; De Angelis and Kleman, 2005, 2007). For example, recent reconstructions of the former Laurentide Ice Sheet (LIS) incorporated ice streams along the northwestern (Stokes *et al.*, 2009), northeastern (De Angelis and Kleman, 2007), southern (Patterson, 1998), southwestern (Evans *et al.*, 2008), and southeastern (Shaw *et al.*, 2006) margins. The reconstruction of the southeastern margin however, was largely conceptual, with ice-stream locations heavily reliant on the assumption that continental-shelf troughs were occupied by high velocity ice.

This study examines the geomorphic evidence for ice streaming in the Newfoundland Ice Cap (NIC) through interpretation of glacial landforms using aerial photographs, Shuttle Radar Topography Mission (SRTM) digital-elevation data and satellite imagery. The study describes the geomorphology of several potential ice-stream signatures, using a detailed study of the Exploits Ice Stream to highlight the characteristic geomorphology of late Wisconsinan ice streaming in the NIC. This work has broader implications for reconstructing ice-sheet history and drift prospecting in the NIC.

## ICE STREAMS

Ice streams can be thought of as tributaries draining large portions of an ice-sheet interior. For example, contemporary ice streams are responsible for up to 90% of ice and sediment discharge from the Antarctic Ice Sheet (Bentley, 1987; Bamber *et al.*, 2000). As a result of this large flux, their occurrence and stability are critical for controlling the

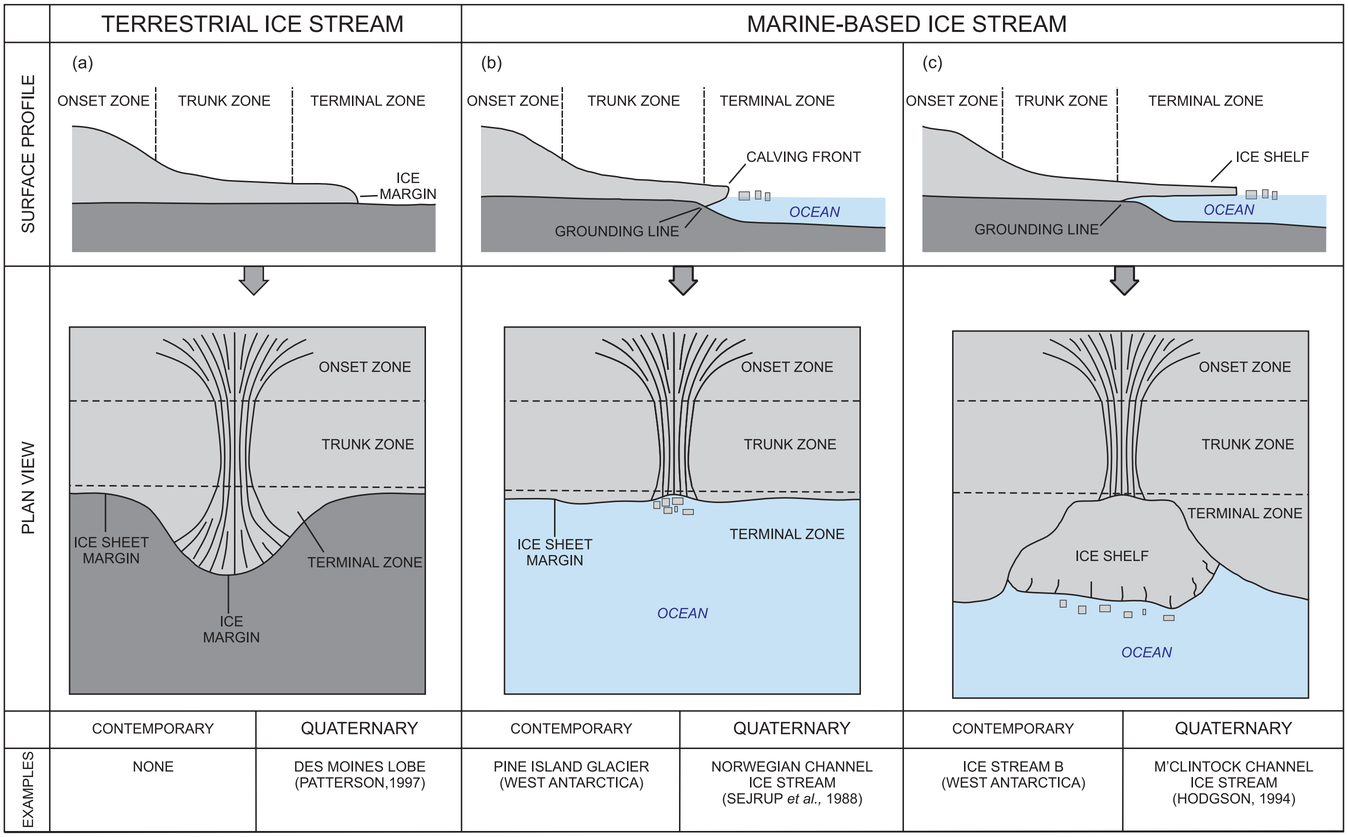


**Figure 1.** *Conceptual models of terrestrial and marine-based ice streams (after Stokes and Clark 1999, 2001). Ice streams can be subdivided into a number of distinct zones that reflect changes in ice-flow dynamics. These include the onset zone where slower moving ice from a wide catchment area is directed into the trunk zone where it achieves its maximum velocity. The ice stream then ends in the terminal zone. For terrestrial ice streams this occurs as a terminal lobe, whereas for marine-based ice steams, ice terminates either along a calving margin or onto an ice shelf.*

dynamic behaviour of ice sheets including the locations of drainage basins and ice divides (Stokes and Clark, 1999; Bennett, 2003). Stokes and Clark (1999) defined ice streams as areas, within an ice sheet, that flow much faster than surrounding ice. They divided ice streams into two distinct categories; one for topographic ice streams, where flow is constrained by variations in topography, such as troughs, and the other for pure ice streams that are unconstrained and bordered solely by slower moving or stagnant ice. It is highly unlikely, however, that a single ice stream exclusively fits one of these categories. For example, ice streams in the LIS ranged from pure ice streams, such as the Dubawnt Lake Ice Stream (Nunavut; Stokes and Clark, 2003) and Maskawa Ice Stream (Saskatchewan; Ross *et al.*, 2009), to those with some degree of topographic control, whether as pronounced as deep shelf troughs such as the M'Clintock Channel Ice Stream (Clark and Stokes, 2001), or as subtle variations in landscape relief (southern LIS; Patterson (1998) and Jennings (2006)).

Ice streams are subdivided into a number of distinct zones that reflect changes in ice dynamics (Figure 1). The onset zone (Figure 1) is marked by a transition from cold-based or slower moving ice in a broad catchment to warm-based or faster moving ice in the main trunk zone. The onset zone ranges from tens to several-hundred-kilometres wide, and is marked by strongly convergent lineations, including drumlins, megaflutes and crag-and-tail hills, and in some cases, ribbed moraine (*e.g.*, Transition Bay Ice Stream; Dyke and Morris, 1988). Up-ice from the onset zone, cold-based conditions can preserve relict non-glacial or preglacial landscapes that appear highly discordant with those of the main ice stream (De Angelis and Kleman, 2008). The initiation of ice streaming in the onset zone probably results from basal ice conditions where either low shear stresses and high pore-water pressure promote basal sliding, or subglacial sediment deformation is prevalent (Klassen, 2001; De Angelis and Kleman, 2007, 2008).

The trunk zone (Figure 1) of ice streams is characteristically narrower than the onset zone and may reach tens to greater than a hundred kilometres in width (*e.g.*, Dubawnt Lake Ice Stream; Stokes and Clark, 2003). Flow-directional landforms typically increase in elongation downstream and toward the central trunk axis, mimicking the velocity field of contemporary ice streams (*e.g.*, Stokes and Clark, 2003; De Angelis and Kleman, 2005, 2007; Dyke, 2008). Landforms display a transition from elongate drumlins and crag-and-tail features to mega-scale glacial lineations, with elongation ratios of up to 41:1 (Dubawnt Lake Ice Stream; Stokes and Clark, 2003). Lateral boundaries along the trunk are commonly abrupt and are marked by shear marginal moraines that record the shear zone between fast and slow flows (Stokes and Clark, 2002). Dyke and Morris (1988) mapped shear moraines along a 68-km-long margin of the Transition Bay Ice Stream.

Ice streams end in a terminal zone that form a lobe in terrestrial settings (*e.g.*, Patterson, 1998; Stokes and Clark, 2003; Evans *et al.*, 2008) and a calving margin or ice shelf in a marine environment (*e.g.*, Clark and Stokes, 2001; De Angelis and Kleman, 2005). Terrestrially-terminating ice streams have no way of rapidly removing ice, resulting in a splayed terminal lobe that acts to lower surface elevations of the ice sheet and enhance fast flow (Figure 1; Stokes and Clark, 2001). Landforms in this zone are typically divergent and display a decrease in elongation ratios toward the terminus (*e.g.*, Stokes and Clark, 2003; Evans *et al.*, 2008). These contrast with marine-based ice streams that evacuate ice rapidly along a calving margin or ice shelf (Figure 1; Stokes and Clark, 2001). Submarine accumulations of ice-contact sediment characterize deposition at the grounding line of marine-based ice streams (*e.g.*, Andrews and MacLean, 2003; Stokes *et al.*, 2005).

In the past, ice streams were primarily identified in ice sheets in areas that coincided with linear depressions (*e.g.*, shelf troughs or major valley systems) in the subglacial topography, and to a lesser extent on subglacial geomorphology (*e.g.*, Denton and Hughes, 1981; Hughes, 1998). More recently, there has been a greater emphasis placed on characteristic landform assemblages or land-systems associated with ice streams. For example, Stokes and Clark (1999) described a set of diagnostic criteria, largely based on geomorphology, to aid in the identification of ice streams. Individually, none of these criteria can be used to confirm ice-stream activity, however the occurrence of several would provide strong support (Stokes and Clark, 1999). The criteria reflect the fundamental characteristics of contemporary ice streams and include:

i) Landform assemblages displaying characteristic convergent flow patterns and footprint dimensions (>20 km wide x 150 km long);
ii) Highly attenuated bedforms (length:width >10:1);
iii) Abrupt lateral margins and shear margin moraines;
iv) Boothia-type erratic dispersal trains (*see* below);
v) Pervasive deformation till; and
vi) Trough mouth fan at marine terminus.

## ICE STREAMS AND DRIFT PROSPECTING

Ice streams played a vital role in ice flow and mass balance of Late Quaternary ice sheets and likely served as important agents of glacial dispersal and till deposition. They are linked to regional variations in till composition and well-defined plumes of far-travelled debris (Klassen, 2001). Therefore, drift prospecting in glaciated terrain should incorporate ice-stream behaviour in the interpretation of dispersal patterns and ice-flow history.

Given appropriate source rock distribution, ice streams generate a diagnostic style of dispersal train known as the Boothia type, which is produced by plug-like ice flow and has abrupt lateral margins (*e.g.*, Dyke and Morris, 1988). In Boothia-type dispersal-trains debris spreads down-ice from a small part of a large source area and travels greater distances than in adjacent areas (Figure 2; Dyke and Morris, 1988). They contrast with Dubawnt-type dispersal trains that spread debris down-ice from a relatively restricted source area and form under normal sustained sheet flow (Figure 2; Dyke and Morris, 1988).

The effects of ice streaming were identified in the till-geochemical record of the LIS (*e.g.*, Dyke and Morris, 1988; Dyke, 2008; Ross *et al.*, 2009). On southeastern Prince of Wales Island, a sharp-sided, plug-shaped plume of limestone–dolomite-rich till, crosscuts much darker, red clastic sedimentary rock that underlie the island's east side. Dyke and Morris (1988) concluded that the plume-shaped dispersal pattern and abrupt margins suggested transportation by an ice stream. The Steensby Inlet Ice Stream transported carbonate-derived till across granitic terrain on northern Baffin Island, where carbonate content was measured at >50%, 32 km down flow of the contact (Dyke, 2008). In both cases, the dispersal plumes display a linear decrease in indicator rock types down ice. This contrasts with the exponential decline that is more typical of sheet-flow dispersal, in which half distances – the distance over which the target mineral decreases concentration by 50% – are over several kilometres (Klassen, 2001; Dyke, 2008). Also, ice streams on the Canadian prairies are linked to the production of anomalously long till-dispersal trains (Ross *et al.*, 2009). Although the geomorphic evidence of the Maskwa Ice Stream is discontinuous, till-geochemistry data indicate aligned composite dispersal trains that extend for over 350 km across Saskatchewan. The dispersal trains display sharp lateral boundaries and are interpreted as ice-stream margins (Ross *et al.*, 2009).

## ICE STREAMS IN THE NEWFOUNDLAND ICE CAP

The NIC formed an independent ice cap over New-

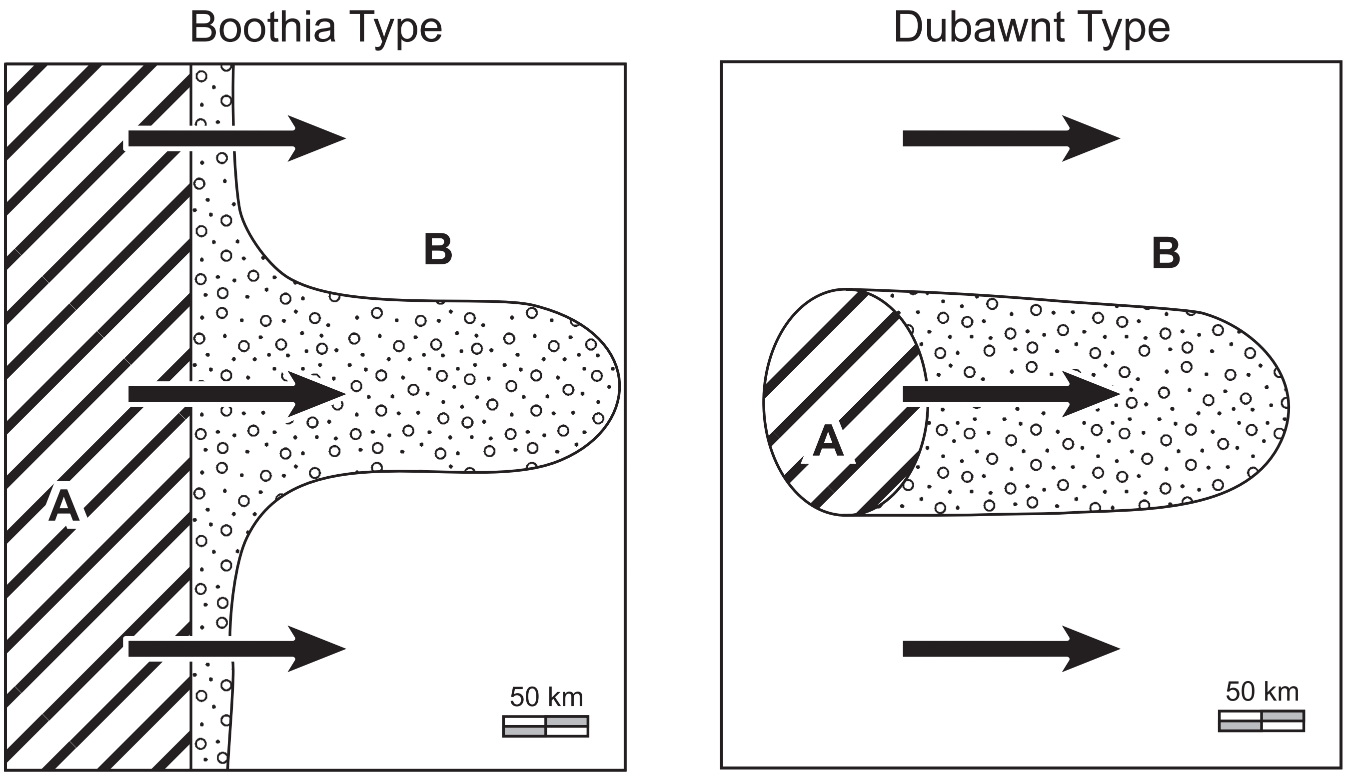


**Figure 2.** *Simplified diagram of Boothia- and Dubawnt-style dispersal trains (after Dyke and Morris, 1988). Boothia-style dispersal trains are believed to be formed by ice streams whereas Dubawnt-style trains form under sustained regional flow. A and B are two distinctly different rock types. Arrows represent ice-flow direction and dots represent dispersal of debris from A.*

foundland during the last glaciation, becoming confluent with the LIS along its northern and western margins. It has been proposed that ice streams drained large portions of Atlantic Canada and more specifically the NIC (*e.g.*, Denton and Hughes, 1981; Hughes, 1998; Shaw *et al.*, 2006). These ice streams were positioned based on the assumption that troughs across the continental shelf were occupied by high-velocity ice. The most recent model by Shaw *et al.* (2006) was guided by a flow-line analysis of the Greenland Ice Sheet that revealed ice divides converging at triple points. Using this observation and the initial assumption that troughs were occupied by high-velocity ice, ice streams and flow divides were positioned accordingly (Figure 3).

Shaw *et al.* (2006) placed the last glacial maximum (LGM) ice extent at the continental shelf edge and identified a major ice stream flowing through the Laurentian Channel (Figures 3 and 4). The location of this ice stream suggested a first-order ice divide that extended south and southeast across Newfoundland, along the axis of the Long Range Mountains, east through central Newfoundland and across the Avalon Peninsula (Figure 3). Second-order divides were located on the southwest and northeast coasts. One such divide along the axis of the Cape Freels peninsula separated ice stream flow in Notre Dame and Trinity basins (Figures 3 and 4). The conceptual model of Shaw *et al.* (2006) suggested that early deglaciation proceeded by calving along deep channel margins until 12 ka BP, when the NIC was at, or near, the modern coast where it disintegrated mostly through ablation on land.

## GEOMORPHOLOGICAL FOOTPRINT OF NEWFOUNDLAND ICE STREAMS

In an effort to gain a better understanding of ice-stream locations and geomorphology in the NIC, this study employed a two-scale mapping approach. Initially a broad-scale assessment was used to locate and characterize flow-sets associated with potential ice streams. Flow-sets are groups of similar landforms that have spatially distinctive and coherent patterns (Clark, 1999). The Exploits flow-set was then selected for a more detailed assessment of the geomorphic footprint to highlight the characteristics of ice streaming within the NIC.

Mapping of ice-stream flow-sets was accomplished by visual exploration of the database of glacial landforms maintained by the Geological Survey of Newfoundland and Labrador. It includes drumlins, flutes, crag-and-tail hills, and ribbed moraine. These landforms were mostly mapped

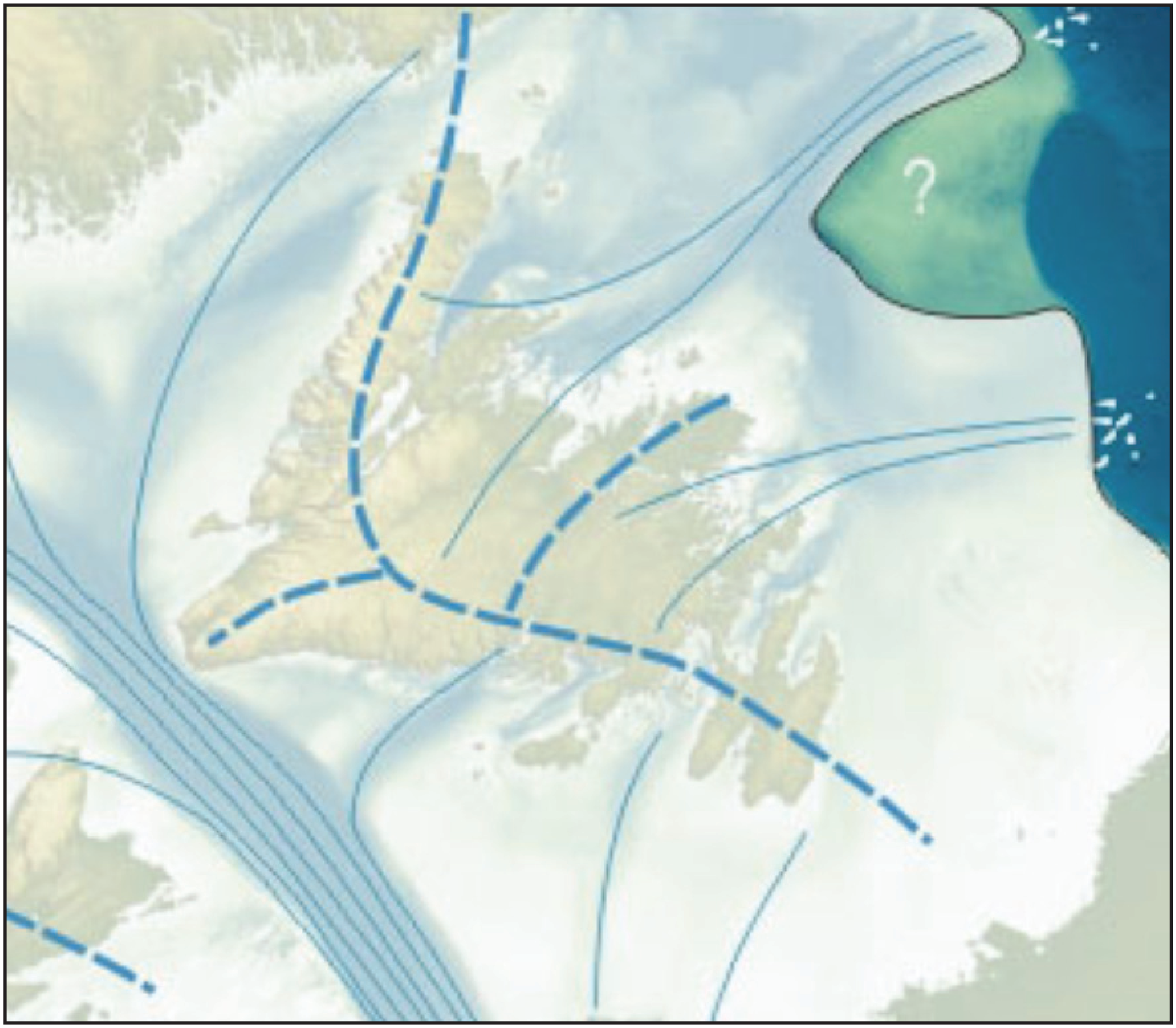


**Figure 3.** *Model of last glacial maximum ice extent for Newfoundland (from Shaw* et al.*, 2006). Generalized flow lines are represented by thin blue lines and thick dashed lines represent major ice divides. Positions of ice streams were interpreted based on the assumption that marine troughs were occupied by high-velocity ice.*

based on interpretation of the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) that has a horizontal resolution of 3 arc seconds (90 m) and absolute vertical accuracy of 16 m. Groups of similar landforms were then sorted into flow-sets following the procedure outlined by Clark (1997, 1999) and Kleman and Borgstrom (1996). Specific attention was focused on the degree of convergence, density, parallelism, and crosscutting relationships of landforms. The SRTM mapping was supplemented with visual inspection of satellite imagery available on Google Earth.

An Island-wide search of the database led to the identification of seven flow-sets that were selected based on their diagnostic landform assemblages, mainly convergent ice-directional landform patterns and attenuated bedforms (Figures 4 and 5). The flow-sets consisted of both onset and trunk zones that extended to the modern coast. Flow-set lengths were typically short, ranging from 30 to 76 km and displayed varying degrees of convergence with down-ice widths typically decreasing anywhere from 33 to 64% from the onset to the trunk (Table 1).

Across Newfoundland there is a notable relationship between topography and flow-set location. Typically, regional slopes dip toward the coast, with the heads of all flow-set locations corresponding with regional topographic highs (Figure 6). Along the south coast, mapped flow-sets

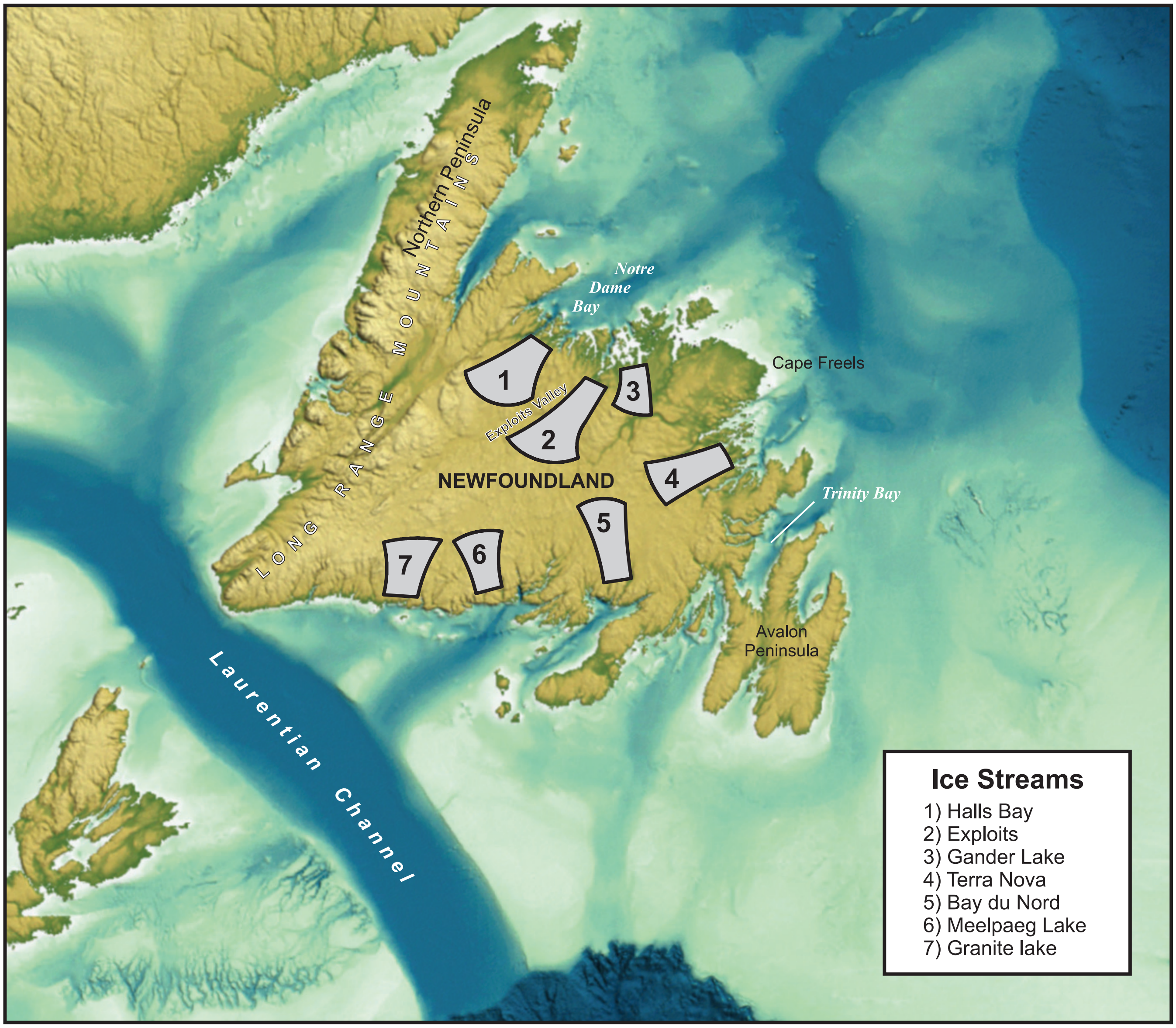


**Figure 4.** *Map of Newfoundland and offshore areas with place names mentioned in text including outlines of the 7 potential ice-stream signatures identified in this study.*

typically terminate at higher elevations (125–250 m asl) than those along the north coast (up to 80 m asl; Figure 6). This is because along the south coast, uplands extend to the coast and are dissected by numerous fjords, whereas in the north and east coasts, coastal lowlands are more common. The relationship between flow-set location and topographic cross-profile is more variable with all but the Terra Nova flow-set displaying some lateral correspondence with topography (Figure 6). The Exploits and Granite Lake flow-sets are positioned relative to large valleys, whereas others coincide with relatively flat (*e.g.*, Gander Lake) or slightly concave-upward terrain (*e.g.*, Meelpaeg Lake).

The flow-sets are also characterized by variable surficial geology. Generally, the surficial sediment thins toward the coast with inland areas having thick overburden, primarily till blanket and hummocky terrain. Down-flow, till veneer is more common whereas both concealed and exposed bedrock dominate at the coast. Depositional landforms are commonly found inland in areas of thicker sediment cover, whereas crag-and-tail hills are more common in areas of thinner sediment at the coast and on uplands. Flow-sets along the south coast are generally characterized by thinner sediment cover compared to those along the northeast coast. Large fields of ribbed moraine are present at the heads of several of the flow-sets (Figure 7).

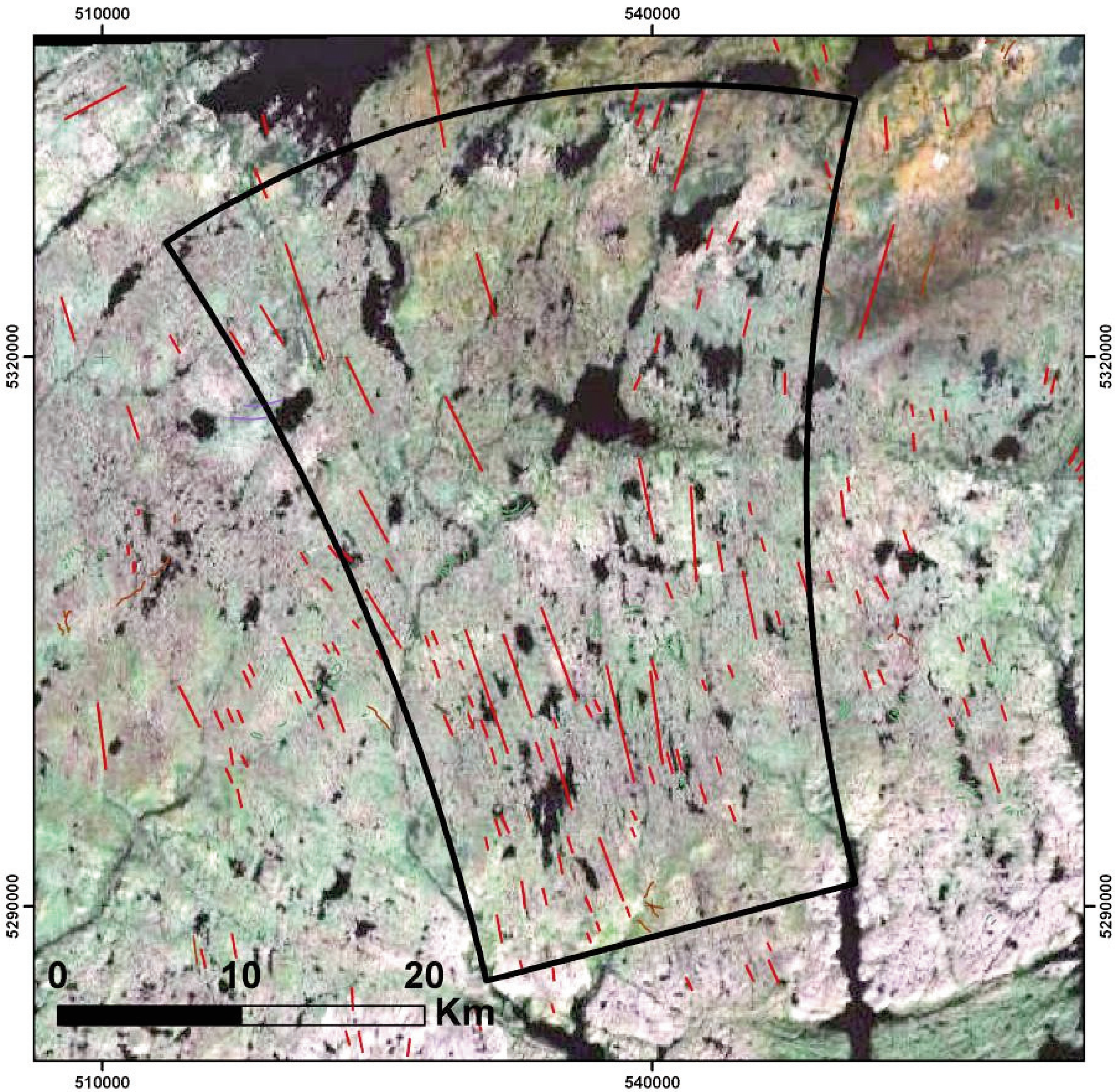


**Figure 5.** *The Meelpaeg Lake flow-set as seen on satellite imagery available on Google Earth. Note the distinct convergence and high density of flow-parallel landforms, represented by red lines.*

The geology underlying mapped flow-sets varies significantly between the north and south coasts of Newfoundland. Along the north coast, flow-sets are typically located on siliclastic sedimentary rocks amidst minor occurrences of volcanic and granitic rocks – the one exception is the Halls Bay flow-set. In the case of the Gander Lake and Exploits flow-sets, the sedimentary rocks are highly folded and strike toward the north and northeast. It is possible that large-scale folding with strike occurring parallel to flow could act to redirect ice and meltwater flow along the structural grain of the bedrock, facilitating fast flow. Along the south coast, flow-sets are located primarily on granitic bedrock with only minor occurrences of sedimentary rock. The exception is the Bay du Nord flow-set, which straddles siliclastic sedimentary rocks inland, and primarily granite rocks coastward.

**Table 1.** During initial broad-scale mapping, groups of similar landforms were sorted into spatially coherent and distinctive patterns called flow-sets. In total seven flow-sets, were identified and characterized. Dimensions are given as overall length x width in the trunk. Convergence is measured as % decrease in width from onset zone to trunk. Tb= Till Blanket, Tv= Till Veneer, Th= Hummocky Terrain, Tr= Ribbed Moraine, Rc= Concealed Bedrock, R=exposed Bedrock.

| Ice Stream Name | Dimensions (km) | Degree of Convergence | Attenuated Bedforms | Bedrock Geology | Surficial Geology |
|---|---|---|---|---|---|
| 1. Halls Bay | 60 x 20 | 64 | Drumlins, Megaflutes and crag-and-tail hills. Max length 3.5 km | Granitic and volcanic rocks | Tv and Tb inland, Rc along coast |
| 2. Exploits | 75 x 25 | 54 | Drumlins, megaflutes and crag-and-tail hills. Max length 5 km | Sedimentary rocks with minor volcanic and granitic rocks | Tb, Th and Tr inland Tv and Rc along coast |
| 3. Gander Lake | 30 x 20 | 33 | Drumlins, megaflutes and crag-and-tail hills | Sedimentary rocks | Tb, Tv, Tr inland. Tv and Rc along coast |
| 4. Terra Nova | 60 x 20 | 45 | Megaflutes and crag-and-tail hills. Max length 5 km | Both sedimentary and granitic rocks | Tb, Th and Tr inland. Rc and Tv along coast |
| 5. Bay Du Nord | 66 x 23 | 36 | Drumlins, megaflutes and crag-and-tail hills. Max length 6 km | Sedimentary rocks inland transitioning to granites near the coast | Tb, Tv, Th, Tr inland. Rc and R along coast |
| 6. Meelpaeg Lake | 47 x 21 | 46 | Megaflutes and crag-and-tail hills. Max length 6 km | Granite with minor occurrences of sedimentary rocks | Tv and Th inland. Rc and R along coast |
| 7. Granite Lake | 46 x 26 | 42 | Metaflutes and crag-and-tail hills. Max length 5 km | Granite with minor occurrences of sedimentary rocks | Tv and Th, inland. Rc and R along coast |

## EXPLOITS ICE STREAM

A case study of the Exploits flow-set is presented to provide a more detailed understanding of the geomorphic footprint of former ice streams in the NIC. This area was selected based on the identification of a particularly well-defined flow-set in the Exploits Valley of north-central Newfoundland. This area was also identified by Liverman *et al.* (2006) as a possible location for ice streaming based on their observations of highly attenuated landforms observed on SRTM DEMs.

The Exploits flow-set was stereoscopically mapped using 1:50 000 aerial photographs, and mapped separately using SRTM DEMs (Figure 8; Blundon *et al.,* 2009). Landforms were digitized along ridge crests and stored in a Geographic Information System (GIS). The following parameters were measured from the digital records: length, orientation, width, and elongation ratio (length/width). Landform mapping was supplemented by bedrock geology and surficial geology maps (Colman-Sadd and Crisby-Whittle, 2002; Liverman and Taylor, 1990).

The Exploits flow-set is largely contained within the lowlands between the Mount Peyton and Hodges Hill intrusive suites (Figure 9a). These lowlands are dominated by siliclastic sedimentary rocks of the Botwood Group. The flow-set has a length of 75 km from the onset to the end of the mapped trunk near the coast and displays a high degree of convergence, narrowing from 55 km near the head to 25 km in the trunk. Boundaries of this flow-set were drawn on the basis of crosscutting landform relationships, landform density, and differences in morphometry. Lineations show a high degree of convergence in the up-ice end with an average azimuth of 53° in the southwest and 19° in the southeast. Lineations in the flow-set were considerably longer (mean = 1730 m, maximum = 5060 m), and had elongation ratios much higher (mean = 5.4, maximum = 18.27) than adjacent older flow signatures (mean and maximum length of 1309 and 2913 m, and mean and maximum elongation ratios of

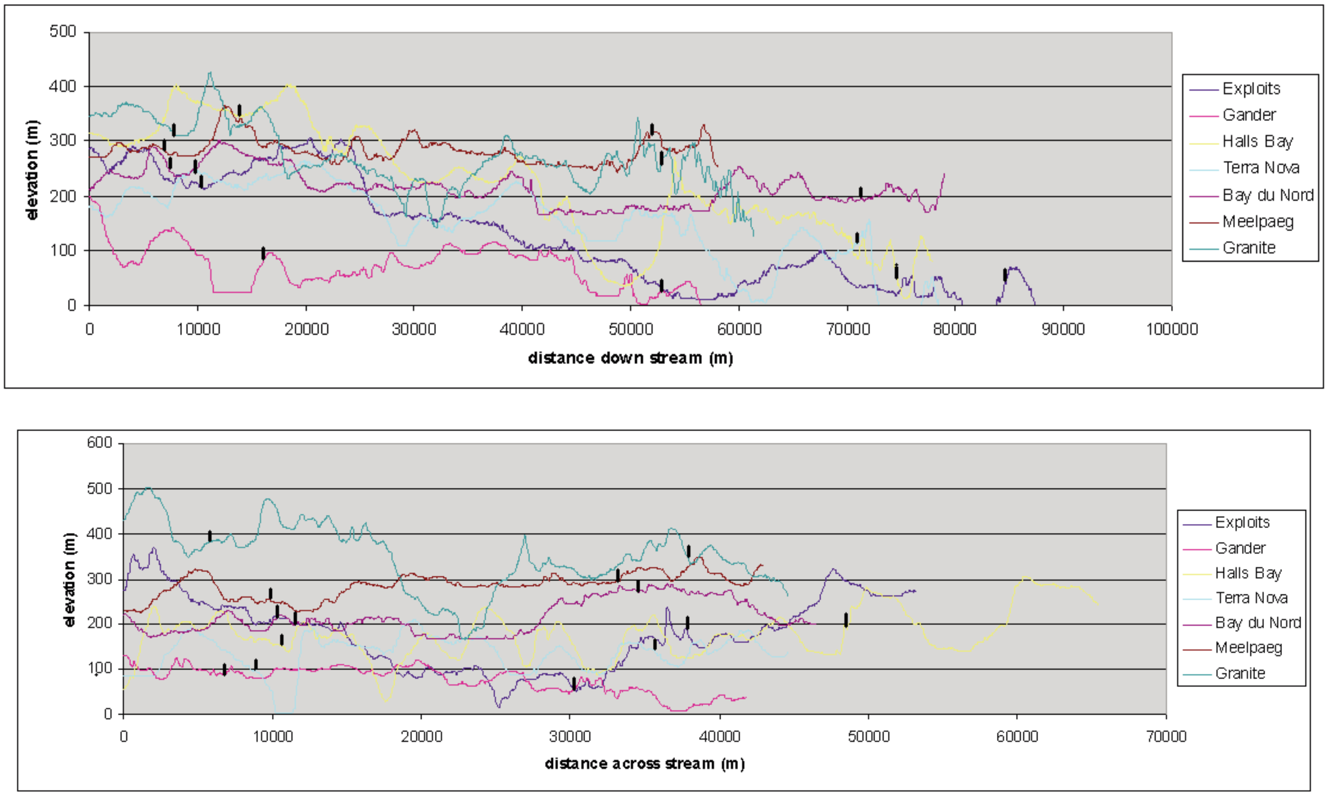


**Figure 6.** *Down- and across-stream topographic profiles for identified flow-sets. Black ticks indicate flow-set margins. Down-stream profiles typically begin near regional topographic highs whereas across-stream flow-set margins show varying degrees of correspondence with topographic highs.*

4.1 and 7.8). Landform densities inside the flow-set were 0.11 landforms per km$^2$, roughly double that outside.

The distribution and morphology of landforms varied within the Exploits flow-set. Drumlins (61%) and ribbed moraine (62%) were more common in the onset zone, whereas megaflutes (56%) and crag-and-tail hills (54%) were slightly more common in the trunk zone. Systematic mapping of landform morphology revealed a marked increase in the mean elongation of landforms downstream and toward the centre line of the flow-set (Figure 9b). The most elongate landforms occur along the central axis of the flow-set and have lengths up to 5060 m and elongation ratios exceeding 18:1. Elongation ratios and length decrease toward the coast with decreasing sediment cover (Figure 9b).

Given the highly variable nature of the flow-set bed, the distribution of landforms varies across surficial and geological units. Drumlins, megaflutes, and ribbed moraine were most commonly mapped (80–90%) in areas of relatively thick till (till blanket, ribbed moraine, and hummocky terrain), with only small proportions of each being found on other surficial units (Figure 9c). Crag-and-tail hills were most common (48%) on thick till but were also documented in thin till (24%) and concealed bedrock (27%). Few landforms were identified over areas of exposed bedrock or non-glacigenic deposits.

## DISCUSSION

### ICE STREAMING IN THE NEWFOUNDLAND ICE CAP

The operation of ice streams in the NIC is inferred from the occurrence of a characteristic landform assemblage proposed by Stokes and Clark (1999). For example, all of the flow-sets were initially identified on the basis of convergent flow-parallel landforms, which elsewhere in the former LIS were used as the primary evidence for ice streams (*e.g.*, Dyke and Morris, 1988; Clark and Stokes, 2001, 2003; De Angelis and Kleman, 2008). Thus, identification of convergent flow patterns can be used as evidence to support the concept of ice streaming in the NIC.

There are variations in the degree of convergence of Newfoundland ice streams with some (*e.g.*, Exploits, Halls Bay and Meelpaeg) displaying higher levels of convergence

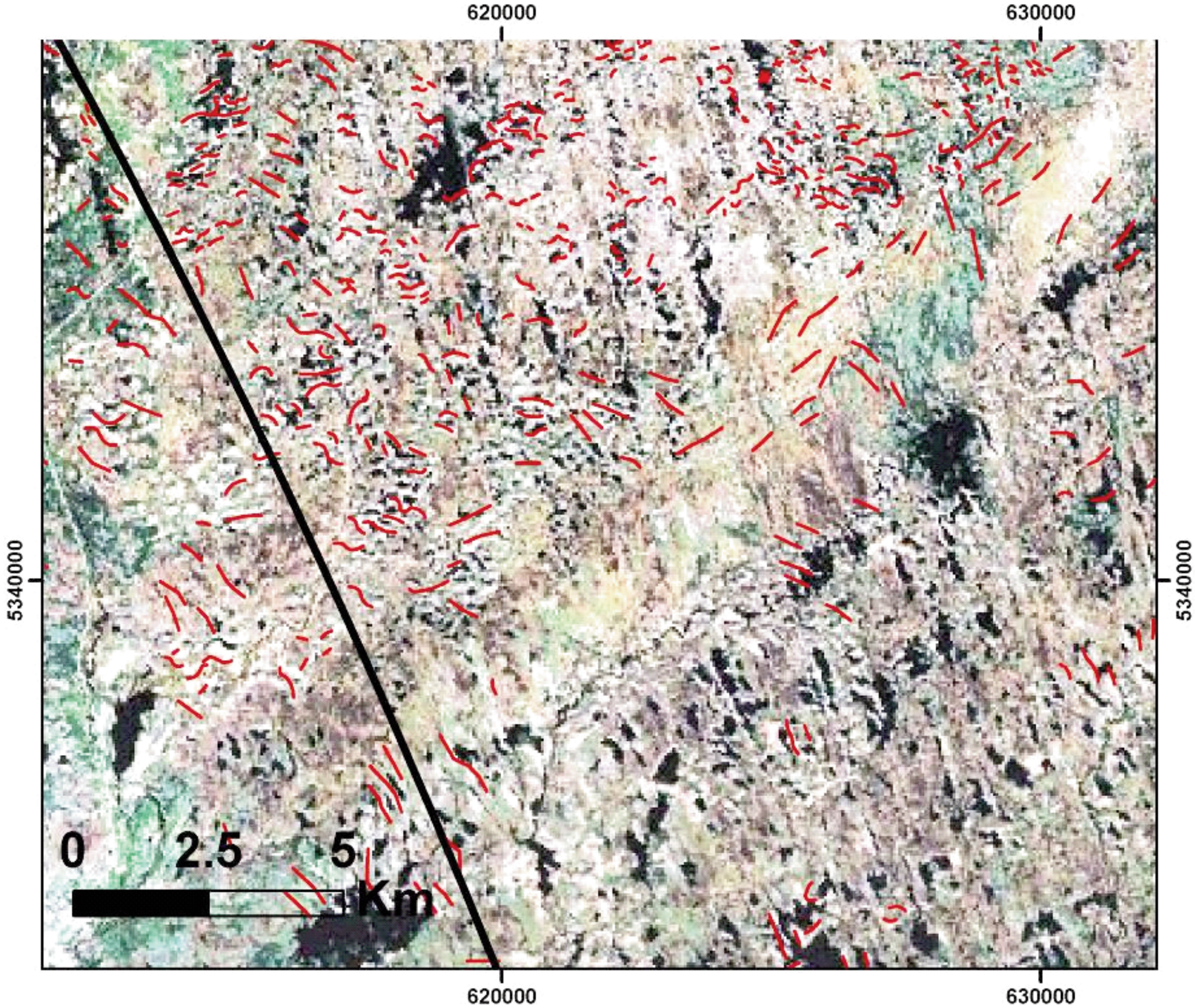


**Figure 7.** *Field of ribbed moraine located near the head of the Bay du Nord flow-set as seen on satellite imagery available on Google Earth. Ribbed moraine are represented by red lines.*

than others (*e.g.*, Terra Nova and Bay du Nord). It is possible that flow-sets displaying limited convergence could represent event swarms that are described as landform assemblages containing abundant flow traces but lacking aligned meltwater channels and the characteristic convergent shape of ice streams (Kleman *et al.*, 2006).

Stokes and Clark (1999) suggested that ice streams have dimensions of greater than 150 km long and 20 km wide. This limit was derived from observations of contemporary ice streams that drain Antarctica. In contrast, the NIC was a much smaller ice mass with a central ice divide and smaller catchments and consequently ice streams at the lower end of the size range are not unexpected (Table 1). Furthermore, several ice streams with dimensions smaller than those proposed by Stokes and Clark (1999) were described for the LIS (*e.g.*, Winsborrow *et al.*, 2004; Stokes *et al.*, 2005; DeAngelis and Kleman, 2005, 2007).

The terminal zones of NIC ice streams were not identified in this mapping study. According to recent reconstructions, the NIC extended to the continental shelf edge (Shaw *et al.*, 2006) and consequently terrestrial-based ice streams identified here may have extended offshore. Recent multibeam mapping in Placentia Bay, Newfoundland, has identified the geomorphic footprint of a former ice stream on the seabed (Brushett *et al.*, 2006), which supports the possibility that NIC ice streams crossed the modern coastline and flowed some distance across the continental shelf. Surprisingly, there is limited geomorphic evidence for the Placentia

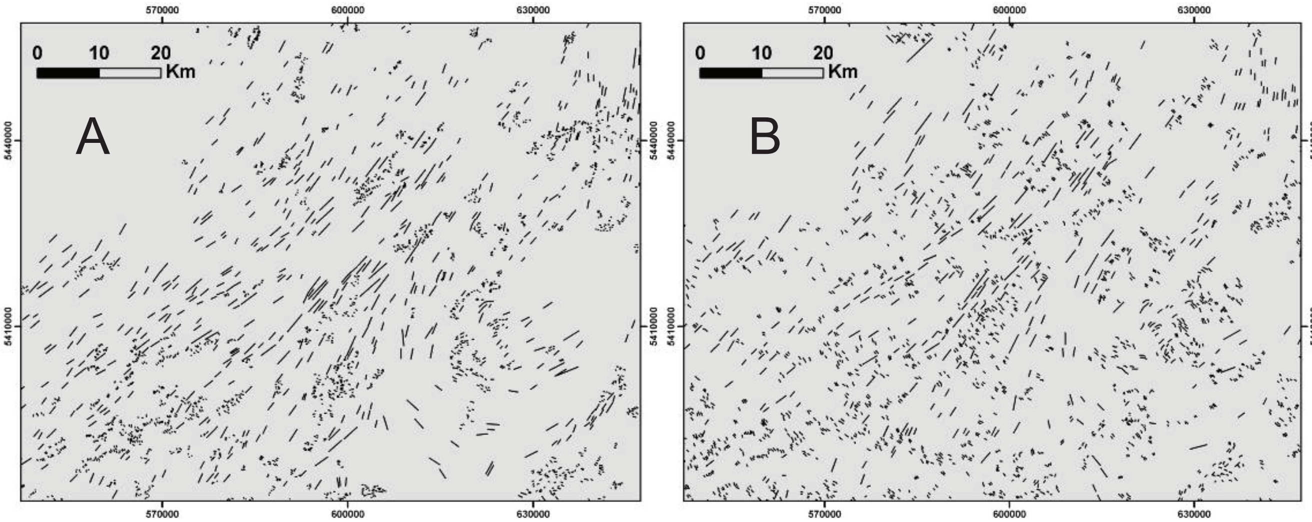


**Figure 8.** *Results of mapping glacial landforms from aerial photographs (A) and SRTM DEMs (B). Mapping from aerial photographs produced more detailed landform maps, particularly for small flow-parallel landforms making it more suitable for detailed landform mapping whereas SRTM DEMs are limited by their 90 m resolution and are more suited to reconnaissance-level mapping, as used during preliminary mapping for this study (Blundon* et al., *2009).*

Bay ice stream inland of the modern coast. Elsewhere in the LIS, marine-based ice streams have been located on the seabed of M'Clintock Channel (Clark and Stokes, 2001) and Lancaster Sound (De Angelis and Kleman, 2005).

Highly attenuated bedforms that display length:width ratios greater than 10:1 have been attributed to formation by fast-flowing ice (Clark, 1994; Stokes and Clark, 2002). Within the Exploits flow-set, the maximum elongation ratio of 18:1 suggests formation by fast-flowing ice. Also, the observed spatial patterns in elongation ratios downstream and toward the centre of the flow-set match expected ice velocity variations within ice-stream flow patterns (Figure 9). A similar pattern is observed within the Dubawnt Lake Ice Stream (Stokes and Clark, 2002, 2003). The occurrence of extensive fields of ribbed moraine in the onset zones of NIC ice streams is consistent with observations from the northeastern portion of the LIS, where former ice streams have been documented (Dyke and Morris, 1988; De Angelis and Kleman, 2008).

## IMPLICATIONS FOR RECONSTRUCTING ICE-FLOW HISTORY

The realization that ice streams operated in the NIC may require a re-evaluation of the landform record and revisions of local ice-flow history. In the Exploits Valley, initial interpretations suggested a single regional ice-flow event to the north and northeast that originated from an ice divide farther south between Middle Ridge and Meelpaeg Lake (Grant, 1974; Rogerson, 1982; Batterson and Taylor, 1998). In this study, the mapping of flow-sets characteristic of former ice-stream behaviour has led to the identification of a previously unrecognized ice-flow event, represented by the Exploits flow-set (Figure 9d). This flow-set is superimposed on the regionally pervasive flow-set, which may indicate that it is post LGM (*cf.,* Kleman and Borgstrom, 1996; Clark, 1999). Hence, the re-evaluation of previous ice-flow reconstructions within the NIC should be considered in light of new evidence of ice streaming.

Traditionally, LGM ice flow was interpreted to have spread radially from multiple ice-accumulation centres located on the Northern Peninsula, central Newfoundland and the Avalon Peninsula (*e.g.*, Grant, 1974; Rogerson, 1982). As deglaciation progressed, accumulation areas were thought to have become isolated from one another, leaving as many as 15 small, short-lived ice caps on the Island (Grant, 1974). Complex local ice-flow patterns have resulted from this glacial history (*e.g.*, Catto, 1998). The existence of ice streams throughout the NIC stands to explain some of this complexity, particularly immediately prior to or during early deglaciation. In this scenario, catchments would likely be much smaller than those proposed during the LGM, separating flow into individual ice-stream catchments rather than draining radially through specific deglacial ice centres. These would then be separated inland and laterally by inter-stream ridges comprising either frozen beds or significantly slower moving ice.

The location of many ice streams in the LIS appears to be related to areas of the ice sheet that are underlain by soft sediments (*e.g.*, Patterson, 1998; Clark and Stokes, 2001; De Angelis and Kleman, 2005, 2007). The flow-sets identified

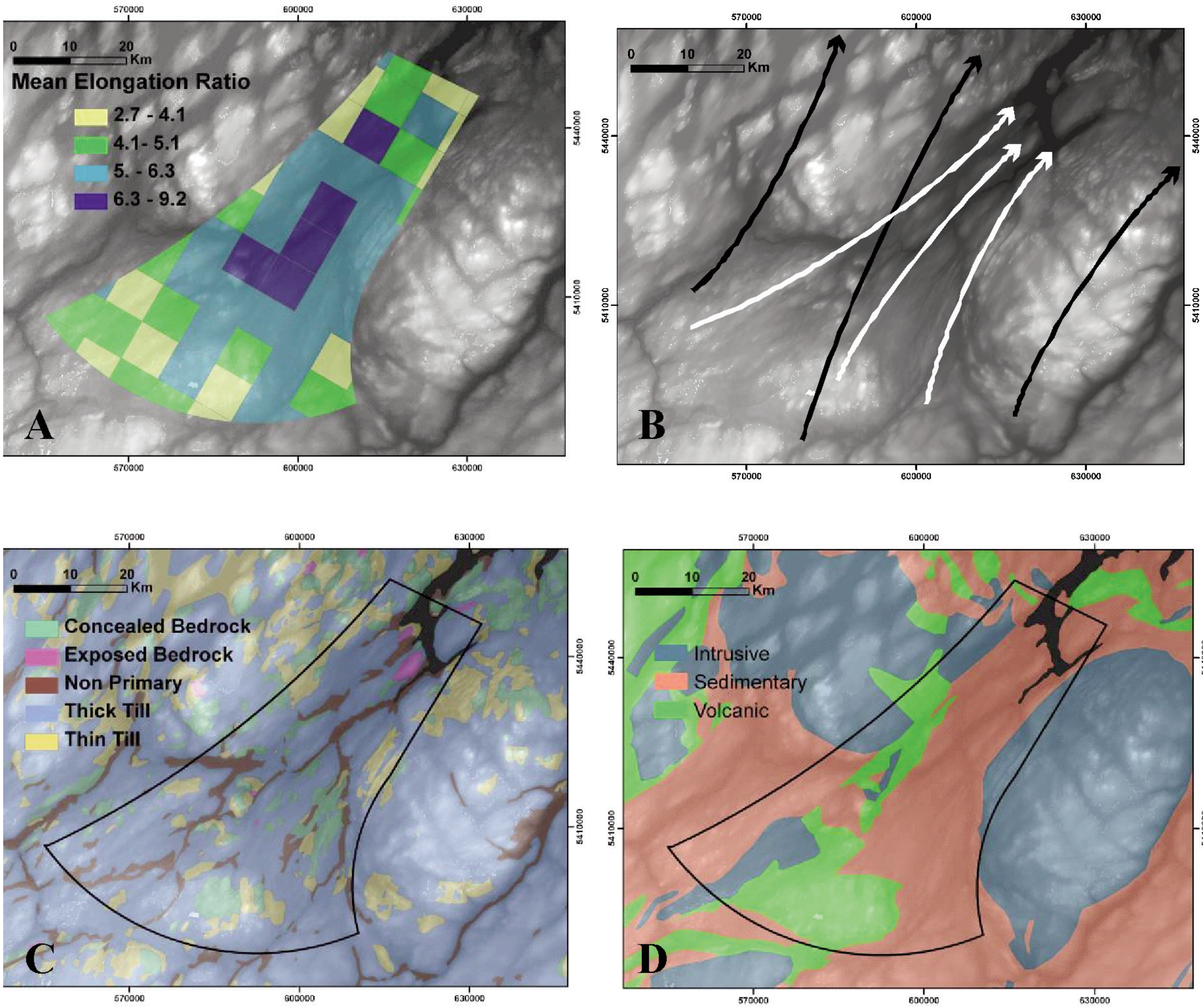


**Figure 9.** *A) Results of analysis of average elongation ratio based on 7.5 km grid. Results show a systematic increase in elongation ratio downstream and toward the centre of the flow-set, matching expected velocity fields within an ice stream. B) Simplified reconstruction of regional ice-flow events. Black lines represent a regional north to northeastward flow event and white lines represent a younger ice-streaming event. C) Simplified surficial geology map of the main study area overlain on SRTM DEM. D) Simplified bedrock geology map. The flow-set is underlain primarily by sedimentary rocks with minor occurrences of volcanic and granitic rocks at both its inland and lateral margins. Note the position of the flow-set between topographic highs created by intrusive granitic rocks (higher terrain indicated by lighter tones in underlying SRTM DEM).*

in the NIC, particularly on the south coast, are characterized by relatively thin sediment cover, whereas inland areas typically have greater sediment thickness. Subglacial deformation requires sufficient sediment thickness to impede drainage of subglacial meltwater allowing them to become saturated, facilitating fast flow through sediment deformation (Stokes and Clark, 2003). Thick till inland suggests that movement could have been initated by subglacial sediment deformation whereas thinner cover down-flow suggests that basal sliding would have been more important for sustaining fast flow downstream. This is consistent with observations by Stokes and Clark (2002, 2003) who reported ice steaming on hard bedrock of the Canadian Shield and Evans *et al.* (2008) who described ice streaming over relatively thin sediment cover, both of which suggest transport by basal sliding rather than sediment deformation.

## IMPLICATIONS FOR DRIFT PROSPECTING IN THE NEWFOUNDLAND ICE CAP

Drift prospecting relies heavily on regional reconstructions of ice-flow history to trace indicators of economic mineralization; thus any reassessment of ice dynamics necessitates a re-evaluation of the approach to drift prospecting. Traditionally, when interpreting geochemical data from Newfoundland, dispersal trains are considered to be short (generally <5 km), diffuse features compared to larger ribbon-like dispersal trains from continental ice sheets (Batterson and Liverman, 2000). Evidence for ice streaming in Newfoundland, which denotes high-velocity ice with the potential to carry sediment long distances, suggests that dispersal trains in Newfoundland may be longer than expected.

Glacial transport distances can be characterized based on their half-distances, which refers to the distance for maximum indicator concentrations to decrease to half their initial value (Gillberg, 1965). Within normal sheet flow, basal transport dominates and indicator debris concentrations decrease exponentially down-ice from its source. Half distances are typically short, hundreds of metres to several kilometres in length (Clark, 1987; Klassen, 2001). In contrast, dispersal trains associated with ice streams in the LIS are characterized by longer transport distances, and typically display a linear decrease in indicator debris concentrations (Dyke and Prest, 1987; Klassen, 2001; Dyke, 2008; Ross *et al.*, 2009). This is a result of the englacial position of debris in ice streams and its minimal modification during transport (Clark, 1987). Similar patterns have been described in pebble lithology counts in Nova Scotia where the Lawrencetown Till, deposited by a former ice stream in the Appalachian Ice Complex, has consistently high erratic content (up to 50%), with little down-ice uptake of local bedrock (Finck and Stea, 1995).

The production of Boothia-type dispersal trains, similar to those observed elsewhere in the LIS (*e.g.*, Dyke and Morris, 1988; Dyke, 2008), should be considered in drift prospecting of areas associated with ice streaming in the NIC. Boothia-type dispersal trains are identified by their convergent flow, sharp lateral margins, and longer anomalously high transport distances (*e.g.*, Dyke and Morris, 1988). Where these dispersal trains have been identified previously, the bedrock geology was relatively simple and identification of the dispersed rock types relatively straight-forward (*e.g.*, Dyke and Morris, 1988). Unfortunately, the complex geology underlying the ice-stream footprints may make the identification of Boothia-style dispersal trains particularly challenging, but is worth investigating given the extensive drift-geochemical data available for some of these areas.

This study focused exclusively on desktop landform mapping of ice-stream footprints in the NIC. Future field-based research might explore several of the following themes: (i) targeted till sampling across footprint margins to test for geochemical signatures of ice-stream dispersal; (ii) investigation of till characteristics within ice-stream footprints to look for evidence of subglacial deformation; and (iii) comparison of till characteristics between the onset and trunk zones to provide sedimentological evidence for variations in ice velocity and subglacial processes across the zone transition. High-resolution bathymetric maps of the seafloor around Newfoundland provide an opportunity to explore the terminal zones of terrestrial ice streams that extend offshore (*cf.* Brushett *et al.*, 2006), whereas glacial systems modeling of the NIC can explore the glaciological, palaeo-climatological and glacial geological conditions that generated ice-streaming dynamics in a relatively small maritime ice cap during the last glaciation.

## ACKNOWLEDGMENTS

Funding for this project was provided by the Geological Survey of Newfoundland and Labrador, Memorial University Graduate Student Work Experience Program and the Natural Sciences and Engineering Research Council of Canada. Phillip Blundon acknowledges the support of a Memorial University graduate fellowship. Terry Sears of the Geological Survey is acknowledged for his assistance with drafting of figures. Dave Liverman and Denise Brushett are thanked for reviews of this manuscript.

## REFERENCES

Andrews, J.T. and MacLean, B.
2003: Hudson Strait ice streams: a review of stratigraphy, chronology and links with North Atlantic Heinrich events. Boreas, Volume 32, pages 4-17.

Bamber, J.L., Vaughn, D.G. and Joughin, I.
2000: Widespread complex flow in the interior of the Antarctic Ice Sheet. Science, Volume 287, pages 1248-1250.

Batterson, M.J. and Liverman, D.G.E.
2000: Contrasting styles of glacial dispersal in Newfoundland and Labrador: methods and case studies. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 00-1, pages 1-31.

Batterson, M.J. and Taylor, D.
1998: Surficial geology and geochemical sampling in the Grand Falls to Glenwood areas (NTS 2D/13, 2D/14, 2E/3). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 98-1, pages 1-8.

Bennett, M.R.
2003: Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. Earth Science Reviews, Volume 61, pages 309-339.

Bentley, C.R.
1987: Antarctic ice streams: A review. Journal of Geophysical Research, Volume 92, pages 8843-8858.

Blundon, P., Bell, T. and Batterson, M.
2009: An evaluation of SRTM digital elevation data for glacial landform mapping in Newfoundland. *In* Current Research. Newfoundland Department of Natural Resources, Geological Survey Branch, Report 09-1, pages 289-303.

Boulton, G.S. and Clark, C.D.
1990: A highly mobile Laurentide Ice Sheet revealed by satellite images of glacial lineations. Nature, Volume 346, pages 813-817.

Brushett, D., Bell, T., Batterson, M.J. and Shaw, J.
2006: Ice-flow history of Placentia Bay, Newfoundland: Multibeam seabed mapping. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 07-1, pages 215-228.

Catto, N.R.
1998: The pattern of glaciation on the Avalon Peninsula of Newfoundland. Géographie Physique et Quaternaire, Volume 52, pages 1-24.

Clark, C.D.
1994: Large-scale ice moulding: a discussion of genesis and glaciological significance. Sedimentary Geology, Volume 91, pages 253-268.

1997: Reconstructing the evolutionary dynamics of former ice sheets using multi-temporal evidence, remote sensing and GIS. Quaternary Science Reviews, Volume 16, pages 1067-1092.

1999: The glaciodynamic context of subglacial bedform generation and preservation. Annals of Glaciology, Volume 28, pages 23-32.

Clark, C.D. and Stokes, C.
2001: Extent and basal characteristics of the M'Clintock Channel Ice Stream. Quaternary International, Volume 86, pages 81-101.

Clark, P.U.
1987: Subglacial sediment dispersal and till composition. The Journal of Geology, Volume 95, pages 527-541.

Colman-Sadd, S.P. and Crisby-Whittle, L.V.J.
2002: Partial bedrock geology dataset for the Island of Newfoundland (NTS 02E, 12H, 12G and parts of 01M, 02D, 02L, 11P, 12A, 12B, 12I). Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File NFLD/2616 version 4.0.

De Angelis, H. and Kleman, J.
2005: Palaeo-ice streams in the northern Keewatin sector of the Laurentide Ice Sheet. Annals of Glaciology, Volume 42, pages 135-144.

2007: Palaeo-ice streams in the Foxe/Baffin sector of the Laurentide Ice Sheet. Quaternary Science Reviews, Volume 26, pages 1313-1331.

2008: Palaeo-ice-stream onsets: examples from the north-eastern Laurentide Ice Sheet. Earth Surface Processes and Landforms, Volume 33, pages 560-572.

Denton, G.H. and Hughes, T.J.
1981: The Arctic ice sheet: an outrageous hypothesis. *In* The Last Great Ice Sheets. *Edited by* G.H. Denton and T.J. Hughes. John Wiley and Sons, New York, pages 437-467.

Dyke, A.S.
2008: The Steensby Inlet Ice Stream in the context of the deglaciation of Northern Baffin Island, Eastern Arctic Canada. Earth Surface Processes and Landforms, Volume 33, pages 573-592.

Dyke, A.S. and Morris, T.F.
1988: Drumlin fields, dispersal trains and ice streams in Arctic Canada. Canadian Geographer, Volume 32, pages 86-90.

Dyke, A.S. and Prest, V.K.
1987: Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. Géographie physique et Quaternaire, Volume 41, pages 237-263.

Evans, D.J., Clark, D.D. and Rae, B.R.
2008: Landform and sediment imprints of fast glacier flow in the southwest Laurentide Ice Sheet. Journal of Quaternary Science, Volume 23, pages 249-272.

Finck, P.W. and Stea, R.R.
1995: The compositional development of tills overlying South Mountain Batholith, Nova Scotia. Department of Natural Resources, Mines and Energy Branch, Paper 95-1, 51 pages.

Gillberg, G.
1965: Till distribution and ice movements on the northern slopes of the Swedish highlands. Geologiska Foreningens i Stockholm Forhandlingar, Volume 86, pages 61-70.

Grant, D.R.
1974: Prospecting in Newfoundland and the theory of multiple shrinking ice caps. *In* Current Research, Part B. Geological Survey of Canada, Paper 74-1B, pages 215-216.

Hughes, T.J.
1998: Ice Sheets. Oxford University Press, Oxford, 343 pages.

Jennings, C.E.
2006: Terrestrial ice streams: a view from the lobe. Geomorphology, Volume 75, pages 100-124.

Klassen, R.A.
2001: A Quaternary geological perspective on geochemical exploration in glaciated terrain. *In* Drift Prospecting in Glaciated Terrain. *Edited by* M.B. McClenaghan, P.T. Bobrowsky and G.E.M. Hall. Geological Society Special Publication No. 185, pages 1-17.

Kleman, J. and Borgstrom, I.
1996: Reconstruction of palaeo-ice sheets: the use of geomorphological data. Earth Surface Processes and Landforms, Volume 21, pages 893-909.

Kleman, J. and Hattestrand, C.
1999: Frozen-bed Fennoscandian and Laurentide ice sheets during the last glacial maximum. Nature, Volume 402, pages 63-66.

Kleman, J., Hattestrand, C., Stroven, A., Jansson, K., De Angelis, H. and Borgstrom, I.
2006: Reconstruction of palaeo-ice sheets: inversion of their glacial geomorphological record. *In* Glacier Science and Environmental Change. *Edited by* P.G. Knight. Blackwell, Oxford, pages 192-198.

Liverman, D.G.E., Batterson, M., Bell, T., Nolan, L., Marich, A. and Putt, M.
2006: Digital elevation models from the Shuttle Radar Topography Mission- New insights into the Quaternary history of Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 06-1, pages 177-189.

Liverman, D.G.E. and Taylor, D.M.
1990: Surficial geology of insular Newfoundland. Newfoundland Department of Mines and Energy, Geological Survey, Scale 1: 500 000, Map 90-08.

Patterson, C.J.
1998: Laurentide glacial landscapes: the role of ice streams. Geology, Volume 26, pages 643-646.

Rogerson, R.J.
1982: The glaciation of Newfoundland and Labrador. *In* Prospecting in Areas of Glaciated Terrain. *Edited by* P.H. Davenport. Canadian Institute of Mining and Metallurgy, Geology Division Publication, pages 37-56.

Ross, M., Campbell, J.E., Parent, M. and Adams, R.S.
2009: Palaeo-ice streams and the subglacial landscape mosaic of the North American mid-continental prairies. Boreas, Volume 38, pages 421-439.

Shaw, J., Piper, D.J.W., Fader, G.B., King, E.L., Todd, B.J., Bell, T., Batterson M.J. and Liverman, D.G.E.
2006: A conceptual model of the deglaciation of Atlantic Canada. Quaternary Science Reviews, Volume 25, pages 2059-2081.

St. Croix, L. and Taylor, D.M.
1991: Regional striation survey and deglacial history of the Notre Dame Bay area, Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 1-8.

Stokes, C.R. and Clark, C.D.
1999: Geomorphological criteria for identifying Pleistocene Ice Streams. Annals of Glaciology, Volume 28, pages 67-74.

2001: Palaeo-ice streams. Quaternary Science Reviews, Volume 20, pages 1437-1457.

2002: Are long subglacial bedforms indicative of fast ice flow? Boreas, Volume 31, pages 239-249.

2003: The Dubawnt Lake palaeo-ice stream: evidence for dynamic behaviour on the Canadian Shield and insights regarding controls on ice stream location and vigour. Boreas, Volume 32, pages 263-279.

Stokes, C.R., Clark, C.D., Derby, D.A. and Hodgson, D.A.
2005: Late Pleistocene ice export events into the Arctic Ocean from the M'Clure Strait Ice Stream, Canadian Arctic Archipelago. Global and Planetary Change, Volume 49, pages 139-162.

Stokes, C.R., Clark, C.D. and Storrar, R.
2009: Major changes in ice stream dynamics during the deglaciation of the north-western margin of the Laurentide Ice Sheet. Quaternary Science Reviews, Volume 28, pages 721-738.

Winsborrow, M.C., Clark, C.D. and Stokes, C.R.
2004: Ice streams of the Laurentide Ice Sheet. Géographie physique et Quaternaire, Volume 58, pages 269-280.