THE GEOMORPHIC FOOTPRINT OF ICE STREAMING IN THE NEWFOUNDLAND ICE CAP MAPPED FROM REMOTELY SENSED DATA

PHILLIP BLUNDON

The Geomorphic Footprint of Ice Streaming in the Newfoundland Ice Cap Mapped from Remotely Sensed Data

By
Phillip Blundon

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Chapter 1: Introduction

1.1 Introduction

Large ice sheets have complex internal architectures, featuring several dynamic and morphological subsystems (*i.e.*, ice domes, ice streams, outlet glaciers and ice shelves; Hughes, 1998). Of these, ice streams are arguably one of the most dynamic components of both contemporary and palaeo ice sheets, commonly controlling the ice sheet configuration, including drainage basin and ice divide locations, as well as local and regional ice sheet topography (Stokes and Clark, 1999; 2001).

Ice sheets are essential components of the climate system due to their marked influence on the earth's energy balance, and ocean and atmospheric circulation (De Angelis and Kleman, 2007). In light of the current changes in the global climate it is critical to understand how past ice sheets behaved in order to determine the magnitude and timing of changes in contemporary ice sheets. A recent conceptual model (Shaw *et al.,* 2006) suggests that ice streams played a major role in the deglaciation of Atlantic Canada, including the Newfoundland Ice Cap (NIC). However this model is largely conceptual, with ice streams primarily being positioned based on the assumption that continental shelf troughs were occupied by high velocity ice. This research presents an opportunity to test the Shaw *et al.* (2006) model and to assess the terrestrial evidence of palaeo-ice stream operation in the NIC.

Although recent observations from the base of contemporary glaciers have greatly improved knowledge of subglacial processes (*e.g.,* Smith *et al*., 2007), the relative ease of access to palaeo-ice stream beds allows researchers to gain insight into their geometry, controls on location, and temporal evolution (*e.g.,* Stokes *et al.,* 2009). Recent developments in remote sensing technologies, such as the development of high-resolution, global digital elevation models (DEMs) produced by the Shuttle Radar Topography Mission (SRTM), permit landscape mapping and visualization at a much broader scale. This allows for the identification of features that were previously unrecognized (*e.g.,* Liverman *et al.,* 2006; Ross *et al.,* 2006) and the re-assessment of established glacial histories.

The use of SRTM DEMs for small-scale landform mapping, however, has not been rigorously tested against traditional mapping techniques. The opportunity to conduct such a test presented itself during geomorphic mapping of ice-stream footprints in the NIC – the main topic of this thesis. Both SRTM generated imagery and an accompanying database of geomorphic features developed at the Geological Survey of Newfoundland and Labrador (GSNL) were available as primary mapping resources. Mapping from this database was tested against mapping from aerial photographs in an effort to identify the amount and type of overlap between mapping sources. Final mapping products were then supplemented with visual inspection of satellite imagery available on Google Earth and SPOT (Satellite Pour l'Observation de la Terre)-5 imagery to indentify and interpret potential ice stream footprints on the island of Newfoundland.

1.2 Thesis Structure

This thesis is presented in "manuscript format" which requires submission of two "independent" papers which are published or publication-ready. The papers comprise the main body of the thesis. Both of these papers have been published in the Geological Survey of Newfoundland and Labrador's annual Current Research report, which is a limited peer reviewed summary of scientific research at the Geologic Survey. Paper #1 (Blundon *et al.*, 2009) describes a comparative analysis of landform data derived from SRTM DEMs and aerial photograph mapping in an effort to test mapping accuracy and identify any sources of bias that may affect data quality. In Paper #2 (Blundon *et al.*, 2010), landform maps from SRTM data and aerial photographs are combined to identify and interpret the geomorphic footprint of potential palaeo-ice streams on the island of Newfoundland. This introductory chapter provides an overview of ice streams and the glacial history of Newfoundland, and a final chapter presents the research conclusions.

1.3 Ice Streams

1.3.1 Introduction

Ice streams are arguably the most dynamic component of contemporary and palaeo-ice sheets and are commonly viewed as the arteries of these ice sheets, controlling flow and ice sheet dynamic processes (Stokes and Clark, 2001). Ice streams are responsible for a disproportionate flux of ice, accounting for up to 90% of ice and sediment transfers within contemporary ice sheets (Bentley, 1987; Bamber, 2000). Thus, their occurrence and stability, both spatially and temporally, is central to the dynamic behaviour of past, present and future ice sheets (Bennett, 2003). While it is possible to observe the beds of ice streams directly (*e.g.*, Smith *et al.*, 2007), most insight into their behaviour is from the study of palaeo ice-stream beds. Once identified, they provide an opportunity to obtain data on subglacial environments and the processes controlling their location and timing (Stokes and Clark, 2001).

1.3.2 Definition

Ice streams are corridors within an ice sheet that flow significantly faster than surrounding ice (up to 0.8 km/year). Swithinbank (1954) defined ice streams as part of an inland ice sheet in which the ice flows more rapidly than, and not necessarily in the same direction as, the surrounding ice. Bentley (1987) further refined this definition by suggesting that an ice stream must be bounded on either side by ice rather than rock.

Glaciological research has shown that ice streaming stems from particular basal conditions that promote fast flow, mainly basal sliding and/or pervasive deformation of subglacial sediment (DeAngelis and Kleman, 2007). However, fast ice flow within ice sheets occurs across a wide range of topographic settings, from well-defined troughs (*i.e.*, topographic ice streams) to areas that show little or no topographic control (*i.e.*, pure ice streams), or combinations of both.

Bennett (2003) suggested that topographic ice streams experience fast ice flow for several reasons. First, thicker ice concentrated in topographic lows creates a greater driving stress at the bed and therefore higher velocities. Second, increased basal temperatures resulting from the insulating properties of thicker ice enhances the rate at which basal ice deforms and promotes basal sliding due to basal melting and lubrication. Third, meltwater is more likely to be concentrated in topographic lows, adding to the reduction of shear stress at the bed of the glacier. When these factors combine, the net result is a tendency for ice flow to accelerate within topographic lows. Contemporary examples of topographically-controlled ice streams include the Amundsen, Beardmore and Byrd glaciers which drain through the Transantarctic Mountains into the western and southern Ross Ice Shelf (Bennett, 2003).

Pure ice streams are bounded on either side by areas of slow or stagnant ice (Stokes and Clark, 2001). Much less is known about the mechanisms controlling flow in pure ice streams, although they are generally associated with corridors of ice which are rheologically weaker than surrounding ice. Alternatively they are associated with a lubricated bed of soft sediment which promotes basal sliding and/or deformation (Bennett, 2003). The only contemporary examples of pure ice streams are found on the Siple Coast of West Antarctica.

1.3.3 Evolution of ice stream theories

By the late 1970s it was widely accepted that large portions of the Greenland and Antarctic ice sheets were drained by discrete outlets of fast-flowing ice (Rose, 1979), which led researchers to search for the locations of palaeo-ice stream beds within many of the northern hemisphere ice sheets (*e.g.,* Denton and Hughes, 1981; Figure 1.1). Much of this early work was guided by discoveries from the Greenland and Antarctic ice sheets that suggested ice stream locations coincided with deep troughs and/or soft deformable sediment. Additionally, the use of satellite imagery in glacial mapping revolutionized the discipline by allowing users a much broader view of the landscape than previously possible, leading to the identification of complex groupings of glacial lineations that were previously unrecognized (*e.g.,* Boulton and Clark, 1990). The discovery of this bed complexity within the Laurentide Ice Sheet (LIS) fundamentally changed the approach to palaeo-glaciological reconstructions and by the mid-1990s a growing number of authors had proposed ice streams draining portions the LIS (*e.g.,* Kaufman *et al.,* 1993; Hodgson, 1994; Marshall *et al.,* 1996; Patterson, 1998). By the late 1990s a large population of potential palaeo-ice stream tracts had been identified, using widely different lines of evidence including but not limited to recognition of distinct dispersal trains (*e.g.,* Dyke and Morris, 1988), convergent landform patterns (Patterson, 1998) and an association with large marine troughs which were occupied by ice streams (Hodgson, 1994). In response, Stokes and Clark (1999) developed a diagnostic landsystem associated with ice streams in an effort to objectify the process of mapping palaeo-ice streams.

1.3.4 Ice Stream Morphology

Ice streams can be categorized as either being terrestrial or marine based (Stokes and Clark, 1999). All contemporary ice streams are marine based (*e.g.,* Siple Coast ice streams), whereas some palaeo-ice streams terminated on land (*e.g.,* the Des Moines lobe of the LIS located in Minnesota; Patterson, 1998). Both ice stream types can be sub-divided into distinct zones that reflect changes in ice dynamics (Stokes and Clark, 2001).

The onset zone characteristically ranges from tens to several hundred kilometres wide, and is typified by convergence and increasing attenuation of bedforms down-ice toward the main ice stream trunk. A transition occurs from cold-based or slower moving ice in the upstream catchment to warm-based, faster moving ice towards the main trunk.

As ice is drawn in from the onset zone it continues to accelerate down the main ice stream where fast ice flow is separated from slower ice flow by a lateral shear margin.

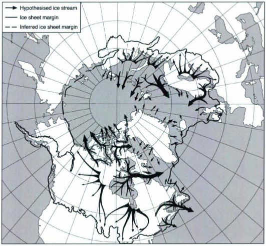

Figure 1.1. Hypothesized positions of northern hemisphere ice streams (black arrows) as predicted by Denton and Hughes, 1981 (from Stokes and Clark, 2001).

The trunk zone is typically narrower than the onset zone, commonly ranging from tens to greater than a hundred kilometres in width. Flow-directional landforms within the trunk include drumlins, mega flutes, mega-scale glacial lineations, and crag-and-tail hills. These landforms typically display an increase in elongation ratio downstream and toward the center of the ice stream, consistent with predicted velocity fields within contemporary ice streams (*e.g.,* Stokes and Clark, 2002; 2003).

The lateral margins of ice streams are commonly abrupt and in some places are recorded by shear moraines, which mark the shear zone between fast and slow flow (*e.g.,* Dyke and Morris, 1988). Terminal areas of terrestrial-and marine-based ice streams show widely differing flow types. The most obvious difference is that terrestrial ice streams commonly terminate in a large divergent lobe of slower moving ice, whereas marine ice streams terminate either directly into the open ocean or into an ice shelf (Stokes and Clark, 2001).

Stokes and Clark (1999) developed a list of diagnostic geomorphic criteria that can be used to aid in the identification of palaeo-ice stream beds. These criteria, developed using the characteristics of contemporary ice streams, 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 ratio >10:1) indicating the presence of high velocity ice;

(iii) abrupt lateral margins marked by strong zonation of landforms and occasionally the presence of shear margin moraines;

(iv) Boothia-type erratic dispersal trains (Dyke and Morris, 1988), that are defined by their plug-like shape and much longer transport of material within the train rather than either side of it;

(v) presence of pervasive deformation till indicating the occurrence of subglacial deformation which likely facilitates fast flow; and

(vi) presence of a trough mouth fan at the marine terminus indicating focused sediment delivery by ice streaming.

1.4 The Newfoundland Ice Cap

1.4.1 Models of Glaciation

Knowledge of the Quaternary glacial history of Newfoundland has evolved considerably since the idea was first proposed by Murray (1882). Early debates focused mainly on determining the role of ice sourced in Labrador (Twenhofel and MacClintock, 1940; Flint, 1940) *versus* one or more local island-based ice cap (Jenness,1960; Lundqvist, 1965). Further detailed reviews of the Quaternary history are presented in Grant (1977, 1989), Rogerson (1982), and Brookes (1982). Following acceptance of island-based ice caps, several models of glaciation were proposed that differ substantially on ice extent: those that supported a minimal ice extent and those that supported maximum ice extent (see discussion in Grant, 1989). The minimal model of ice extent suggests that Last Glacial Maximum ice was restricted to lowland terrestrial areas, with ice margins located near the present day coast (*e.g.,* Dyke and Prest, 1987; Grant, 1989) The maximum model of ice extent suggests ice extended from local sources out onto the continental shelf, with ice margins located near the shelf edge (Dyke *et al.*, 2002). More recently, Stea (2004) proposed an intermediate model of ice extent for the Atlantic Canada in which ice from Newfoundland sources grew and coalesced with the Laurentide ice flowing through the Laurentian Channel, producing ice cover that extended to the continental shelf.

A new model of the southeastern margin of the LIS (Shaw *et al.,* 2006) supports an intermediate model of ice extent and suggests that ice streams played a critical role in the deglaciation of Atlantic Canada. The model is largely conceptual, based principally on the assumption that ice streams occupied major topographic troughs in the continental shelf. This model is constrained by observational data such as geophysical and sampling evidence on shelf moraines, radiocarbon dates on offshore marine sediments, and flow-parallel features on shelves. Furthermore, recent discoveries of convergent flow patterns in Placentia Bay have confirmed ice stream operation in offshore areas (Brushett *et al.*, 2007). A location map of place names discussed is provided in Figure 1.2.

1.4.2 Glacial History of Newfoundland

During the Last Glacial Maximum the island of Newfoundland supported its own ice cap, the NIC, which was largely independent from the LIS with the exception of parts of the Great Northern Peninsula (Grant, 1989). At 21 ka BP ice reached its maximum extent, with ice margins reaching near the edge of the continental shelf edge (Figure 1.3). A first-order ice divide, that extended south and southeast across Newfoundland, separated flow toward the northeast coast from flow toward the south and west coasts which drained into a large ice stream occupying the Laurentian Channel. Second-order divides extended over southwestern Newfoundland and Cape Freels, separating flow into ice streams located in the Trinity and Notre Dame basins. Ice streams occupying the Hermitage and Halibut channels drained the south coast (Figure 1.3).

The model suggests that relatively early retreat was the result of calving along deep water channels (Shaw *et al.,* 2006). By18 ka BP (Figure 1.4) the delivery of large volumes of ice to the ocean significantly lowered ice elevations far inland and caused ice margins to retreat from their positions on the continental shelves (Shaw *et al.,* 2006). By 14 ka BP (Figure 1.5) the Laurentian Channel had deglaciated triggering the large scale radial drainage of ice from the NIC leading to massive ice cap disintegration (Shaw *et al.,* 2006). By this time the NIC was largely isolated from the LIS, with calving margins reaching the south and southwest coasts via drainage through topographically-controlled outlets (fiords; Shaw *et al.,* 2000, Shaw, 2003). After 13 ka BP ice margins were at or near the modern coast, with further deglaciation taking place mainly through ablation of land based ice. Deglacial ice dispersal centers were located over the Long Range Mountains, The Topsails, Middle Ridge and the Avalon Peninsula (Gosse *et al.*, 1995; Grant, 1989).

Figure 1.2. Location map of Newfoundland and offshore areas including places named in text.

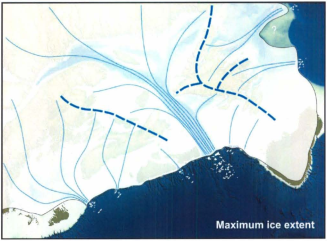

Figure 1.3. Maximum Ice Extent. Thin blue lines are simplified flow lines. Thick dashed lines indicate the positions of major ice divides (from Shaw *et al.*, 2006).

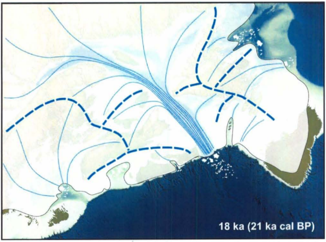

Figure 1.4. Ice margins at 18 ka (from Shaw *et al.,* 2006).

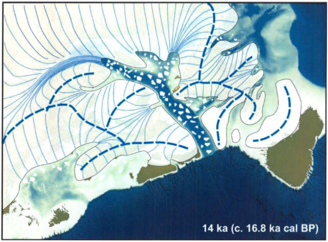

Figure 1.5. Ice Margins at 14ka (from Shaw *et al.,* 2006).

1.4.3 Ice Streams in Newfoundland

The concept of ice streaming in the NIC is not a new one. In the early 1980s Denton and Hughes (1981) suggested that numerous ice streams drained the eastern LIS, including the NIC (Figure 1.1). In their reconstructions, drainage divides were positioned based on the assumption that troughs in the continental shelf were occupied by high velocity ice. Hughes (1998) advanced this view by depicting a major ice stream in the Laurentian Channel with smaller ice streams draining through fiords and embayments on the north, east and south coasts of Newfoundland.

Although research continued on the identification of ice streams beds elsewhere in the LIS (e.g., Andrews et al., 1985; Dyke and Morris, 1988), a review by Stokes and Clark (2001) revealed few proposed ice streams in the eastern LIS. Shaw et al. (2006) developed a conceptual model of the eastern LIS in which ice streams play a major role. This reconstruction was based on the assumption that deep shelf channels were occupied by high-velocity ice and from this flow divides were deduced. This process was guided by observations of the Greenland Ice Sheet (Bamber *et al.,* 2000) that suggest flow lines in catchments converged on glacier outlets.

In 2005, a 'glacial map' and database of glacial landforms of Newfoundland was produced from previous mapping by the provincial and federal geological surveys and published literature (Bell *et al.,* 2005). Research was continued by Liverman *et al.* (2006) who used STRM DEMs to map landforms across the island of Newfoundland. This mapping revealed complex landform assemblages that were previously unrecognized, particularly large-scale streamlined features which vary in morphology from linear, elongate shapes to drumlin-like forms and crag-and-tail hills. Liverman *et al.* (2006) suggested ice streaming may have occurred in the NIC based on observations of elongate large-scale lineations that have elsewhere been linked to fast flow (*c.f.* Stokes and Clark, 2002, 2003). The Grand Falls area, Bonavista Peninsula, and areas north of Facheaux Bay were identified as possible locations of ice streaming based on observations of elongate landforms (Liverman *et al.,* 2006).

More recently Brushett *et al.* (2007) have identified landform assemblages in Placentia Bay that show characteristics of ice streaming as defined by Stokes and Clark

(1999). These assemblages include drumlins, flutes, mega-lineations, and crag-and-tail hills which converge from regional dispersal centers to flow down the main axis of the bay. This convergent flow pattern is interpreted to represent the onset zone of fast ice farther down the bay (Brushett *et al.,* 2007).

1.5 Landform mapping from remotely sensed data

The palaeoglaciological reconstruction of ice sheets requires the synthesis of multiple datasets across a variety of scales (Smith *et al*., 2006), with landform maps forming the basis of these reconstructions (*e.g.,* De Angelis and Kleman, 2005, 2007; Stokes *et al.,* 2009). For this reason, accurate mapping of landforms is critical if this process is to provide reliable reconstructions.

Traditional methods of mapping glaciated landscapes include field mapping and aerial photograph interpretation (*e.g.,* Kleman and Hattestrand, 1999). Developments in remote sensing technologies have made available tools in the form of satellite imagery and DEMs which have revolutionized the way palaeoglaciological research is approached, allowing for reconstructions of large portions of former ice sheets (*e.g.,* De Angelis and Kleman, 2005, 2007; Clark *et al.,* 2000; Kleman *et al.,* 1997; Jansson and Glasser, 2005) and discovery of previously unrecognized internal complexity within former ice sheets (*e.g.,* Boulton and Clark, 1990). With these tools it is possible for a researcher to conduct widespread glacial mapping in a systematic manner, at a variety of spatial scales, thus promoting greater analysis and coherence of all evidence (Clark, 1997).

DEMs are becoming a primary data source for landform mapping, particularly with the wide availability of national and global datasets, such as SRTM digital elevation data. Within areas of the former LIS, SRTM DEMs have been increasingly used in landform mapping applications that have led to the identification of previously unrecognized landform assemblages (*e.g.,* Campbell, 2005; Ross and Parent, 2007; Shaw *et al.,* 2010). On the island of Newfoundland, Liverman *et al.* (2006) used SRTM digital elevation data in reconnaissance-level mapping of glacial landforms, where it was noted that DEMs were particularly useful in identification of large-scale flow-directional landforms such as drumlins, flutes and crag-and-tail hills.

Though the methodology for large-scale ice sheet reconstructions is well established (*e.g.,* Clark, 1997), the primary source data can contain random or systematic errors, which then become reproduced in the research (Smith *et al.,* 2006). For example, when using digital elevation data, relief shading is the preferred method of landscape visualization because of its ability to highlight subtle variations in the surface topography and permit their realistic depiction and interpretation (Smith and Clark, 2005). Relief shading uses an idealized light source to illuminate the landscape at a specified azimuth and elevation, however, the method has limitations. Relief shading can introduce possible bias into landform mapping by systematically highlighting landforms which are aligned at 90° to the light source, *i.e.*, azimuth biasing. Azimuth biasing is most pronounced when mapping linear landforms and the use of multiple illumination azimuths aids in the identification and elimination of spurious landform assemblages.

1.6 Research rationale

Offshore marine geological records indicate that ice streams have played an important role in abrupt climate changes in the past. For example, the palaeo-ice stream that operated in the Hudson Strait was responsible for the discharge of such large volumes of ice, the resultant melt cooled North Atlantic waters enough to alter ocean circulation and produce abrupt shifts in climate (Andrews and MacLean, 2003). Furthermore, the last deglacial period was abruptly interrupted by a reversal to glacial conditions, the Younger Dryas cold event, which is thought to have largely been caused by rapid meltwater/iceberg discharge into the Arctic Ocean from the Keewatin ice dome (Tarasov and Peltier, 2006). As ice streams are one of the main conduits for draining the interior of ice sheets, ice streams draining the Keewatin ice dome would have likely been responsible for much of the iceberg discharge in this area, significantly contributing to freshwater input. For this reason it is critical for glaciological studies to locate the beds of palaeo-ice streams and assess their impacts on global palaeo-climates and ice sheet evolution.

The extent, retreat and flow geometry of the LIS are relatively well understood (*e.g.,* Dyke *et al.,* 2002), however little is known about detailed flow dynamics. It is acknowledged that ice streams played a vital role in determining ice sheet dynamics and therefore it is critical to locate and study their beds if we are to understand their functioning and impacts on ice sheets. Recent investigations of the former LIS have revealed numerous palaeo ice-streams, including major ice streams along the northwestern (Stokes *et al.,* 2009), northeastern (De Angelis and Kleman, 2008), southern (Patterson, 1998), and southwestern margins (Evans *et al.,* 2008).

In the southeastern margin of the former LIS developments have been much more fragmented. There has been no systematic study of glacial landforms on the island of Newfoundland in the context of ice streaming and furthermore there has been no validation of proposed ice streaming (*e.g.,* Shaw *et al.,* 2006) using the characteristic landform assemblage that has been associated with ice streaming (*e.g.,* Stokes and Clark, 1999). This research explores the geomorphic footprint of potential ice streams within the NIC while at the same time providing a test of the Shaw *et al.* (2006) model. Given the importance of mineral development to the Newfoundland economy, this research also permits for a re-evaluation of traditional approaches to drift prospecting in light of new evidence of ice stream operation.

A first step in the process of evaluating ice stream footprints involved mapping glacial features from SRTM DEMs. Mapping glacial landforms from SRTM DEMs is widely practiced (e.g ., Lowell and Fisher, 2005; Hickin and Levson, 2008), although there have been no rigorous tests of it suitability for this application. Testing glacial mapping from SRTM DEMs against mapping from aerial photographs allows for the identification of overlap (the amount and type of features mapped) between mapping sources. One aim of this work is to improve future mapping procedures using this technology.

1.7 Research Questions

What is the amount and type of overlap between landform data derived from SRTM DEMs and aerial photographs?

Detailed landform maps produced using SRTM DEMs, aerial photographs, and a combination of mapping from SRTM DEMs and aerial photographs are compared to determine the similarities and differences from the various mapping sources.

Are there any systematic biases that may negatively effect data quality and if so what impact do they have?

Mapping results were examined to determine if there are biases associated with each mapping source, and if so what are the causes of these biases. These biases were then examined to determine their effects on mapping quality.

Is there landform evidence to support the concept of ice streaming in the NIC as proposed by Shaw *et al.* (2006)?

The type and distribution of landforms are examined using the criteria outlined by Stokes and Clark (1999) for identifying palaeo-ice stream beds in an effort to test the hypothesis of ice streaming in the NIC as proposed by Shaw *et al.* (2006).

What is the characteristic geomorphic footprint of ice streaming in the NIC?

The landform record of several potential ice stream footprints are examined and characterized with the aim of identifying a landform assemblage characteristic of ice streaming within the NIC. These are then compared with mapping of ice stream footprints from elsewhere in the LIS.

1.8 References

Andrews, J.T., Stravers, J.A., and Miller, G.H.
1985: Patterns of glacial erosion and deposition around Cumberland Sound, Frobisher Bay and Hudson Strait, and the location of ice streams in the eastern Canadian Arctic. *In* Models in Geomorphology. *Edited by* M.J. Woldenburg. Allen & Unwin, London. Pages 93-117.

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.

Bell, T., Liverman, D.G.E., Batterson, M.J., Catto, N., Marich, A., McCuaig, S., Putt, M., Shaw, J., and Taylor, D.
2005: Deglacial ice dynamics in Newfoundland. *In* Water, Ice, Land, And Life: The Quaternary Interface. Canadian Quaternary Association 2005 Conference June 5-8, 2005, University of Manitoba, Winnipeg, Manitoba. Abstract Volume, page A4.

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.J.
2009: An evaluation of SRTM digital elevation data for glacial landform mapping in Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch. Report 09-1, pages 289-303.

Blundon, P., Bell, T., and Batterson, M.J.
2010: Ice streaming in the Newfoundland Ice Cap: Implications for the reconstruction of palaeo-ice flow and drift prospecting. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch. Report10-1, pages 143-157.

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.

Brookes, I.A.
1982. Ice marks in Newfoundland: A history of ideas. Géographie physique et Quaternaire, Volume 36, pages 139-163.

Brushett, D., Bell, T., Batterson, M.J., and Shaw, J.
2007: 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.

Campbell, J.E.
2005: SRTM DEM imagery: Previously unrecognized regional-scale ice streams, ice flows indicators and glacial landforms in Saskatchewan. *In* Water, Ice, Land, and Life: The Quaternary Interface. Canadian Quaternary Association 2005 Conference June 5-8, 2005, University of Manitoba, Winnipeg, Manitoba. Abstract Volume, page A12.

Clark, C.D.
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.

Clark, C.D., Knight, J.K., and Gray, J.T.
2000: Geomorphological reconstruction of the Labrador sector of the Laurentide Ice Sheet. Quaternary Science Reviews, Volume 19, pages 1343-1366.

Clark, C.D., Evans, D.J., and Piotrowski J.A.
2003: Palaeo-ice streams: an introduction. Boreas, Volume, 32, pages 1-3.

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.

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

De Angelis, H. and Kleman, J.
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 Hughes, T.J. John Wiley and Sons, New York, pages 437-467.

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.

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., Andrews, J.T., Clark, P.U., England, J.H., Miller, J.H., Shaw, J. and Veillette, J.J.
2002: The Laurentide and Innuitian ice sheets during the last glacial maximum. Quaternary Science Reviews, Volume 21, pages 9-31.

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.

Flint, R.F.
1940: Late Quaternary changes of level in western and southern Newfoundland. Bulletin of the Geological Society of America, Volume 51, pages 1757-1780.

Gosse, J.C., Grant, D.R., Klein, J., and Lawn, B.
1995: Cosmogenic $_{10}$Be and $_{26}$Al constraints on weathering zone genesis, ice cap basal conditions, and Long Range Mountains (Newfoundland) glacial history. CANQUA-CGRG Joint meeting 1995, Programme, Abstracts and Field Guides. Department of Geography, Memorial University of Newfoundland, page 19.

Grant, D.R.
1977: Glacial style and limits, the Quaternary stratigraphic record, and changes of land and ocean level in the Atlantic provinces, Canada. Géographie Physique et Quaternaire, Volume 31, pages 247-260.

Grant, D.R.
1989: Quaternary Geology of the Appalachian region of Canada. *In*: Quaternary Geology of Canada and Greenland. *Edited by* R.J. Fulton. Geological Survey of Canada, Geology of Canada, pages 393-440.

Hickin, A.S. and Levson, V.M.
2008: Are streamlined landforms in the northern Cordillera evidence of ice streams? *In* Quebec 2008: 400 Years of Discoveries. Joint Meeting of the Geological Association of Canada, Mineralogical Association of Canada, Society of Economic Geologists and the Society for Geology Applied to Mineral Deposits. May 26-28, 2008. Québec City Convention Centre, Québec.

Hodgson, D.A.
1994: Episodic ice streams and ice shelves during retreat of the northwestern most sector of the late Wisconsinan Laurentide Ice Sheet over the central Canadian Arctic Archipelago. Boreas, Volume 23, pages 14-28.

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

Jansson, K.N. and Glasser, N.F.
2005: Using Landsat 7 ETM+ imagery and Digital Terrain Models for mapping glacial lineaments on former ice sheet beds. International Journal of Remote Sensing, Volume 26, pages 3931- 3941.

Jenness, S.E.
1960: Late Pleistocene Glaciation of Eastern Newfoundland. Bulletin of the geological Society of America, Volume 71, pages 161-180.

Kaufman, D.S., Miller, G.H., Stravers, J. A., and Andrews, J.T.
1993: Abrupt early Holocene (9.9-9.6 ka) ice-stream advance at the mouth of Hudson Strait, Arctic Canada. Geology, Volume 21, pages 1063-1066.

Kleman, J., Hattestrand, C., Borgstrom, I.A., and Stroeven, A.
1997: Fennoscandian palaeoglaciology reconstructed using a glacial geological inversion model. Journal of Glaciology, Volume 43, pages 283-299.

Kleman, J. and Hattestrand, C.
1999: Frozen-bed Fennoscandian and Laurentide Ice Sheets during the Last Glacial Maximum. Nature, Volume 402, pages 63-66.

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.

Lowell, T.V. and Fisher, T.G.
2005. What if we had looked from space first? Using SRTM DEM data to generate alternative hypothesis for deglaciation of the Laurentide Ice Sheet. *In* Water, Ice, Land, and Life: The Quaternary Interface. Canadian Quaternary Association 2005 Conference June 5-8, 2005, University of Manitoba, Winnipeg, Manitoba. Abstract Volume, page A52.

Lundqvist, J.
1965: Glacial Geology in Northeastern Newfoundland. Geologiska Foreningens i Stockholm Forhandlingar, Volume 87, pages 285 -306.

Marshall, S.J., Clarke, G., Dyke, A.S., and Fisher, D.A.
1996: Geologic and topographic controls on fast flow in the Laurentide and Cordilleran Ice Sheets. Journal of Geophysical Research, Volume 101, pages 827-839.

Murray, A.
1882: Glaciation of Newfoundland. Proceedings and Transactions of the Royal Society of Canada, Volume 1, pages 55-76.

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.

Rose, K.E.
1979: Characteristics of ice flow in Marie-Byrd Land, Antarctica. Journal of Glaciology, Volume 24, pages 63–75.

Ross, M., Parent, M., Benjumea, B., and Hunter, J.
2006.The late Quaternary stratigraphic record northwest of Montréal: regional ice-sheet dynamics, ice-stream activity, and early deglacial events. Canadian Journal of Earth Sciences. Volume 43, pages 461-485.

Ross, M. and Parent, M.
2007: The complex glacial landsystems of the Canadian prairies as revealed by SRTM datasets and sub-regional 3D geomodels. *In* CANQUA Ottawa 2007. Canadian Quaternary Association Conference, June 4-8, 2007. Carleton University, Ottawa, Ontario, Canada.

Shaw, J.
2003: Submarine moraines in Newfoundland coastal waters: implications for the deglaciation of Newfoundland and adjacent areas. Quaternary International, Volume 99-100, pages 115-134.

Shaw, J., Grant, D. R., Guilbault, J., Anderson, T.W., and Parrott, D.R.,
2000: Submarine and onshore end moraines in southern Newfoundland: implications for the history of late Wisconsinan ice retreat. Boreas, Volume 29, pages 295-314.

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.

Shaw, J., Sharpe, D., and Harris, J.
2010: A flowline map of glaciated Canada based on remote sensing data. Canadian Journal of Earth Science, Volume 47, pages 89-101.

Smith, A.M., Murry, T., Nicholis, K.W., Makinson, K., Aoalgeirdottir, G., Behar, A.E., and Vaughan, D.G.
2007: Rapid erosion, drumlin formation, and changing hydrology beneath an Antarctic ice stream. Geology, Volume 35, pages 127-130.

Smith, M.J. and Clark, C.D.
2005: Methods for the visualization of digital elevation models for landform mapping. Earth Surface Processes and Landforms, Volume 30, pages 885–900.

Smith, M.J., Rose, J., and Booth, S.
2006: Geomorphological mapping of glacial landforms from remotely sensed data: An evaluation of the principal data sources and an assessment of their quality. Geomorphology, Volume 76, pages 148-165

Stea, R.R.,
2004: The Appalachian Glacier Complex in Maritime Canada. *In* Quaternary Glaciations – Extent and Chronology, Part II. *Edited by* Ehlers, J., and Gibbard, P.L. Developments in Quaternary Science, Volume 2b. Elsevier, Amsterdam, pages 213-232.

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

Stokes, C.R. and Clark, C.D.
2001: Palaeo-ice streams. Quaternary Science Reviews, Volume 20, pages 1437-1457.

Stokes, C.R. and Clark, C.D.
2002: Are long subglacial bedforms indicative of fast ice flow? Boreas, Volume 31, pages 239-249.

Stokes, C.R. and Clark, C.D.
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., 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.

Swithinbank, C.W.M.
1954: Ice streams. Polar Record, Volume 7, pages 185-186.

Tarasov, L., and Peltier, W.R.
2006: A calibrated deglacial drainage chronology for the North American continent: evidence of an Arctic trigger for the Younger Dryas. Quaternary Science Reviews, Volume 25, pages 659-688

Twenhofel, W.H., and McClintock, P.
1940: Surface of Newfoundland. Bulletin of the Geological Society of America, Volume 51, pages 1665-1727.

1.9 Co-authorship Statement

As principal author I have relied on numerous people for assistance and guidance in preparation of this thesis and subsequent research papers; however, I took the leading role in all phases of project design, data collection and analysis, and manuscript preparation. My supervisors, Dr. Trevor Bell and Dr. Martin Batterson, appear as co-authors on the versions of the manuscripts that have been published. As co-authors they have contributed significantly to the identification of specific research objectives and project design as well as contributing editorial reviews during the preparation of each manuscript for publication. Data collection and analysis was completed by the primary author. As the sole author of this thesis and the primary author of the research papers contained within, I accept responsibility for all errors and omissions that appear in this work.

Chapter 2: An evaluation of SRTM digital elevation data for glacial landform mapping in Newfoundland

Blundon, P., Bell, T., and Batterson, M.J.

2009: An evaluation of SRTM digital elevation data for glacial landform mapping in Newfoundland. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch. Report 09-1, pages 289-303.

2.1 Abstract

This paper describes a comparative study of glacial landform mapping from northeast Newfoundland, Canada, using aerial photograph interpretation and a SRTM digital elevation model (DEM). The study assessed the amount and type of overlap between landform data derived from a SRTM DEM and aerial photographs and explored systematic mapping biases that may negatively affect data quality. Results indicate that interpretation from 1:50 000 aerial photographs produced more detailed landform maps than those from the SRTM DEM. This was likely the result of large differences in horizontal resolution between mapping sources ($\leq$10 m for aerial photographs and 90 m for SRTM DEM). The SRTM data permitted identification of larger scale landforms, particularly ribbed moraine, which were only selectively recorded on aerial photographs. Analysis of landform distribution and surficial geology provided similar results for the two datasets: mapped-landform concentrations were highest in areas of thick till and lower in till veneer and bedrock. The SRTM DEM was successful in the identification of regional ice-flow trends and landform patterns. The use of multiple illumination angles avoided bias in the mapping of linear features in the SRTM DEM, while the integration of supplemental data, such as bedrock and surficial geology, improved overall mapping quality, particularly for flow-parallel landforms. Although lacking the finer detail of aerial photographs, the efficiencies offered by SRTM data for reconnaissance mapping of glacial landforms are confirmed.

2.2 Introduction

Traditional methods of mapping glaciated terrain, including field mapping and aerial photograph interpretation of 1:50 000 map sheets, are generally time intensive, subjective, and lead to the development of bottom-up approaches to large scale ice-sheet reconstruction. Recent developments in remote-sensing technologies have made available digital elevation models (DEMs) that allow landscape visualization at a variety of scales. With these products it is possible to conduct glacial mapping across larger areas in a systematic manner, thus promoting a top-down approach that allows greater analysis and synthesis of evidence at the ice sheet scale (Clark, 1997).

With the release in 2003 of an almost globally extensive topographic dataset from the Shuttle Radar Topography Mission (SRTM), high resolution DEMs for Newfoundland and Labrador became readily available. Application of these DEMs has the potential to increase mapping speed and to promote a better understanding of regional ice-flow histories (*e.g.,* reconnaissance-level mapping of large areas of Labrador). In an effort to begin such systematic, cost-effective mapping, the Geological Survey of Newfoundland and Labrador has developed a preliminary glacial landform dataset for the island of Newfoundland, interpreted from SRTM data (Liverman, unpublished data, 2008). Although SRTM data may significantly increase the efficiency of landform mapping, there has been no systematic attempt to assess product quality, nor has there been an evaluation of whether the data are best employed in combination with other products.

This paper reports on a comparative study of landform mapping from northeast Newfoundland using data derived from three sources: aerial photographs, SRTM DEM, and a combination of aerial photographs and SRTM data. These are evaluated to assess the amount and type of overlap between landform data derived from SRTM DEMs and aerial photograph interpretation and to explore systematic mapping biases that may negatively affect data quality. The results of this study will assist in the preparation of regional ice flow maps based on landform data derived from interpretation of traditional aerial photographs and recent SRTM data.

2.3 Shuttle Radar Topography Mission (SRTM)

The Shuttle Radar Topography Mission was flown by the Space Shuttle Endeavour during February 2000, producing the first global, large-scale topographic dataset. The SRTM provides a high quality DEM at 3-arc-second (~90 m) resolution between latitudes 58°S and 60°N. To capture elevation data of Earth's surface, SRTM used interferometry, a technique in which two images of the same area are taken from different vantage points. In the case of SRTM, this was achieved by using two antennas: one within the cargo bay of the shuttle and another on the end of a 60-m long mast deployed from the shuttle. The interferometry radar used phase/range differences measured from the two different vantage points to obtain elevation data with an absolute accuracy of ±16 m and relative accuracy of ±6 m (Farr *et al.,* 2007). The SRTM radar contained two types of antenna panels, C-band and X-band. The near-global topography was generated from the C-band radar data, which were processed at the Jet Propulsion

Laboratory and distributed through the United States Geological Survey's EROS Data Center (http://edc.usgs.gov/srtm/data/obtainingdata.html).

The SRTM data differ from traditional remote-sensing data in several key characteristics. For example, the horizontal resolution of 1:50 000 aerial photographs, while not explicitly stated, is likely less than 10-m compared to the 90-m resolution provided by a SRTM DEM. Also, aerial photographs have elements of image interpretation in the form of tonal and textural data that aid in landform identification (Campbell, 2002). In contrast, SRTM DEMs lack surface textural data, and tonal variations reflect slope angle and aspect rather than surface reflectance properties.

2.3.1 Glacial mapping using SRTM

The use of SRTM data for glacial and surficial mapping is an increasingly common practice in Canada since its release in 2003 (Table 2.1). The SRTM data address the need for rapid, reconnaissance-level geological mapping of remote areas (*e.g.,* Matile *et al.,* 2003, 2007; Mei *et al.,* 2005) and regional-scale reconstructions of ice-sheet dynamics from mapped glacial lineations and their crosscutting patterns (*e.g.,* Lowell and Fisher, 2005). Although some of these studies have limited ground-truthing, and in some cases the DEMs are supplemented with other remote-sensing data (*e.g.,* Mei *et al.,* 2005; Hickin and Levson, 2008), interpretations from SRTM data appear to be largely untested against traditional mapping sources.

Table 2.1 Locations and descriptions of previous glacial mapping projects in Canada utilizing SRTM data

Author	**Location**	**Primary Use**	**Additional Comments**
Matile *et al.*, 2003, Matile and Keller, 2007	Manitoba	Reconnaissance mapping to produce 1:250 000 and 1:1 000 000 scale surficial geology maps	Limited ground truthing
Campbell, 2005	Saskatchewan	Identification of previously unmapped large-scale landforms for regional ice flow mapping	Identifies potential ice streams based on mapping of large-scale glacial lineations
Mei *et al.*, 2005	Northern Alberta	Surficial mapping of inaccessible areas	SRTM used in conjunction with RADARSAT-1, Landsat and Indian Remote Sensing Satellite images
Lowell and Fisher, 2005	Southern Canada and northern USA	Interpretations of large-scale landforms	SRTM DEMs used to reconstruct a deglacial history of the southern Laurentide Ice Sheet
Liverman *et al., 2006*	Newfoundland	Interpretations of surficial geology, particularly glacial landforms	SRTM DEMs useful for interpreting large scale oriented landforms such as flutes, drumlins and crag-and-tail hills
Ross and Parent, 2007	Canadian prairies	Identification of obscured streamlined terrain	In conjunction with borehole data SRTM DEM led to the identification of large scale tributary flow within the southwestern Laurentide Ice Sheet
Batterson and Taylor, 2007	Newfoundland	Mapping geomorphic features to aid in ice flow reconstructions	Used to supplement ice flow mapping from aerial photographs and striations.
Hickin and Levson, 2008	Northeastern British Columbia and Northwestern Alberta	Mapping of large scale streamlined landforms of the former Cordilleran and Laurentide ice sheets	Used in conjunction with LiDAR DEMs

2.4 Study Area

The study area covers approximately 13 000 km² and includes 13 1:50 000 NTS map sheets in northeastern Newfoundland (2D/11, 2D/12, 2D/13, 2D/14, 2D/15, 2E/2, 2E/3, 2E/4, 2E/5, 2E/6, 2E/7, 12A/9, and 12A/16; Figure 2.1.). The largest communities in the study area are Gander and Grand Falls–Windsor. Several smaller communities including Lewisporte, Botwood and Norris Arm are located along the coast. The study area extends inland 60 km from the most southerly arm of the Bay of Exploits, the modern basin for the Exploits River.

2.4.1 Bedrock Geology and Physiography

Bedrock in the study area typically increases in age from east to west. Eastern and southeastern areas are underlain by Cambro-Ordovician siliciclastic marine sedimentary rocks of the Gander Zone, inferred to have formed along the continental margin of the early Iapetus Ocean. Farther west, bedrock consists of marine siliclastic rocks (including sandstones, conglomerates, and siltstones) and island-arc volcanic and volcaniclastic rocks ranging in age from Cambrian to Silurian and comprising parts of the Dunnage Zone (Colman-Sadd and Crisby-Whittle, 2002). After the closing of the Iapetus Ocean, these rocks, along with those of the Gander Zone, were intensely folded, imparting the northeast – southwest structural trend observed in the bedrock. This structural trend has the potential to complicate mapping of subglacial bedforms in the area because the main ice-flow trend is also northeast. All rocks were crosscut during the Siluro-Devonian by gabbros and granites of the Mount Peyton and Hodges Hill Intrusive suites. These granitoids now form the local topographic highs in the study area (Mount Peyton – 487 m; Hodges Hill – 569 m).

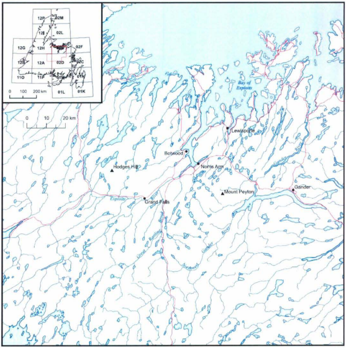

Figure 2.1 Map of study area.

The regional topography slopes gently coastward. Areas underlain by volcanic rocks tend to have higher elevation, likely reflecting their greater resistance to weathering and erosion compared to the adjacent sedimentary rocks. The coastline is composed of headlands separating numerous smaller bays and inlets. Several major rivers, including the Exploits River, Great Rattling Brook, Gander River and Northwest Gander River, occupy valleys that typically follow the softer siliclastic bedrock of the Dunnage Zone.

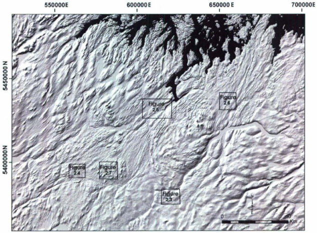

Figure 2.2. False-shaded SRTM image of study area with locations of subsequent figures outlined by boxes. Image is illuminated from the northwest.

2.4.2 Surficial Geology and Glacial History

The surficial geology is dominated by varying thicknesses of sediment. Concealed and exposed bedrock dominates coastal areas whereas till cover increases inland, ranging from till veneer to thick till blanket in central and southern regions (Liverman and Taylor, 1990). Topographic highs, such as Hodges Hill and Mount Peyton, are characterized by thin and discontinuous sediment cover, although the presence of erratics indicates that the area was once ice covered. Typically the slopes of topographic highs are mantled with sediment, with the up-ice (southwest) side having thicker till deposits than the down-ice side. The southern margin of the study area is dominated by extensive fields of hummocky till terrain (Liverman and Taylor, 1990). Low-lying areas along the coast generally contain either glaciofluvial or glaciomarine sediments. Marine limit for the area is placed at 58 m above sea level based on the elevation of a raised delta surface at Laurenceton, near Botwood (MacKenzie and Catto, 1993). Large river valleys, such as the Exploits and those of its tributaries, contain extensive glaciofluvial sand and gravel deposits. Major meltwater channels and esker complexes are commonly aligned with these large valleys.

Regional glacial histories have been compiled by a number of previous workers including Rogerson (1982), Grant (1974, 1989), St. Croix and Taylor (1991) and Batterson and Taylor (1998). A three-phase sequence of glacial events has been proposed (St. Croix and Taylor, 1991; Batterson and Taylor, 1998). The earliest flow was an eastward ice advance, evidence for which was observed across much of northeastern Newfoundland (St. Croix and Taylor, 1991; Scott, 1994; Batterson and Taylor, 1998) and with a likely source in The Gaff Topsails. The second flow, which is repeatedly described as the dominant ice flow, was to the northeast from an ice divide arching across south-central Newfoundland from Middle Ridge to Meelpaeg Lake (Grant, 1974; Rogerson, 1982). St. Croix and Taylor (1991) subdivided this flow into an earlier northeastward flow followed by a later more northward flow into the Bay of Exploits. The third flow is described as a localized eastward flow, most likely representing re-advance of a remnant ice cap west of Grand Falls during Younger Dryas cooling (St. Croix and Taylor, 1991).

2.5 Data and Methods

2.5.1 Glacial Landforms

A range of subglacial landforms were mapped for use in this study. Subglacial landforms are defined as longitudinal or transverse accumulations of sediment formed below active ice (Rose, 1987; Benn and Evans, 1998). Longitudinal subglacial landforms are features which are aligned parallel to flow and include flutes, drumlins and megaflutes (Plate 2.1), with divisions being defined based on differences in length and elongation ratio (Table 2.2). Rose (1987) suggested that flutes, drumlins and megaflutes form a continuum of bedforms. In an effort to simplify classification, all longitudinal subglacial bedforms in this study are classified as flutes. Ribbed moraine occurs as fields of coalescent crescentic ridges of sediment lying transverse to former ice flow (Benn and Evans 1998; Plate 2.2). These ridges have lengths ranging from 45 to 16 000 m (mean = 688 m), widths from 17 to 1100 m (mean = 278 m) and heights ranging from 1 to 64 m (mean = 17 m; Benn and Evans, 1998; Dunlop and Clark, 2006). An additional class of elongate bedforms has been mapped – crag-and-tail hills. These are generally either erosional or depositional features consisting of a resistant bedrock crag at the up-ice end and a tail of less resistant bedrock or sediment down-ice (Benn and Evans, 1998; Plate 2.3).

Plate 2.1. Oblique aerial photograph of low relief flutes in central Labrador (feature in center part of photograph is approximately 1.5 km long). Ice flow was from bottom left to top right.

Plate 2.2. Oblique aerial photograph of ribbed moraine on the central Avalon Peninsula, Newfoundland (Trans Canada Highway in foreground). Ice flow was from the north or top to bottom in the photograph.

Plate 2.3. Photo of crag-and-tail hill from the Strange Lake area, northern Labrador. Ice flow was eastward (right to left). The feature is approximately 4 km long from the crag (high point) to the eastern end.

Table 2.2. Classification of flow-parallel landforms by dimensions (m) according to Rose (1987). Elongation ratio is defined as length (l) divided by width (w).

Landform	Typical Length	Typical Height	ElongationRatio
Flute	< 100	< 3	> 4
Drumlin	> 200	> 5	< 4
Megaflute	>100	< 5	> 4

2.5.2 Study Approach

The standard desk-top approach to landform and surficial geology mapping involves stereoscopic viewing and interpretation of stereo-pairs of aerial photographs ranging in scale from 1:50 000 to 1:12 500 or larger. Landform mapping using a digital DEM, however, requires visualization of the data using various illumination angles, shaded-relief effects and vertical stretching. In this study, it is hypothesized that the aerial photograph interpretation produces the most complete landform dataset because of the characteristics of aerial photographs that aid in the interpretation of landforms (*e.g.,* tone, texture).

2.5.3 Data Sources and Analysis

The landform database derived from stereoscopic viewing and interpretation of stereo-pairs of 1:50 000-scale black and white aerial photographs, here named AERIAL, was generated by the lead author. To ensure completeness of mapping many areas were re-examined after initial interpretation. The landform database generated from SRTM data interpretation, named SRTM, was compiled by Liverman (unpublished data, 2008). It was originally designed to provide island-wide landform mapping at a reconnaissance level. A second SRTM based dataset, know as SRTMAerial, was compiled by the lead author to test whether a combination of aerial photograph and SRTM DEM interpretation would generate a more complete landform database than SRTM data alone. Surficial and bedrock geology maps were referenced to avoid misinterpretation of geologic structure as depositional glacial landforms.

Seamless SRTM elevation data were downloaded and imported into *Global Mapper* software from which two DEMs were produced with false-shaded illumination from the northeast and the northwest. Landform height in all three datasets was measured using the SRTM elevation data. The landform width was either measured from aerial photographs or SRTM DEMs, and landform length was generated in *ArcMap*. Mapping was supplemented by 1:50 000 scale topographic, surficial geology (Liverman and Taylor, 1990) and bedrock geology (Colman-Sadd and Crisby-Whittle, 2002) maps, and consultations with geologists who have extensive knowledge of the study area.

Qualitative visual inspection of mapping accuracy was supplemented by analysis based on spatial distribution of landform type and surficial geology. Surficial units identified by Liverman and Taylor (1990) were reclassified as follows: 1) thick till, including till blanket, hummocky terrain and areas of ridged till; 2) thin till or till veneer; 3) concealed bedrock; 4) exposed bedrock and; 5) other, including alluvium, colluvium, glaciofluvial sand and gravel, and marine sediments

2.6 Results

Data trends are presented first for the study area as a whole and then by individual landform type. In each of the three datasets ribbed moraine was the most common landform type, constituting more than 75% of all delineated landforms (Table 2.3). Flutes were the next most common, representing 14% of all landforms mapped in AERIAL and between 7 and 9% in SRTM and SRTMAerial. Crag-and-tail hills were least common and represented less than 8% of all landforms. AERIAL typically had higher total landform counts than both SRTM and SRTMAerial (Table 2.3).

Table 2.3 Individual and total landform counts for each dataset

Landform	AERIAL	SRTM	SRTMAerial
Ribbed Moraine	2848	2645	2599
Flute	500	221	258
Crag and Tail	288	180	264
Total	**3636**	**3046**	**3121**

Table 2.4 Variation in landform length and width between datasets; mean value in parentheses

Landform	AERIAL	SRTM	SRTMAerial
Ribbed Moraine			
Length (m)	90 – 2700	200 – 2200	200 – 2300
	(355)	(550)	(620)
Width (m)	125 – 300	150 – 350	150 – 375
	(195)	(225)	(220)
Flute			
Length (m)	500 – 5000	315 – 3150	600 – 6000
	(1560)	(1265)	(1700)
Width (m)	120 – 640	150 – 380	150 – 450
	(306)	(326)	(310)
Crag-and-Tail Hill			
Length (m)	300 – 3000	370 – 2000	500 – 3250
	(1300)	(1100)	(1400)
Width (m)	96 – 650	250 – 700	250 – 600
	(310)	(420)	(430)

2.6.1 Ribbed Moraine

The AERIAL dataset had the highest number of ribbed moraine (n = 2848) followed by SRTM (n = 2645) and SRTMAerial (n = 2599; Table 2.3). In each dataset more than 85% of the ribbed moraine was identified in areas of thick till, whereas at most only 20% was identified in areas of till veneer. SRTM and SRTMAerial generally produced slightly higher percentages of ribbed moraine within terrain classified as concealed bedrock or 'other'.

Although the counts for ribbed moraine are consistent across each of the three datasets, visual inspection suggests that there was significant variation in the scale of landform classified as ribbed moraine, with those mapped from SRTM generally being larger (Table 2.4). For example, mean length and width was 550 m and 225 m, respectively, for SRTM, in contrast to 355 m and 196 m for AERIAL. Height measurements were similar for all datasets (mean = 2.9 m). As predicted, larger-scale ribbed moraine was readily identified on all datasets (Figure 2.3).

Mapping of ribbed moraine from AERIAL and SRTM does not reproduce the same spatial pattern (Figure 2.4). It generally has a wider spatial distribution on SRTM compared with solely aerial photograph interpretation alone and typically occurs in areas classified as hummocky moraine by Liverman and Taylor (1990), such as in the southern margin of the study area. A similar association was also noted by Liverman *et al.* (2006). Ribbed moraine was most easily identified on SRTM when false illumination was from the northeast which was normal to the presumed ice-flow direction (Figure 5).

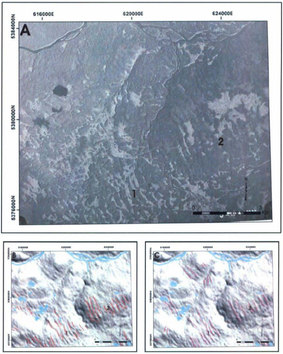

Figure2.3. A) Aerial photograph of large ribbed moraine aligned with long axis northwest-southeast. 1 and 2 indicate locations where large ribbed moraine were mapped from both aerial photographs and SRTM DEMs B) SRTM image illuminated from northeast showing ribbed moraine mapped from aerial photos (red lines). C) SRTM image illuminated from northeast showing ribbed moraine mapped from SRTM DEMs (pink lines).

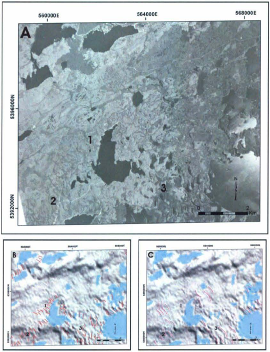

Figure 2.4. A) Aerial photograph of ribbed moraine field. 1 indicates location of subtle ribbed moraine mapped from aerial photographs but not SRTM DEMs. 2 and 3 indicate locations where ribbed moraine mapped from SRTM DEMs were larger than those mapped from aerial photographs. B) SRTM image illuminated from the northeast. Red lines represent ribbed moraine mapped from aerial photographs. C) SRTM image illuminated from northeast. Pink lines represent ribbed moraine mapped from SRTM.

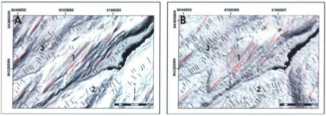

Figure 2. 5. A). SRTM image illuminated from the northwest. 1 indicates where flutes mapped from SRTM (red lines) are preferentially highlighted when the illumination angle is perpendicular (northwest) to their long axis (northeast). B) SRTM image illuminated from the northeast. 2 and 3 indicate locations where ribbed moraine (Black lines) are best viewed when the illumination is perpendicular to long axis of the landform (northwest).

2.6.2 Flutes

Flute counts from AERIAL (n = 500) are substantially higher than those from SRTM (n = 221) or SRTMAerial (n = 258; Table 2.3). The large discrepancy suggests that flutes are likely under-represented in SRTM-based mapping (Figures 2.5 and 2.6). For instance, an additional 43 flutes, or 20%, were identified on the SRTM DEM when combined with aerial photograph interpretation.

Flutes are most commonly mapped in areas of thick till (65-94%), and only 10% in areas of till veneer. Twice as many flutes were mapped in concealed bedrock from SRTM and SRTMAerial compared to AERIAL; however, they represented a minor percentage (20%) of the overall count.

The mean length of mapped flutes varied from one database to another with the longest ones in SRTMAerial (1700 m) and shortest ones in SRTM (1266 m; Table 2.4). Mean width and height measurements for flutes varied much less among databases, ranging between 306 and 326 m and 4.8 and 5.6 m, respectively.

2.6.3 Crag-and-Tail Hills

AERIAL (n = 288) and SRTMAerial (n = 264) had significantly more mapped crag-and-tail hills than SRTM (n = 180; Table 2.3.). Landform counts for crag-and-tail hills identified in areas of thick till ranged from 34 to 83%, whereas only 30% were mapped in till veneer. As anticipated, there were many more crag-and-tail hills (40%) identified on concealed bedrock compared to the other landform types.

Crag-and-tail hills were on average 200-300 m longer and 100 m or so narrower on both Aerial and SRTMAerial compared to SRTM alone (Table 2.4). Crag-and-tail hills were more readily visible on SRTM imagery than flutes and ribbed moraine (Figure 2.7) and their heights (mean = 17 m), were generally significantly greater than for other landforms mapped (mean = 2.9 m for ribbed moraine and 5.2 m for flutes).

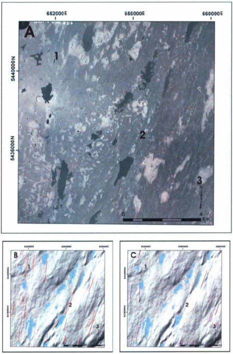

Figure 2.6. A) Aerial photograph of low-relief flutes trending to north-northeast. Areas with flutes identified in aerial photograph mapping but not from SRTM DEMs are indicated by 1, 2 and 3. B) SRTM image illuminated from the northeast with flutes mapped from air photos (red lines). C) SRTM image illuminated from northeast with flutes mapped from SRTM (pink lines).

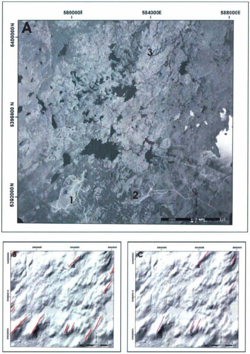

Figure 2.7. A) Aerial photograph of an area of crag-and-tail hills. Areas where similar landforms were mapped from both aerial photographs and SRTM DEMs are indicated by 1, 2 and 3. B) SRTM image illuminated from the northwest with crag-and-tail hills mapped from air photos (red lines). C) SRTM image illuminated from northwest with crag and tail hills mapped from SRTM (pink lines).

2.7 Discussion

This study indicates that mapping from aerial photographs facilitates the identification of a greater number of landforms than mapping solely from SRTM DEMs. Use of the SRTMAerial dataset (*i.e.,* some aerial photograph interpretation included), improved the delineation of elongate landforms. Nonetheless, landforms were significantly under-represented in landform counts derived from SRTM-based mapping as compared to those derived from aerial photograph interpretations (Table 2.3).

The highest numbers of all landforms were, with the exception of crag-and-tail hills, located over areas of thick till. Based on the accepted definition of subglacial landforms (see above), the results indicate that mapping undertaken using the three datasets yields landforms in areas where thick surficial sediment should allow for their development. A reduction in landform counts over thin till agrees with this outcome. However, the observed increase in ribbed moraine and flute counts on concealed bedrock in the SRTM and SRTMAerial databases is contrary to what would be expected as landform counts should decrease as sediment thickness and cover decrease. This suggests that flutes and ribbed moraine may be misinterpreted in some instances on SRTM data and the greater detail provided by aerial photograph interpretation produce more accurate results in comparison with SRTM-based interpretations.

In contrast, crag-and-tail hills appear to be correctly interpreted based on their association with predicted surficial geology. Given their composition, crag-and-tail hills should be located in areas with significant near-surface bedrock. Our results showed that 70% of crag-and-tail hills were identified on areas mapped as concealed bedrock or till veneer, whereas units mapped as exposed bedrock and 'other' had generally low (less than 5%) landforms counts.

Landform dimensions typically varied significantly between datasets with AERIAL generally having smaller landforms than SRTM-based interpretations. Some of the features identified in AERIAL had dimensions that would not allow them to be interpreted on the SRTM DEM. For example, low profile flutes with widths as low as 125 m would likely not be discernable on SRTM DEMs due to inadequate visualization of tonal differences produced by relief shading. This apparent size biasing was not as significant an issue during the identification of crag-and-tail hills, as they typically have widths and heights that can readily be detectable from shadows produced by false shading. These results are similar to those presented by Liverman *et al.* (2006), who suggested that SRTM DEMs are best suited for mapping large scale oriented landforms. Though not directly tested, this observation has implications for the mapping of subtle glacial landforms such as esker and meltwater channels which would likely not be detectable on SRTM DEMs *(cf.,* subtle ribbed moraine and flutes).

The divergent results for ribbed moraine counts and their corresponding sizes suggest that their identification in each of the three datasets has benefits and limitations. In many cases, ribbed moraine were mapped in similar areas, although individual moraine mapped from aerial photographs were generally shorter, narrower and less widespread than those mapped from SRTM (Figure 2.3). For reasons similar to those identified for flutes (*i.e.,* low profiles which do not allow visualization on SRTM DEMs), it would seem that aerial photograph interpretation allows for identification of moraines that are not detectable using SRTM. However, it also appears that mapping derived from SRTM is capable of identifying larger ribbed moraine, not observed on aerial photographs. SRTM data may depict more widespread and larger moraine owing to the ability of radar to penetrate vegetation that might otherwise mask glacial landforms (Graham and Grant, 1991). Although ribbed moraine mapped from aerial photographs and SRTM DEMs had different dimension and distributions, they generally show similar directional trends. In all cases, ribbed moraine was within the dimensions described by Dunlop and Clark (2006).

It is critical to recognize the potential role of illumination angles and relief shading in introducing bias into landform mapping from SRTM DEMs. Elongate landforms such as flutes and crag-and-tail hills were best observed when illuminated from the northwest, as the dominate ice flow in this area was toward the northeast. When illumination was shifted to the northeast, few if any elongate landforms could be identified (Figure 2.5). As a result, much of the mapping of elongate landforms was undertaken using a northwest illumination, although a northeast illumination was used to check for landforms with differing alignments. A similar result can be seen in mapping ribbed moraine. As ribbed moraine are typically aligned transverse to the dominant ice-flow, in this case northeast, their ridge crests were most easily mapped when highlighted from this same angle (Figure 2.5). Although illumination biases were recognized and accounted for in this study, in other areas where ice-flow histories are complex, the use of multiple view angles is critical to accurately identify all landforms produced from separate ice-flow events.

The regional bedrock structural trend in the study area is generally toward the northeast, similar to that of the dominant palaeo-ice-flow direction. This may cause some misinterpretation of bedrock structure as elongate landforms. Where possible, it is recommended that supplemental surficial and bedrock geological data be used to help eliminate mapping errors using SRTM. As expected, mapping of landforms from SRTM was significantly improved by knowledge generated through aerial photograph interpretations. Similarly, satellite imagery has been utilized by several authors (*e.g.*, Campbell, 2005; Mei *et al.*, 2005) to supplement mapping from SRTM. Although this methodology does not provide the same level of detail as aerial photograph interpretation, overlaying the high resolution satellite imagery over SRTM DEMs has the potential to eliminate some of the shortcomings in mapping from SRTM alone (*e.g.*, a lack of tonal and textural data).

Although mapping of each dataset produced variable results, the regional trends in landform patterns observed in aerial photographs are similar to those in SRTM, suggesting that for regional-scale landform mapping, SRTM data are adequate. Additionally, SRTM mapping was accomplished in significantly less time than aerial photograph mapping, highlighting its value in reconnaissance level survey. Further, the regional approach provided by SRTM mapping, while perhaps not as detailed, allows for a better synthesis of glacial history over larger areas than that permitted through aerial photograph interpretation.

2.8 Conclusions

Recently released SRTM DEMs have the potential to revolutionize landform mapping, yet until now limited tests of the accuracy of maps derived from such data have been conducted. Results of this study indicate that:

1) Interpretation of SRTM DEMs leads to the identification of fewer landforms than interpretation from aerial photographs. This is because of the higher resolution, and the tonal and textural variations offered by aerial photographs, which allow visualization of subtle landforms that cannot be seen through relief-shading effects in SRTM DEMs.

2) Mapping from SRTM DEMs was slightly improved for elongate landforms, (flutes and crag-and-tail hills), by added knowledge derived from aerial photograph mapping.

3) The small scale of SRTM DEMs permits interpretation of larger landforms that might normally be missed in larger scale aerial photographs (*e.g.,* ribbed moraine) because of the coarser resolution and more basic topographic characteristics of SRTM DEMs (*e.g.,* elevation, slope angle and aspect)

4) Although landform counts varied between datasets, similar regional trends in landform type and associated surficial geologic units are consistent with known results, indicating that SRTM mapping is capable of identifying regional landform distributions accurately.

5) Azimuth biasing effects introduced by false shading must be recognized and accounted for if mapping is to be considered accurate.

6) Depending on the application, each method has its particular advantages. Detailed landform mapping is better suited to aerial photograph interpretations where higher image resolution aids in more detailed interpretation. The efficiency of SRTM mapping promotes its use in the production of preliminary, reconnaissance level ice-flow mapping of remote areas.

2.9 Acknowledgements

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2.10 References

Batterson, M.J. and Taylor, D.M.

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.

Batterson, M.J. and Taylor, D.M.

2007: Till geochemical surveys and preliminary Quaternary mapping of the Burin Peninsula and adjacent areas. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 07-1, pages 197-214.

Benn, D.I. and Evans, D.J.A.

1998: Glaciers and Glaciation. Arnold, London, 734 pages.

Campbell, J.B.

2002: Introduction to Remote Sensing, 3rd ed. The Guilford Press, New York, 621 pages.

Campbell, J.E.

2005: SRTM DEM imagery: Previously unrecognized regional-scale ice streams, ice flows indicators and glacial landforms in Saskatchewan. *In* Water, Ice, Land, and Life: The Quaternary Interface. Canadian Quaternary Association 2005 Conference June 5-8, 2005, University of Manitoba, Winnipeg, Manitoba. Abstract Volume, page A12.

Clark, C.D.

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.

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 Mine and Energy, Geological Survey Branch, Open File NFLD/2616 version 4.0.

Dunlop, P. and Clark, C.D.
2006: The morphological characteristics of ribbed moraine. Quaternary Science Reviews, Volume 25, pages 1668-1691.

Farr, T.G., Rosen, P., Caro, E., Crippen, R., D, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Wemer, M., Oskin, M., Burbank D., and Alsdorf, D.
2007: The Shuttle Radar Topography Mission. Reviews of Geophysics, Volume 45, pages 1-33.

Graham, D.F. and Grant, D.R.
1991: A test of airborne, side-looking synthetic aperture radar in central Newfoundland for geological reconnaissance. Canadian Journal of Earth Sciences, Volume 28, pages 257-265.

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

Grant, D.R.
1989: Quaternary geology of the Atlantic Appalachian region of Canada. *In* Quaternary Geology of Canada and Greenland. *Edited by* R.J. Fulton. Geological Survey of Canada, no.1, pages 391-440.

Hickin, A.S. and Levson, V.M.
2008: Are streamlined landforms in the northern Cordillera evidence of ice streams? *In* Quebec 2008: 400 Years of Discoveries. Joint Meeting of the Geological Association of Canada, Mineralogical Association of Canada, Society of Economic Geologists and the Society for Geology Applied to Mineral Deposits. May 26-28, 2008. Québec City Convention Centre, Québec.

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.

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. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 06-1, pages 177-189.

Lowell, T.V. and Fisher, T.G.
2005. What if we had looked from space first? Using SRTM DEM data to generate alternative hypothesis for deglaciation of the Laurentide Ice Sheet. *In* Water, Ice, Land, and Life: The Quaternary Interface. Canadian Quaternary Association 2005 Conference June 5-8, 2005, University of Manitoba, Winnipeg, Manitoba. Abstract Volume, page A52.

MacKenzie, C. and Catto, N.R.
1993: Quaternary geology of the Botwood (NTS 2E/03) map area. *In* Current Research, Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 93-1, pages 139-148.

Matile, G.L.D., Keller, G.R., Thorleifson. L.H., and Pyne, D.M.
2003: Quaternary mapping progress in southern Manitoba Phanerozoic terrane: 2-D and 3-D. Report of Activities 2003. Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, 2003, GS-30, pages 231-238.

Matile, G.L.D. and Keller, G.R.
2007: Surficial geology compilation of Manitoba, Canada. Geological Society of America Abstracts with Programs. Geological Society of America Annual Meeting & Exposition. 28-31 October, 2007. Colorado Convention Center, Denver, Colorado. Volume 39, page 83.

Mei, S., Fenton, M.M., and Paulen, R.C.
2005: Integrations of remote-sensing and geological data as aids to mapping surficial sediments in northwestern Alberta. Alberta Energy and Utilities Board, Alberta Geological Survey, Earth Sciences Report ESR 2005-03.

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.

Rose, J.
1987: Drumlins as part of a glacier landform continuum. *In* Drumlin Symposium *Edited by* Menzies, J.and Rose. Balkema, Rotterdam, pages 103-116.

Ross, M. and Parent, M.
2007: The complex glacial landsystems of the Canadian prairies as revealed by SRTM datasets and sub-regional 3D geomodels. *In* CANQUA Ottawa 2007. Canadian

Quaternary Association Conference, June 4-8, 2007. Carleton University, Ottawa, Ontario, Canada.

Scott, S.
1994: Surficial geology and drift exploration of Comfort Cove-Newstead and Gander River Map areas (NTS 2E/7 and 2E/2). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch. Report 94-1, pages 29-42.

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.

Chapter 3: Ice streaming in the Newfoundland Ice Cap: Implications for the reconstruction of palaeo-ice flow and drift prospecting

Blundon, P., Bell, T., and Batterson, M.J.

2010: Ice streaming in the Newfoundland Ice Cap: Implications for the reconstruction of palaeo-ice flow and drift prospecting. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch. Report10-1, pages 143-157.

3.1 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.

3.2 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, with ice streams driving most of this active 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. This 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.

3.3 Ice streams

Ice streams can be thought of as the drainage routes for large portions of an ice-sheets 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 is critical for controlling the 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; topographic ice streams whose flow is constrained by variations in topography, such as troughs; and pure ice streams that are unconstrained and bordered solely by slower moving or stagnant ice. It is highly unlikely that a single ice stream exclusively fits one of these categories. For example, palaeo-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 can be sub-divided into a number of distinct zones that reflect changes in ice dynamics (Figure 3.1). The onset zone 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 is thought to result 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 3.1) 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 *et al.,* 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 (*e.g.,* Dubawnt Lake Ice Stream; Stokes and Clark, 2003). Lateral boundaries along the trunk are commonly abrupt and are sometimes marked by shear marginal moraines that record the shear zone between fast and slow flow (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 forms 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.,* Evans *et al.,* 2008; Stokes and Clark, 2003). These contrast with marine-based ice streams which 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).

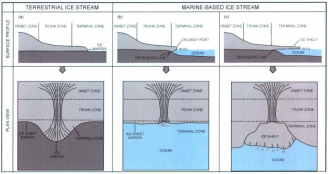

Figure 3.1. Conceptual models of terrestrial and marine-based ice streams (after Stokes and Clark 1999, 2001). Ice streams can be subdivided into a number of distinct zones that reflect changes in ice flow dynamics. These include the onset zone where slower moving ice from a wide catchment area is directed into the trunk 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.

Initially, palaeo-ice streams were primarily identified in ice sheets in areas which 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 landsystems associated with palaeo-ice streams. For example, Stokes and Clark (1999) described a set of diagnostic criteria, largely based on geomorphology, to aid in the identification of palaeo-ice streams. Individually, none of these criteria can be used to confirm palaeo-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 (>20km wide x 150km long);

(ii) highly attenuated bedforms (length:width >10:1);

(iii) abrupt lateral margins and shear margin moraines;

(iv) Boothia-type erratic dispersal trains;

(v) pervasive deformation till;

(vi) trough mouth fan at marine terminus.

3.3.1 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-traveled 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 are thought to 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 3.2; 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 3.2; 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-down flow of the contact (Dyke, 2008). In both cases, the dispersal plumes display a linear decrease in indicator lithologies 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 on the order of 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 records indicate aligned composite dispersal trains that extend for over 350 km across Saskatchewan that display sharp lateral boundaries and are interpreted as ice stream margins (Ross *et al.,* 2009).

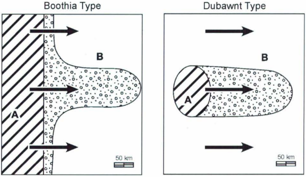

Figure 3.2. Simplified diagram of Boothia and Dubawnt style dispersal trains (after Dyke and Morris, 1988). Boothia style dispersal trains are believed to be formed by ice streams whereas Dubawnt style trains form under sustained regional flow. A and B are two distinctly different rock types. Arrows represent ice-flow direction and dots represent dispersal of debris from A

3.3.2 Ice Streams in the Newfoundland Ice Cap

The NIC formed an independent ice cap over Newfoundland 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 largely 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 3.3).

Shaw *et al.* (2006) placed the last glacial maximum ice extent the continental shelf edge and identified a major ice stream flowing through the Laurentian Channel (Figure 3.3 and 3.4). The location of this ice stream dictated 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 3.3). 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 (Figure 3.3). 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 largely through ablation on land.

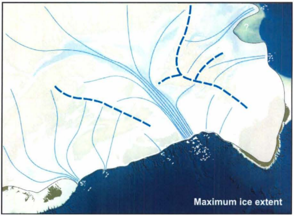

Figure 3.3. Model of last glacial maximum ice extent for Newfoundland (from Shaw *et al.*, 2006). Generalized flow lines are represented by thin blue lines and thick dashed lines represent major ice divides. Positions of ice streams were interpreted based on the assumption that marine troughs were occupied by high velocity ice.

3.4 Geomorphologic 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.

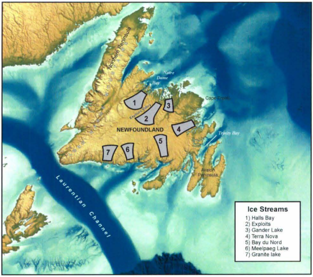

Figure 3.4. Map of Newfoundland and offshore areas with place names mentioned in text including outlines of the 7 potential ice stream signatures identified in this study.

Mapping of ice-stream flow-sets was accomplished by visual interpretation and mapping from a database of glacial landforms maintained by the Geological Survey of Newfoundland and Labrador which includes features such as drumlins, flutes, crag-and-tail hills, and ribbed moraine. These landforms were mostly mapped 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 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 cross-cutting 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 3.4 and 3.5). 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 from 33 to 64 % from the onset to the trunk (Table 3.1). 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 3.6). Along the south coast, mapped flow-sets typically terminate at higher elevations (125-250 m asl) than those along the north coast (up to 80 m asl; Figure 3.6). Along the south coast, uplands extend to the coast and are dissected by numerous fiords 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 3.6). The Exploits and Granite flow-sets are positioned relative to large valleys, whereas others coincide with relatively flat (*e.g.,* Gander) or slightly concave-upward terrain (*e.g.,* Meelpaeg Lake).

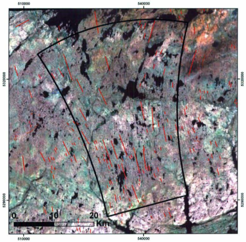

Figure 3.5. The Meelpaeg Lake flow-set as seen on satellite imagery available on Google Earth. Note the distinct convergence and high density of flow-parallel landforms, represented by red lines.

Table 3.1. 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	Degree of Convergence	Attenuated Bedforms	Bedrock Geology	Surficial Geology
Granite Lake	46 x 26	42	Megaflutes and crag-and-tail hills. Max length 5 km.	Granites with minor occurrences of sedimentary rocks	Tv and Th, inland. Rc and R along coast.
Meelpaeg Lake	47 x 21	46	Megaflutes and crag-and-tail hills. Max length 6 km.	Granites with minor occurrences of sedimentary rocks	Tv and Th inland. Rc and R along coast.
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
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.
Gander Lake	30 x 20	33	Drumlins, megaflutes and crag-and-tail hills. Max length 3 km.	Sedimentary rocks	Tb, Tv, Tr inland. Tv and Rc along coast.
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
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.

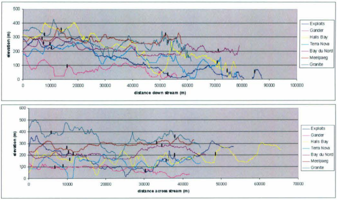

Figure 3.6. Down and across stream topographic profiles for identified flow-sets. Black ticks indicate flow-set margins. Down stream profiles typically begin near regional topographic highs whereas across stream flow-set margins show varying degrees of correspondence with topographic highs.

The flow-sets are also characterized by variable surficial geology. Generally, the surficial sediment thins towards 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 3.7).

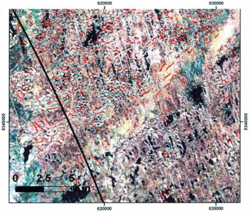

Figure 3.7. Field of ribbed moraine located near the head of the Bay Du Nord flow-set as seen on satellite imagery available on Google Earth. Ribbed moraine are represented by red lines.

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 rock – the one exception is the Halls Bay flow-set. In the case of the Gander and Exploits flow-sets, the sedimentary rocks are highly folded with strike toward the north and northeast. It is possible that large scale folding with strike occurring parallel to flow could act to re-direct 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 granites coastward.

3.4.1 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 3.8; 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).

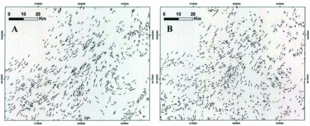

Figure 3.8. Results of mapping glacial landforms from aerial photographs (A) and SRTM DEMs (B). Mapping from aerial photographs produced more detailed landform maps, particularly for small flow-parallel landforms making it more suitable for detailed landform mapping whereas SRTM DEMs are limited by their 90 m resolution and are more suited to reconnaissance level mapping, as used during preliminary mapping for this study (Blundon *et al.,* 2009).

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 cross-cutting 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 degrees in the southwest and 19 degrees 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 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 towards 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.

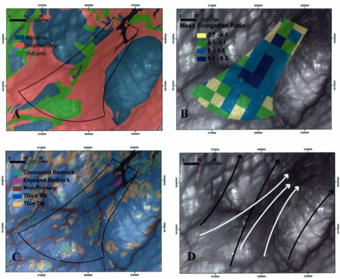

Figure 3.9. A) Simplified bedrock geology map. The flow-set is underlain primarily by sedimentary rocks with minor occurrences of volcanic and granitic rocks at both its inland and lateral margins. Note the position of the flow-set between topographic highs created by intrusive granitic rocks (higher terrain indicated by lighter tones in underlying SRTM DEM). B) Results of analysis of average elongation ratio based on 7.5 km grid. Results show a systematic increase in elongation ration downstream and toward the center of the flow-set, matching expected velocity fields within an ice stream.
C) Simplified surficial geology map of main study area overlain over SRTM DEM.
D) Simplified reconstruction of regional ice flow events. Black lines represent regional north to north-easterly flow event and white lines represent younger ice streaming event.

3.5 Discussion

3.5.1 Ice Streaming in the Newfoundland Ice Cap

The operation of palaeo-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; 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 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 palaeo-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 and have dimensions that are proportional to the large source area and volume of ice available to them. In contrast, the NIC was a much smaller ice mass (roughly 130 times smaller) with a central ice divide and smaller catchments and consequently much lower volumes of ice available to feed ice streams. For this reason 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.*, 2007), which supports the possibility that NIC ice streams crossed the modern coastline and flowed some distance across the continental shelf. There is limited geomorphic evidence for the Placentia Bay ice stream inland of the modern coast, which is not surprising as ice streams do not have to start at the source of glaciation. 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. 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).

3.5.2 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, early 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 9 d). This flow-set is superimposed on the regionally-pervasive flow-set which may indicate that it is post LGM (*c.f.* 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 centers 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 around the island (Grant, 1974). Complex local ice-flow patterns have resulted from this complex glacial history (*e.g.*, Catto, 1998). The existence of ice streams within 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, deformable sediments (*e.g.,* Patterson, 1998; Clark and Stokes, 2001; De Angelis and Kleman, 2005, 2007). The flow-sets identified 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 initiated by subglacial sediment deformation whereas thinner cover down-flow suggests that basal sliding would have been a 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 describe ice streaming over relatively thin sediment cover, both of which suggest transport by basal sliding rather than sediment deformation.

3.5.3 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 meters 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 (Fink 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 lithologies 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 (*c.f.*, Brushett *et al.*, 2007), 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.

3.6 Acknowledgements

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3.7 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 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

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.

Bennett, M.R.
2003: Ice streams as the arteries of and 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 Mines and Energy, Geological Survey Branch. Report 09-1, pages 95-109.

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.

2007: 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.

Clark, C.D.

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.

Clark, C.D.
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 Mine 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.

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

De Angelis, H. and Kleman, J.
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 Hughes, T.J. 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 Prest, V.K.
1987: Late Winsconsinan and Holocene history of the Laurentide Ice Sheet. Géographie physique et Quaternaire, Volume 41, pages 237-263.

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.

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. Geological Survey of Canada, Paper 74-1B, pages 215-216.

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

Jennngs, 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, Bobrowsky, P.T., and Hall, G.E.M. Geological Society Special Publication No. 185, pages 1-17.

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

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.

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.

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.

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 parries. 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* 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.

Stokes, C.R. and Clark, C.D.
2001: Palaeo-ice streams. Quaternary Science Reviews, Volume 20, pages 1437-1457.

Stokes, C.R. and Clark, C.D.
2002: Are long subglacial bedforms indicative of fast ice flow? Boreas, Volume 31, pages 239-249.

Stokes, C.R. and Clark, C.D.
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.

Chapter 4: Summary and Conclusions

4.1 Introduction

A recent model of the southeastern part of the Laurentide Ice Sheet (LIS), including the Newfoundland Ice Cap (NIC), suggested that ice streams had a major role in the deglaciation of the region (Shaw *et al.,* 2006). The model, however, was largely conceptual with few empirical tests for validation. New advances in remote sensing technology, such as the 2003 release of Shuttle Radar Topography Mission (SRTM) digital elevation data, present the opportunity to investigate glacial landscapes at a scale and efficiency that were previously unfeasible. Data from an island-wide landform mapping program using SRTM data (Liverman *et al.,* 2006) were combined with relevant supplementary data, including surficial geology, striation records, and more detailed mapping using aerial photographs, to facilitate a research approach that integrated various scales and sources of data. This thesis adds to the initial island wide mapping project (Liverman *et al.,* 2006) by assessing the amount and type of overlap between mapping sources and investigating sources of error associated with mapping using SRTM. It provides, for the first time, a verification of ice-operation on the terrestrial portion of the NIC, highlighting the need to re-evaluate previously mapped areas for ice streaming.

This chapter discusses the outcomes and implications of the four initial research questions addressed in this thesis:

1) *What is the amount and type of overlap between landform data derived from SRTM DEMs and aerial photographs?*

A comparative analysis of landform mapping approaches indicated that landform mapping from SRTM DEMs produced less detailed maps than those based on aerial photographs. It was also demonstrated that SRTM-based maps were more effective when combined with aerial photograph mapping. Although landform counts varied significantly between datasets, the regional trends in landform distribution and ice-flow directions remained consistent across all data sources. This suggests that while there was some compromise in effectiveness, SRTM DEMs can be used in reconnaissance level mapping to gain an initial understanding of regional ice flow histories.

2) Are there any systematic biases that may negatively affect data quality and if so what impact do they have?

Interpretations of glacial landforms from DEMs have the potential for systematic errors in landform identification, such as those produced by relief shading effects, which may affect mapping quality. In this study, the 90 m horizontal resolution of SRTM DEMs restricted the opportunity to map glacial landforms smaller than this size (*e.g.,* small flow-parallel landforms and ribbed moraine). Additionally, the superior tonal and textural properties of aerial photographs allowed visualization of features which cannot be detected using relief shading alone in DEM visualization. This is likely due to their low amplitude, and hence their faint signature using shading. The recent release of a new global 30 m resolution global DEM provides an opportunity to address some of the resolution limitations of SRTM DEMs.

Though aerial photograph mapping was able to produce more detailed landform maps, SRTM DEMs were able to identify large-scale, ice-flow features that were not visible on aerial photographs. By combining new, higher resolution, DEMs with similar quality satellite imagery and relevant geological data, large-scale systematic mapping projects can be completed in considerably less time than conventional aerial photograph and field mapping. Such mapping can provide the basis for ice-cap wide reconstructions that are critical in light of new evidence of ice streaming.

3) *Is there landform evidence to support the concept of ice streaming in the NIC as proposed by Shaw et al. (2006)?*

Initial mapping has led to the identification of several flow-sets that have landform assemblages typical of ice streaming (*c.f.,* Stokes and Clark, 1999). More detailed aerial photograph mapping of the Exploits flow set confirms ice stream operation in the NIC, thus providing a positive test of the Shaw *et al.* (2006) model. The results of this study, however, suggest that ice sheet architecture is somewhat more complex than conceptually depicted by Shaw *et al.* (2006). For example, they proposed that a single large ice stream drained through the Notre Dame Channel. The pattern presented here suggests greater complexity with three topographically-controlled flow sets (Halls Bay, Exploits, and Gander) converging into Notre Dame Bay. In other words, the interior of the ice cap was likely drained by smaller, topographically-controlled, tributary-style ice stream networks that drained into larger offshore troughs that contained the larger ice streams depicted by Shaw et al., 2006. This is similar to the situation of contemporary ice streams in Antarctica (*e.g.*, Bamber *et al.*, 2000) and palaeo-ice streams in the northeastern LIS (*e.g.*, De Angelis and Kleman, 2005, 2007).

Past failures to identify ice streams in the NIC were likely the result of a number of factors. First, improvements in remote sensing technologies, such as the release of SRTM DEMs, have provided researchers with the tools necessary to map large areas, at multiple scales, in a manner that was previously impossible, thus allowing for more systematic reconstructions of ice-flow events. Secondly within the last decade there have been numerous developments in the field of glacial geomorphology that have provided researchers with criteria that can be used to aid in the identification of ice streams.

4) *What is the characteristic geomorphic footprint of ice streaming in the Newfoundland Ice Cap?*

The geomorphology of ice stream beds in the former NIC was characterized using the results from island-wide flow set mapping and a detailed study of the former Exploits Ice Stream. All of the flow sets are defined by convergence of attenuated flow-parallel landforms, typically drumlins, mega flutes and crag-and-tail hills, as well as fields of ribbed moraine near the onset zone. The convergence and attenuation of such landforms have formed the basis for the reconstruction of many ice streams elsewhere. Strongly convergent landform patterns and highly attenuated bedforms with elongation ratios up to 18:1 and spatial patterns that mimic expected velocity patterns within an ice stream (*e.g.*, Stokes and Clark, 2002, 2003) support the concept of ice streaming in the NIC.

The flow sets are characterized by thicker sediment coverage inland that thins near the coast. This suggests that basal and/or internal deformation was responsible for sustaining fast flow in these inland areas, whereas in down-flow areas that have considerably less sediment cover, basal sliding was more active. Additionally, all flow set locations are correlated to regional topography whether down flow, across flow or both, with flow-sets typically extending inland to regional topographic highs and flowing along the regional slope toward the coast. Based on this observation it is suggested that subglacial topography is the most important factor in controlling the location and flow of ice streams within the NIC.

4.2 Implications and considerations for future research

Glacial research in Newfoundland has gone through a number of cycles of investigation, the most recent being a regional approach that has focused mainly on 1:50 000-scale map sheet reconstructions. The identification of potential ice stream flow-sets using an integrated landform mapping approach highlights the need to re-examine the process of reconstructing ice flow history in Newfoundland and the incorporation of new landform evidence for ice stream activity. The recent release of 30 m ASTER DEMs provides an opportunity to overcome many of the issues related to resolution that were addressed in Blundon *et al.* (2009). However, these studies still need to be supplemented with mapping from aerial photographs or satellite imagery. A consistent, systematic attempt to map the entire island of Newfoundland using the highest resolution remotely sensed data will be required to fully reconstruct palaeo-ice sheet evolution and architecture. This task has been completed elsewhere in the LIS (*e.g.*, De Angelis and Kleman, 2005, 2007; Stokes *et al.*, 2009) and would likely provide valuable new insights into the glacial dynamics of the NIC.

The NIC was largely marine based, with ice extending out to the continental shelf edge in many areas. For this, reason both terrestrial and offshore records need to be combined as they represent a continuous glacial record. Recent multibeam mapping of glacial landforms in offshore areas (*e.g.*, Brushett *et al.*, 2007) is the beginning of this process. However, more work in both offshore and terrestrial areas is needed to collect sufficient data for a fully integrated model.

The identification of ice streaming in the NIC necessitates a re-evaluation of the traditional approach to drift prospecting. Ice streams elsewhere in the LIS produce Boothia-type dispersal trains defined by a plug-like shape and greater transport of material within compared to outside the dispersal train. The distance of glacial dispersal within ice-streams identified on the island may be significantly greater than has previously been considered. This is likely reflected in the linear decrease in indicator concentrations downstream that is associated with englacial transport above a deforming or sliding bed compared to an exponential decrease in indicator concentrations associated with sheet flow (Klassen, 2001; Dyke, 2008). For these reasons ice streams need to be incorporated into future drift prospecting projects. Further field-based research may explore several of the following themes: (i) targeted till sampling across footprints to test for geochemical signatures of ice stream dispersal; (ii) investigation of till characteristics within ice stream footprints to test 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 transition zone. This information can be used to further confirm ice stream operation and to develop dispersal models specific to small, island-based glacial systems.

Glacial systems modeling provides the opportunity to explore the glaciological, palaeo-climatological and glacial geological conditions that generated ice streams in a relatively small maritime ice cap, such as the NIC. In this approach large-scale mapping, such as used in this study, can test and calibrate future ice sheet models. Recent models of the LIS (*e.g.*, Stokes and Tarasov, 2010) have been able to identify numerous areas of fast ice flow within the ice sheet. However, the resolution of the Stokes and Tarasov model is large and many of the ice streams identified in this study would be below the detection limit. Nonetheless, large-scale landform mapping studies could act to calibrate island specific models or future models with higher resolutions.

4.3 Concluding remarks

Although conceptually proposed for the NIC (*e.g.*, Denton and Hughes, 1981; Hughes, 1998; Shaw *et al.*, 2006), ice stream operation has now been confirmed within marine (Brushett *et al.*, 2007) and terrestrial (Blundon *et al.*, 2010) areas. Onshore, ice stream footprints are characterized by landform assemblages similar to those identified by Stokes and Clark (1999) including: convergence of flow-parallel landforms and the presence of elongate landforms with length:width ratios of up to 18:1. The location of these flow sets appears to be strongly correlated with variations in local topography, highlighting the fundamental role topography plays in controlling ice stream location in the NIC. The identification of ice streaming in the NIC necessitates a re-evaluation of traditional approaches to reconstructing ice flow history in Newfoundland, taking into account the critical role ice streams played in controlling internal ice sheet dynamics.

The recognition of ice stream footprints was accomplished through the application of a multi-scale landform mapping approach. This multi-scale approach has been facilitated by technological advances, such as the release of the SRTM DEMs and the use of GIS. Although SRTM was capable of identifying similar trends in regional ice flow, the biases identified in this work need to be accounted for in an effort to produce accurate landform maps, which can then be used as the basis for future island-wide ice cap reconstructions. With the recognition that ice streams operated in marine areas (*e.g.*, Brushett *et al.*, 2007), offshore geological records need to be combined with terrestrial mapping in order to gain a complete understanding of the dynamics of the NIC.

4.4 References

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.

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

Blundon, P., Bell, T., and Batterson, M.J.
2010: Ice streaming in the Newfoundland Ice Cap: Implications for the reconstruction of palaeo-ice flow and drift prospecting. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch. Report10-1, pages 143-157.

Brushett, D., Bell, T., Batterson, M.J., and Shaw, J.
2007: 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.

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.

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

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 Hughes, T.J. 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.

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

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, Bobrowsky, P.T., and Hall, G.E.M. Geological Society Special Publication No. 185, pages 1-17.

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. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 06-1, pages 177-189.

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.

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

Stokes, C.R. and Clark, C.D.
2002: Are long subglacial bedforms indicative of fast ice flow? Boreas, Volume 31, pages 239-249.

Stokes, C.R. and Clark, C.D.
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. and Tarasov, L.
2010: Ice streaming in the Laurentide Ice Sheet: A first comparison between data-calibrated numerical model output and geological evidence. Geophysical Research Letters, Volume 37, L01501.

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.