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THE ROLE OF ICE DYNAMICS ON DRIFT DISPERSAL IN THE NEWFOUNDLAND ICE CAP: PRELIMINARY INVESTIGATIONS

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ABSTRACT

Recent research suggests that ice streams – zones of faster moving ice in ice sheets – represent a major uncertainty in our understanding of ice-sheet dynamics, and their role in sediment dispersal. Traditionally, approaches used in drift prospecting have considered normal ice-sheet flow as the primary method for transporting glacial sediment from its source region; sediment dispersal involving ice streaming behaviour, however, must consider increased glacial erosion and transportation.

In contrast to the rapid decline (negative exponential) in glacial dispersal distance in areas of normal ice-sheet flow, conceptual models and limited field evidence suggest a linear decline with distance down-ice, in areas influenced by ice streaming. Using till-geochemical data, e.g., *rubidium (Rb) concentrations, our analysis shows that glacial dispersal in two areas of former ice streaming in the Newfoundland Ice Cap displays a distinct linear decline in dispersal distance, with higher Rb concentrations persisting for longer distances down-ice (5-10 times longer) compared to adjacent areas that experienced normal ice-sheet flow. Follow-up analysis will test if ice-stream dispersal patterns have both elevated element concentrations and more diverse geochemical signatures compared to those from normal ice-sheet flow.*

INTRODUCTION

Drift prospecting is a method of exploration primarily used within the mineral resource sector. It is based upon the premise that indicator minerals of economic importance, found within glacial deposits (primarily till), can be traced back to their source in bedrock and relies heavily on the reconstruction of ice-flow history and surficial geology mapping (Batterson and Liverman, 2001; Klassen, 2001; Blundon *et al.*, 2010).

Newfoundland and Labrador has a rich history of drift exploration. Numerous mineralization occurrences have been discovered in the Province using traditional drift prospecting techniques such as striation mapping, clast-fabric analysis, till geochemistry, and surficial geology mapping (Batterson and Liverman, 2001; McClenaghan and Kjarsgaard, 2001; McClenaghan *et al.*, 2002). An example is the Strange Lake Y–Zr–REE deposit on the Québec–Labrador border (Batterson and Liverman, 2001).

Newfoundland's complex glacial terrain resulted from the interaction between numerous small ice caps making up what is locally known as the Newfoundland Ice Cap (NIC; Batterson and Liverman, 2001; Stea and Finck, 2001). Distinct centres of ice accumulation occurred on the Long Range Mountains, central Newfoundland, and on the Avalon Peninsula (Batterson and Liverman, 2001). Evidence suggests that Newfoundland's complex glacial history stems from shifting ice centres and divides during the last glacial period (*e.g.,* Catto, 1998), coupled with the occurrence of ice streaming (Figure 1; Blundon *et al.*, 2010). Ice streams represent areas of fast flow within an ice sheet and potentially influence ice-flow patterns, ice dynamics and ice margin configuration (Stokes and Clark, 2001). This study describes how ice-dispersal patterns may be affected by ice streaming behaviour, and examines the till-geochemistry data for two former ice-stream locations in central Newfoundland for characteristic signatures.

ICE STREAMS AND THE NEWFOUNDLAND ICE CAP

Ice streams are dynamic tributaries of fast-flowing ice within an ice sheet that can reach velocities in excess of 800 m y^{-1} (Tulaczyk *et al.*, 2000; Benn and Evans, 2010; Livingstone *et al.*, 2012). Contemporary ice streams in the Antarctic Ice Sheet are more than 20 km wide and 150 km long (Stokes and Clark, 1999). Ice streams are subdivided into three zones: an onset zone of ice convergence and accelera-

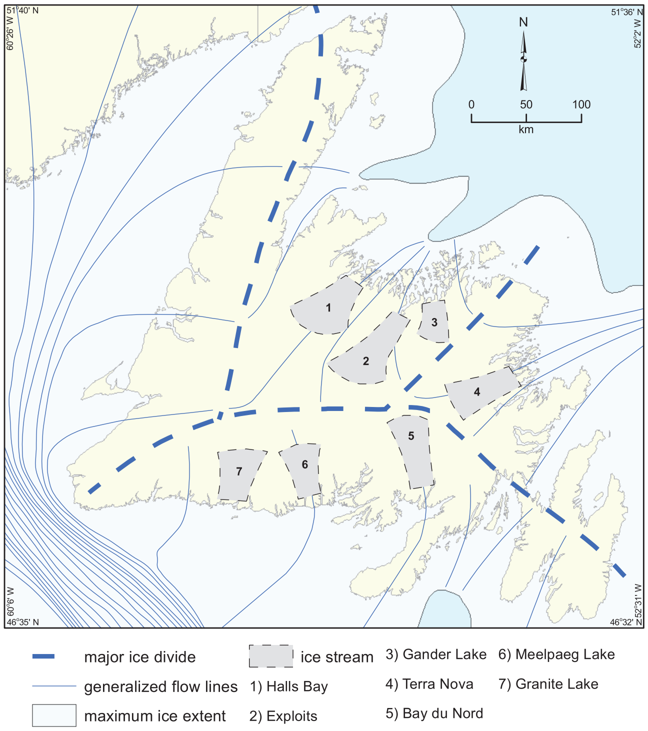

Figure 1. *Model of ice margins at 16 Ka (modified from Shaw* et al.*, 2006) and the position of the seven ice streams proposed by Blundon* et al. *(2010).*

tion, an elongated trunk zone with sustained fast ice flow, and a terminal zone of ice deceleration, either ending as a calving margin in the sea or as a lobate ice margin on land (Stokes and Clark, 1999). Accordingly, the subglacial footprint of an ice stream is typically characterized by pervasively streamlined landforms; for example, drumlins and megaflutes in the onset zone and mega lineations in the trunk zone (Everest *et al.*, 2005; De Angelis and Kleman, 2008; Blundon *et al.*, 2010; Livingstone *et al.*, 2012).

In 2010, seven ice-stream footprints were identified in the NIC using a two-scale mapping approach. Using visual exploration and interpreting the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), Blundon *et al.* (2010) used the glacial landform database maintained by the Geological Survey of Newfoundland and Labrador (GSNL) to conduct a broad scale assessment in order to identify and map flow sets (*i.e.,* groups of similar landforms having consistent patterns) associated with potential ice streams on the Island. Their attention particularly focused on the degree of convergence, density, parallelism, and crosscutting relationships of ice-directional landform assemblages and attenuated bedforms such as crag-and-tail hills, megaflutes, and drumlins (Figure 2). Those ice streams mapped in the NIC during the last glaciation were typically smaller – ranging from 30 to 75 km long and 20 to 26 km wide – which likely reflects its overall smaller dimensions and ice catchments (Blundon *et al.*, 2010).

ICE STREAMS AND DRIFT PROSPECTING

Ice streams represent a major uncertainty in our understanding of ice sheet dynamics (Stokes and Tarasov, 2010) and as a result, any re-assessment of ice dynamics or sediment dispersal involving an ice stream must include a re-evaluation of the methods used in drift prospecting. Traditionally, approaches used in drift prospecting have considered normal ice-sheet flow as the primary method for transporting glacial sediment from its source region implying that ice will slowly move from the centre of an ice sheet to its terminus in a uniform manner. Recently however, the focus has been on how ice streams influence the highly dynamic nature of sediment dispersal within ice sheets (Bennett, 2003; Evans *et al.*, 2008; Ottesen *et al.*, 2008; Stokes *et al.*, 2009; Blundon *et al.*, 2010) and the importance of ice streams with respect to drift prospecting.

When investigating variations in dispersal patterns it is important to consider ice streams as they are responsible for discharging huge amounts of ice and glacial sediment from the centre portion of an ice sheet and are linked to well-defined tracks of far-travelled debris (Stokes and Clark, 2001; Bennett, 2003; Blundon *et al.*, 2010; Livingstone *et al.*, 2012). Although research has been completed on the dispersal of glacial sediment under normal ice-sheet flow (Shilts, 1976; Clark, 1987; Alley *et al.*, 1997; Broster *et al.,* 1997; Klassen, 1999; McMartin and McClenaghan, 2001; McClenaghan *et al.*, 2002; Harris and Bonham-Carter, 2003; Larson and Mooers, 2004), few studies have focused on the dispersal patterns of glacial sediment beneath ice streams (Stokes and Clark, 2001; Everest *et al.*, 2005; Ross *et al.*, 2009; Blundon *et al.*, 2010). The traditional approaches used in drift prospecting fail to include an interpretation of how ice stream behaviour affects dispersal patterns of glacial debris with respect to economic mineralization.

Mathematical models focused on the dispersal of glacial sediment under normal ice-sheet flow have been developed (Boulton, 1996; Hildes *et al.*, 2004; Larson and Mooers, 2004; de Winter *et al.*, 2012) using decay constants, half distances, and transport distances in order to model the distribution of indicator minerals down-ice (Clark, 1987). However, the glacial-dispersal model proposed by Shilts (1976) has been most frequently used in the literature. Shilts' model constructed for normal ice sheet flow demonstrated a negative exponential decay of indicator minerals down-ice with a rapid decrease (roughly 50%) of glacial sediment deposited close to the source region (Figure 3; Shilts, 1976; Clark 1987; Klassen, 1999; Harris and Bonham-Carter, 2003; Larson and Mooers, 2004).

Within an ice-stream footprint, evidence suggests that the concentration gradient of glacial sediment does not fol-

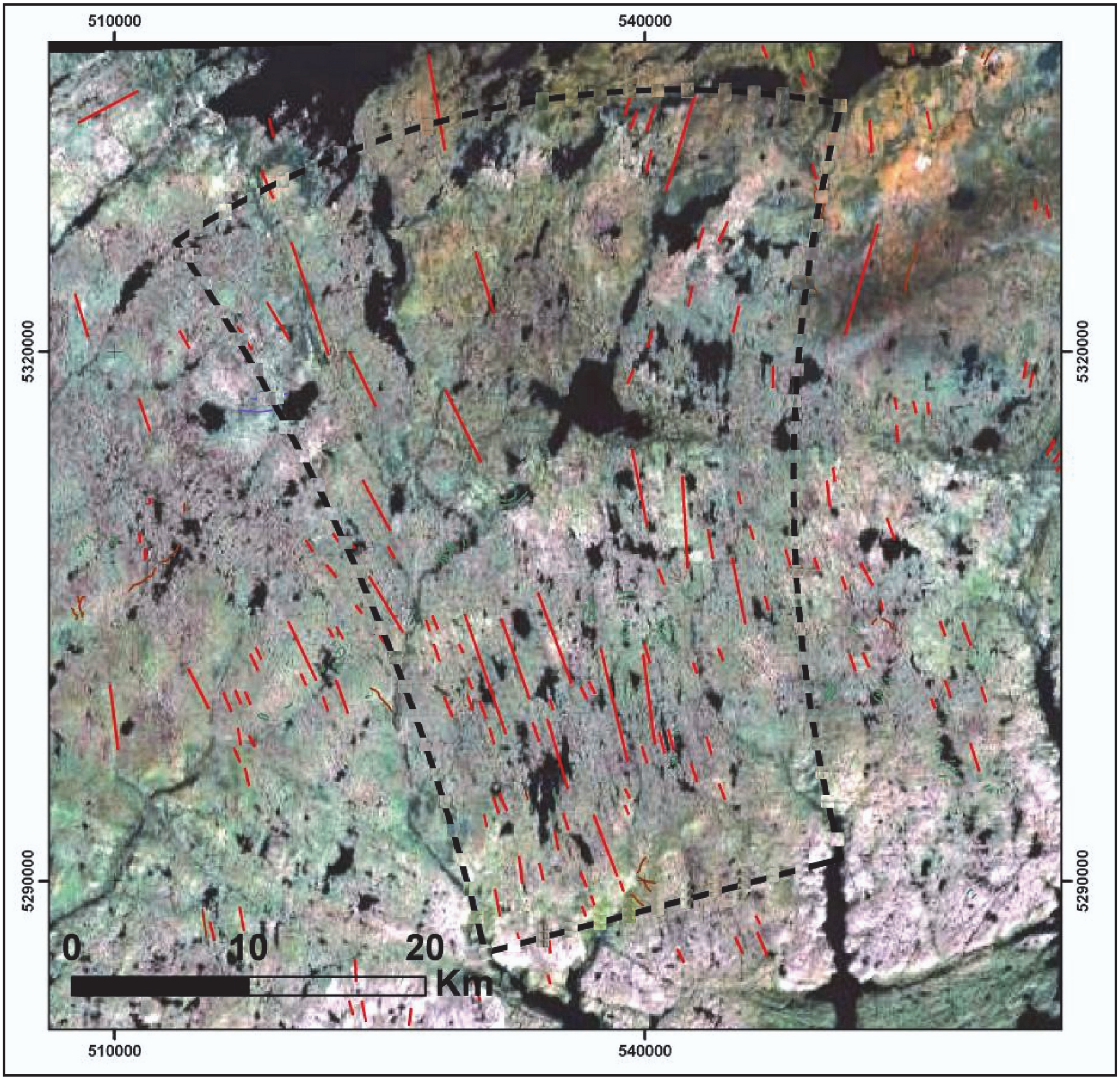

Figure 2. *The subglacial footprint of the former Meelpaeg Lake ice stream on the south coast of Newfoundland, as mapped by Blundon* et al. *(2010).* See *Figure 1 for location of footprint (#6). Red lines represent flow-parallel landforms (crag-and-tail hills, megaflutes, and drumlins) identified from aerial photograph interpretation. Note the distinct convergence and high density of landforms in the onset and trunk zones, respectively.*

low Shilts' model, but rather a linear decrease in sediment concentration down-ice would be more accurate (Figure 4; Clark 1987; Klassen, 1999; Dyke, 2008) due to the combination of englacially entrained sediment and rapid ice flow. This would allow a higher concentration of glacial sediment to remain in the ice over longer distances. As a result, the deposition rate of sediment under ice stream flow would be substantially slower than deposition under normal ice sheet flow and subsequently longer dispersal trains would form. For example, Dyke (2008) documented high concentrations (>50%) of carbonate-derived till remaining in the footprint of the Steensby Inlet Ice Stream in Baffin Island up to 32 km down-ice from the source region. The following section describes whether ice streams in the NIC produced negative exponential dispersal patterns associated with normal ice sheet flow or linear trends as suggested by recent evidence (Dyke, 2008).

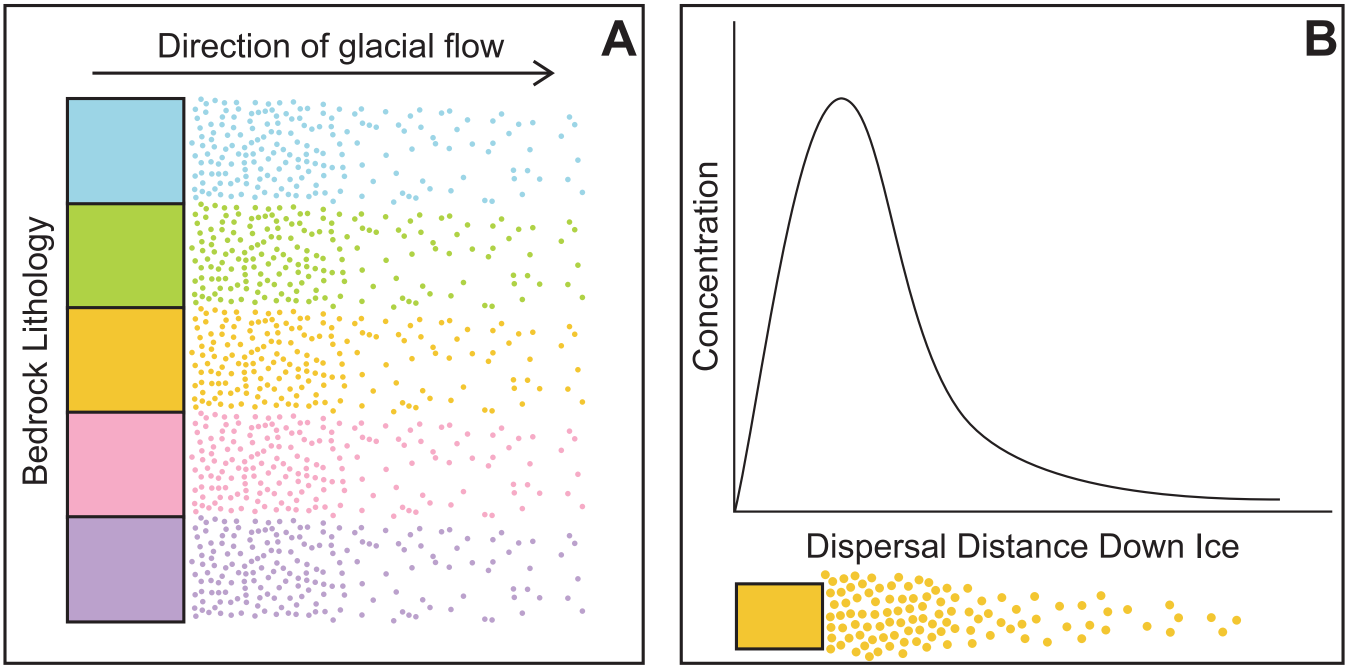

Figure 3. *A) Spatial distribution of glacial sediment under normal ice-sheet flow; and B) Negative exponential distance-decay model proposed for glacial sediment under normal ice-sheet flow (modified from Shilts, 1976). The maximum concentration of sediment is close to the source region with a rapid decrease in the concentration of sediment (roughly 50%) at its half distance.*

DATA SOURCES AND ANALYSIS

In an effort to understand how ice streams disperse glacial sediment, this study employed till-geochemistry data made available in the Geoscience Resource Atlas Online by the GSNL. Till samples were collected across the Island of Newfoundland (Figure 5) using the Geological Survey of Canada guidelines summarized in McClenaghan *et al.* (2013). Further information on the procedures and protocols used by the GSNL Geochemical Laboratory to prepare till samples for analysis can be found in the Till Sediment Geochemistry help file associated with the Geoscience Resource Atlas Online (*http://geoatlas.gov.nl.ca/custom/help/till-geochemhelp.html*).

This study focused on the Exploits and Gander ice stream footprints because they contain the highest till-geochemical data coverage of all seven paleo-ice streams identified in Newfoundland. Distance-decay curves were created using rubidium (Rb) due to its abundance in granitic bedrock of distinct composition that exist near the onset zones of both the Exploits and Gander ice stream footprints.

Prior to analyzing the data in ArcMap 10.2, missing values were removed from the dataset using Microsoft Excel. Using the 3–D analyst tool, distance-decay curves were created using the point profile function in ArcMap 10.2 for each element of interest. The data associated with each point profile created was then exported into Microsoft Excel. To create a distance-decay curve, moving point averages were calculated using median values of the concentration data in order to emphasize the long-term trend for each distance-decay curve. Median values were used to create distance-decay curves instead of averages to ensure that the position of the midpoint on the trend line corresponded to real sample points instead of halfway points. The use of real sample points instead of halfway points decreases the error associated with the trend line.

DRIFT-DISPERSAL PATTERNS

For this study, specific attention focused on the differences between distance-decay curves produced in areas of normal ice sheet flow and ice stream flow. A comparative study was also conducted to determine if distance-decay curves for Rb behaved in a similar linear fashion within the Exploits and Gander ice stream footprints. As Figure 6 illustrates, three separate point profiles were plotted in areas containing the highest density of till-geochemical data and directly down-ice from a granitic bedrock of distinct composition near the onset zone.

First, a distance-decay curve (B-B’) was plotted for Rb in an area of normal ice-sheet flow between the Exploits and Gander ice stream footprints due to an abundance of till-geochemistry data sites and a distinct granitic outcrop in the

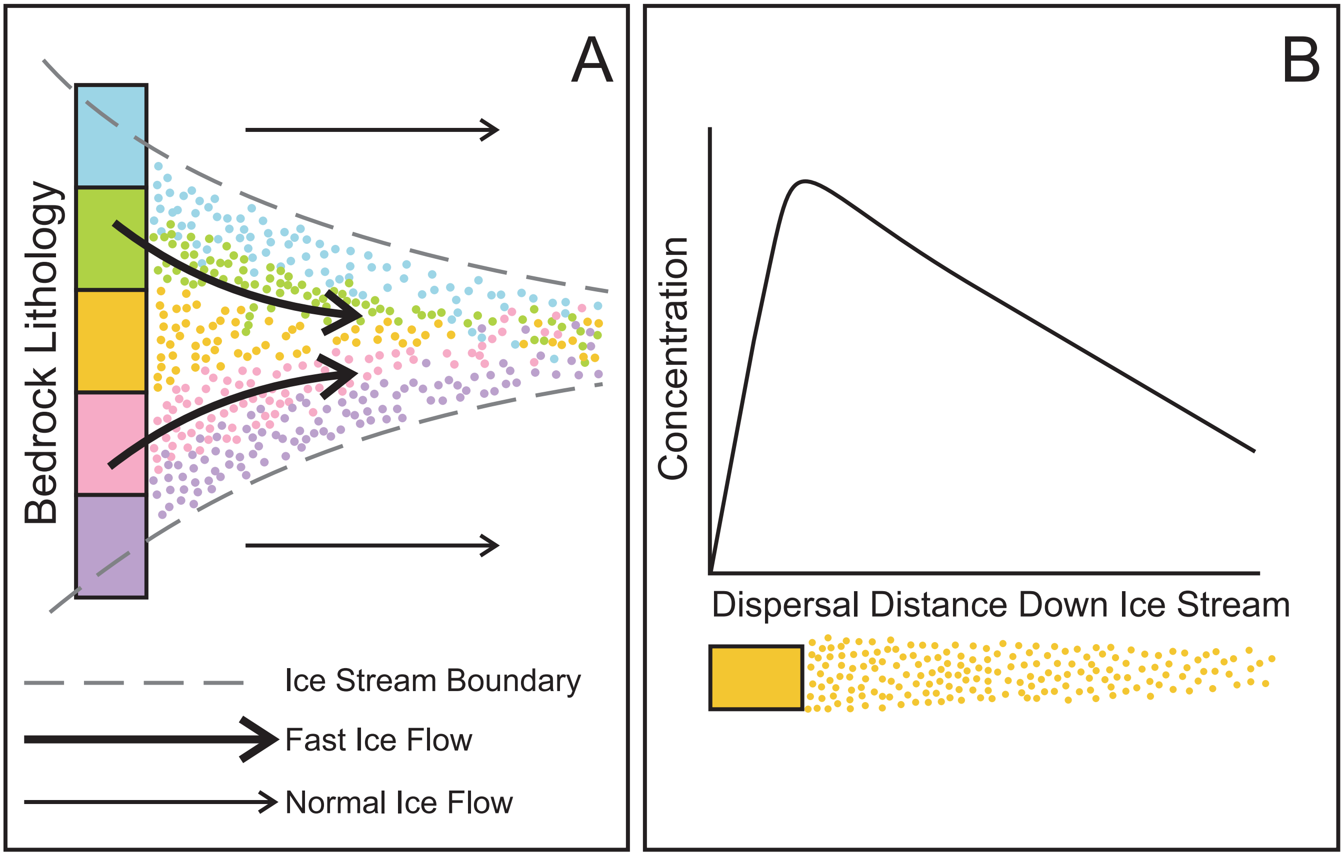

Figure 4. *A) Spatial distribution and subsequent channelling of glacial sediment under ice-stream flow; B) Linear distance-decay model proposed for glacial sediment down-ice under ice-stream flow. Due to funnelling ice, englacially entrained sediment, and rapid ice flow, a higher concentration of glacial sediment is able to remain in the ice column over long distances allowing for longer dispersal trains.*

area. The beginning of the distance-decay curve (B) intersects the granitic outcrop and extends to the coast (B'). According to the distance-decay curve produced, Rb reached its maximum concentration within the glacial sediment as the glacier moved over the granitic outcrop and within a distance of approximately 10 km down-ice from the source, the Rb concentration decreased by >50% resulting in a negative exponential trend.

Second, distance-decay curves were plotted for Rb within the Exploits and Gander ice stream footprints. The distance-decay curves for the Exploits and Gander ice stream footprints were created near the west and east lateral margins, respectively. This was due to a combination of the density of till-geochemistry sites as well as a granitic outcrop just south of their positions in the onset zones. Both distance-decay curves extend past the terminal zones proposed by Blundon *et al.* (2010) to account for glacial sediment carried to the coast by ice streaming. The distance-decay curve for the Gander ice stream footprint extends south of its proposed dimensions due to the availability of till-geochemistry data sites in the area; however, the distance-decay curve for the Exploits ice stream footprint does not fully extend south into its onset zone due an absence of till-geochemistry data in the area.

As illustrated by its distance-decay curve (A-A') in Figure 6, the initial Rb concentration within the Exploits ice stream footprint decreased by approximately 50% over a distance of 117 km in a linear fashion. As well, the Gander ice stream footprint produced a linear distance-decay curve (C-C') as the initial Rb concentration decreased by approximately 75% over a distance of 70 km.

Due to their varying dimensions, the distance-decay curve produced within the Gander ice stream footprint is much shorter than that of the Exploits ice stream footprint, but they are comparable as they both illustrate a linear decrease in Rb concentration down-ice stream from their source regions. Similarly, whereas their initial Rb concentrations vary, the distance-decay curves generated within both the Exploits and Gander ice stream footprints suggest that higher concentrations of Rb will remain for longer distances down-ice under ice-stream flow just as field evidence suggested for carbonate-derived till (Dyke, 2008). In our

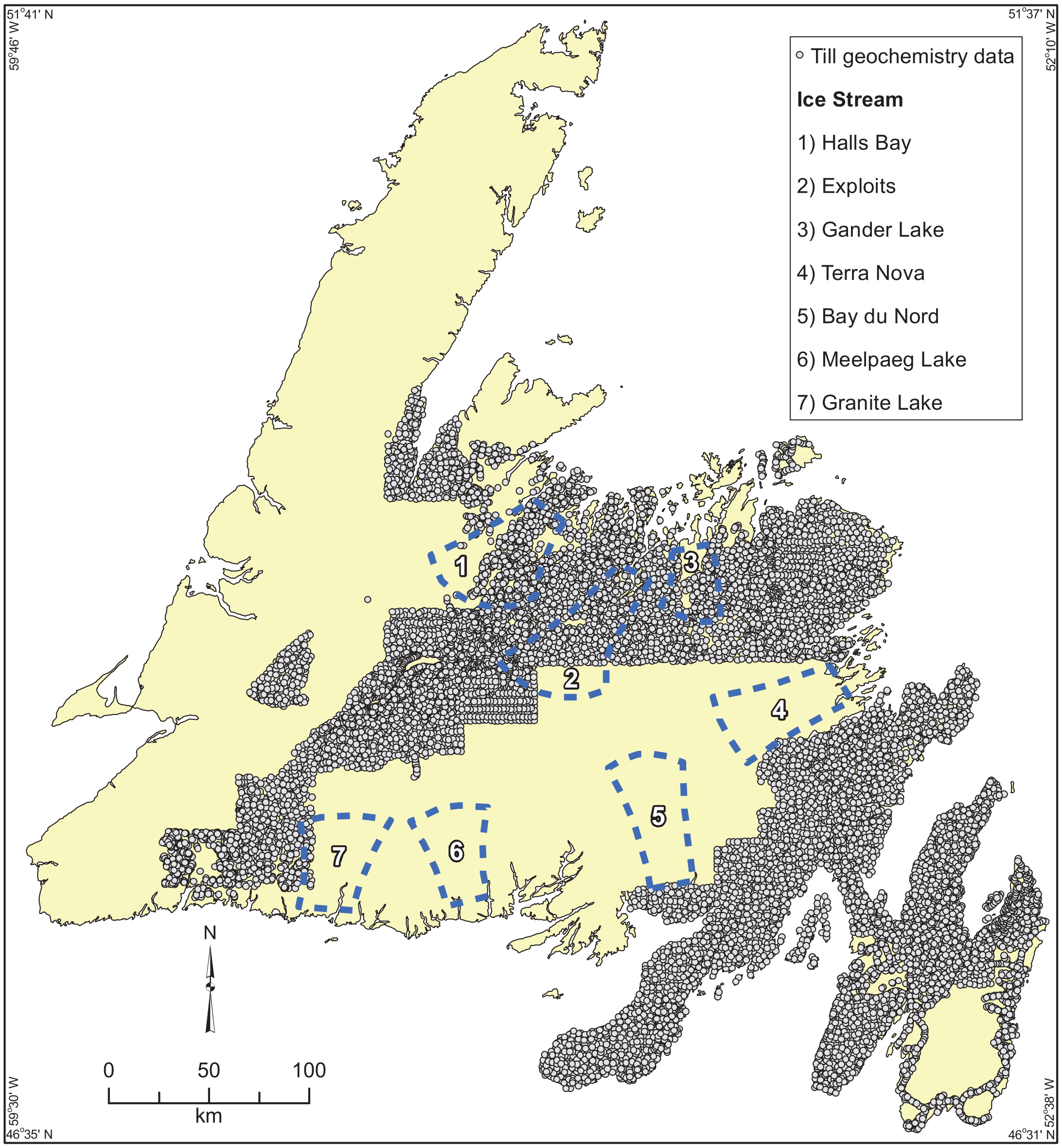

Figure 5. *The distribution of till-geochemistry sites on the Island of Newfoundland and position of proposed ice stream footprints by Blundon* et al. *(2010).*

analysis, similar linear trends also existed for elements such as Ba, Be, K, La, Sc, and Zn within these ice-stream footprints.

FURTHER RESEARCH

Whereas the occurrence of ice streams in the NIC does not alter the traditional drift prospecting techniques used in areas of normal ice-sheet flow, it does require an alternative interpretation of the till-geochemical data to account for the modified drift dispersion in areas influenced by ice streaming behaviour. This study focused on the differences in dispersal patterns between normal ice-sheet flow and ice-stream flow. Further research will: i) investigate lake-sediment geochemistry data for similar dispersal patterns within ice-stream footprints; ii) relate higher element concentrations in ice stream footprints back to stronger ice flow and erosion; and iii) determine whether a broader range of elements exist within ice-stream footprints due to its convergent onset zone.

Ice streams are associated with powerful glacial erosion and have the ability to move large quantities of glacial sediment down-ice (Stokes and Clark, 2001). A comparative study using till-geochemistry data will provide the necessary means to investigate whether ice streams in the NIC were capable of entraining higher element concentrations than areas influenced by normal ice-sheet flow. Assuming a varied bedrock lithology exists in the onset zone, it is expected that a wider range of elevated element concentrations will exist within the trunk zone due to the convergent ice flow in the onset zone. To investigate, further research will compare the range of elements found at a corresponding distance down-ice from similar bedrock within the trunk zone of an ice stream footprint and an adjacent area influenced only by normal ice-sheet flow.

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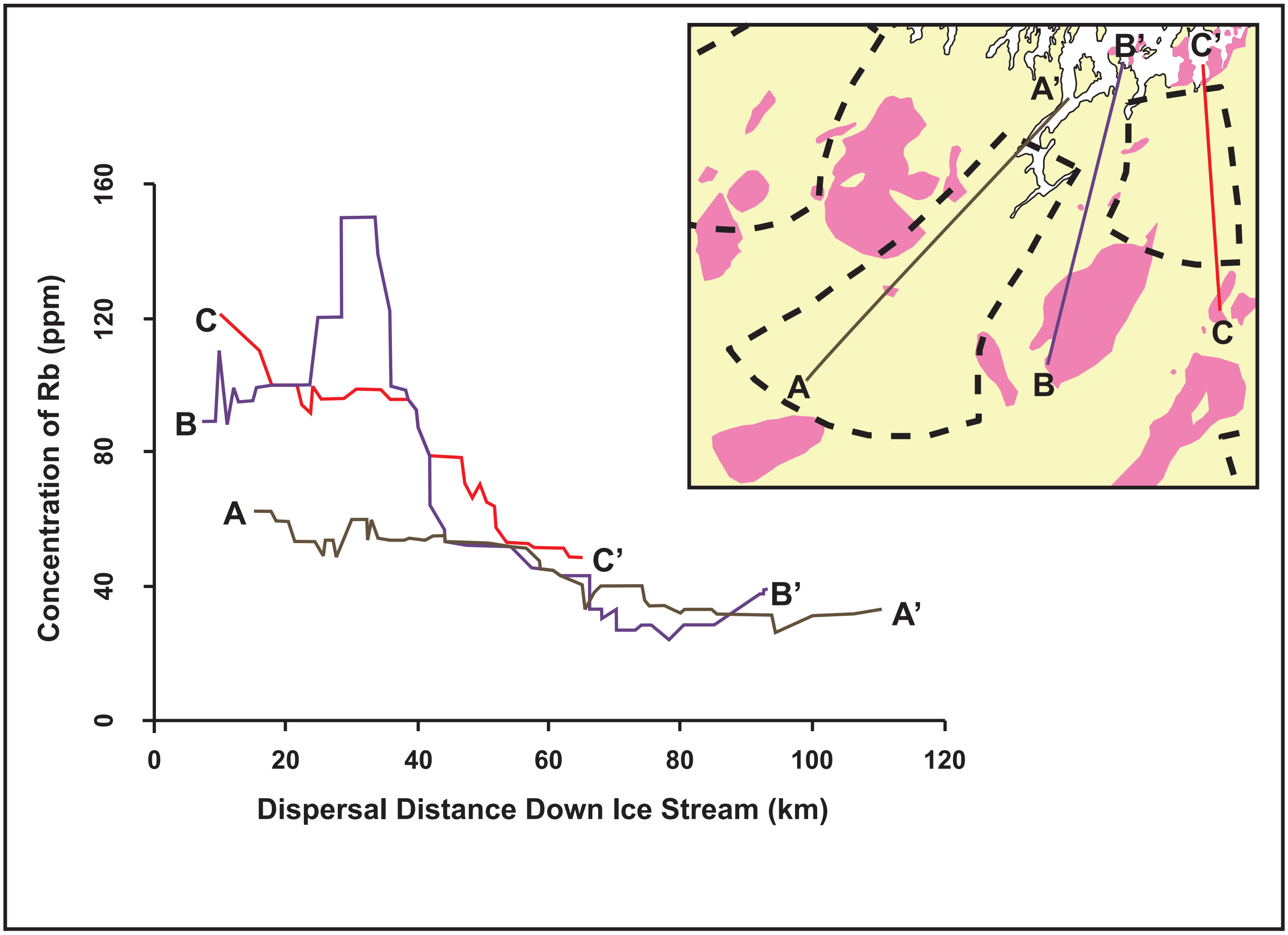

Figure 6. *The resulting distance-decay curves for rubidium (Rb) under normal ice-sheet flow and ice-stream flow. The red and brown linear distance-decay curves were graphed using Rb concentrations within the Exploits and Gander ice-stream footprints. The purple negative exponential distance-decay curve was graphed using Rb concentrations located in the area between the ice-stream footprints. The shaded light mauve polygons in the inset map represent areas of granitic bedrock.*

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