Geological Survey of Canada
Scientific Presentation 166

NET EVOLUTION OF SUBGLACIAL SEDIMENT TRANSPORT IN THE QUEBEC-LABRADOR SECTOR OF THE LAURENTIDE ICE SHEET, QUEBEC AND NEWFOUNDLAND AND LABRADOR

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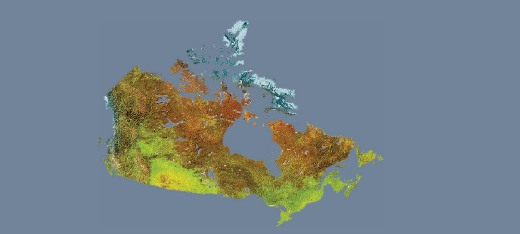


Summary of Research

Ice streams play a significant role in dispersing sediment from the inner regions of ice sheets to their margins. However, the effects of ice streaming on divide migration and the effects of ice stream catchment organization on sediment dispersal patterns are not well-documented, especially within the interior regions of ice sheets.

To investigate the effects of ice divide migration and changing ice stream catchment zones on dispersal, an area within the heart of the Quebec-Labrador (Q-L) sector of the Laurentide Ice Sheet (LIS) was selected to investigate the impact of ice divide migration on glacial sediment dispersal. This location is an ideal setting for this investigation as it has an updated ice-flow chronology and included the identification of an ice divide migration across the study area.

Previous work detailing dispersal within the study area was limited to regions of economic interest and qualitative data on clast dispersal (Figure 1; Klassen and Thompson, 1993). Subglacial dynamics for a part of the study area were also estimated using lake density, landform density, landform elongation, and ^{10}Be abundance data (Rice et al., 2020). This work identified several glacial terrain zones (GTZs). However, it was unknown how glacial dispersal patterns would correlate to the established ice-flow chronology and estimated subglacial conditions and whether dispersal data could provide additional insights into subglacial dynamics and the effects of ice streams on erosion, transportation and dispersal of glacial sediments.

Till sample analysis was conducted on three different size fractions (ranging from till matrix to boulders). Principal component analysis (PCA) was also used to characterize geochemical dispersal patterns and determine the provenance of the till, revealing patterns that were not detectable using single-element or single mineral distribution maps. The results were integrated into the broader context of regional till dispersal and ice sheet evolution, providing important constraints for glacial system models and subglacial process models.

Our results provide insights into the regional glacial dynamics and their evolution in a core region of the LIS. Specifically, the sediment record and provenance analysis provide evidence for relatively uniform, warm-based conditions and subglacial dynamics during an early northeast ice-flow phase (Flow 1). The preservation of regional dispersal patterns from this early flow is explained by a shift from actively flowing warm-based ice to a more polythermal base, including zones of colder, more sluggish ice which resulted from ice divide migration. These dynamic ice conditions and the subsequent development of narrow ice stream catchment zones reshaped some pre-existing dispersal patterns, thus creating palimpsest trains and new dispersal patterns within the warm-based areas of the younger ice-flow phases. Subglacial sediment provenance analysis thus provides unique and important insights that can improve ice sheet dynamics reconstructions.

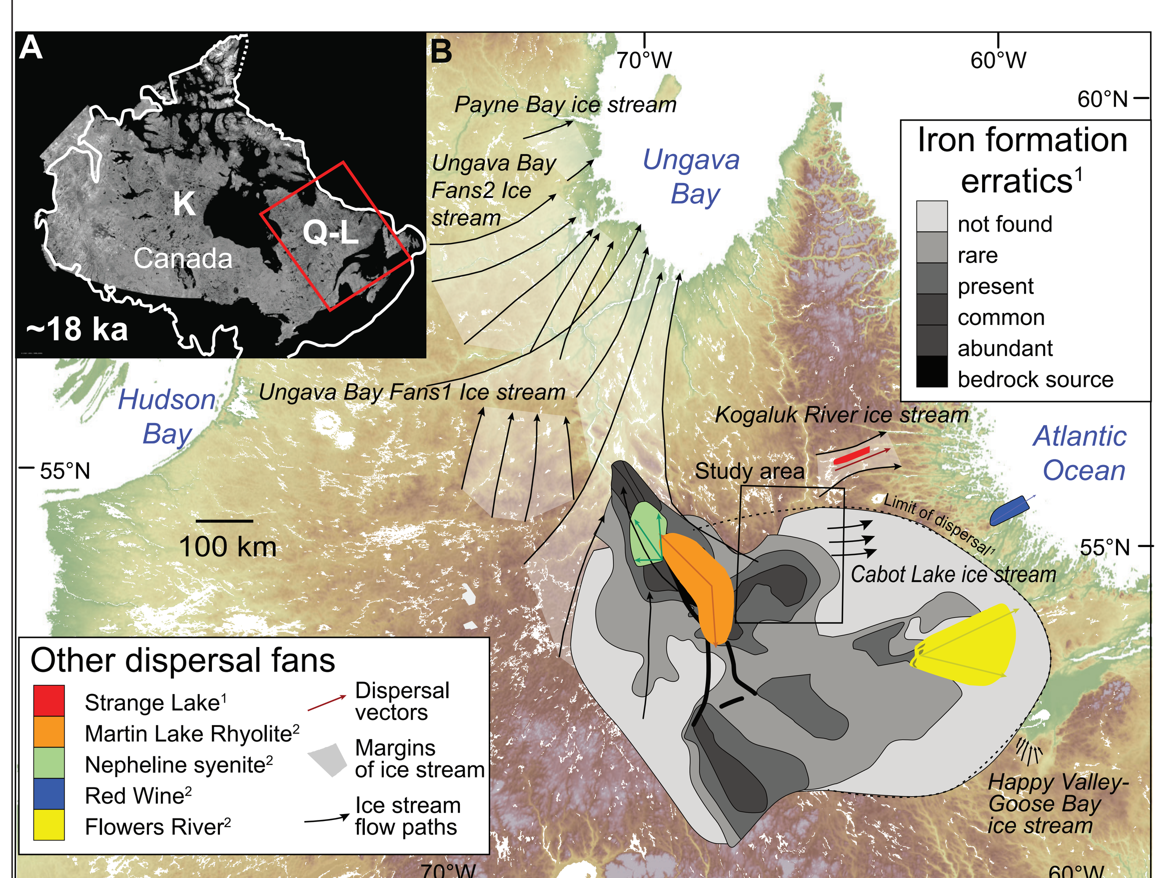


Figure 1. (A) Extent of the Laurentide Ice sheet (white outline) at 18 ^{14}C ka BP(Dyke, 2004) with the two major domes indicated: the Keewatin (K) in the northwest and the Quebec- Labrador (Q-L) in the east. The red box indicates the location of the larger figure. (B) Digital Elevation Model (DEM) of the Ungava Peninsula with regional ice streams from Margold et al. (2015) compilation overlain (black arrows). The dispersal patterns identified by Klassen and Thompson (1993) have also been overlain. These dispersal patterns are more linear near the coastal regions and become more fan-shaped inland, indicating reworking by multiple ice-flow phases. The dispersal pattern of iron formation pebbles is an amoeboid-shaped dispersal fan, indicating significant reworking during subsequent ice-flow phases. The base map was created using data downloaded from https://open.canada.ca/data/eng/dataset/

Study area and Previous work

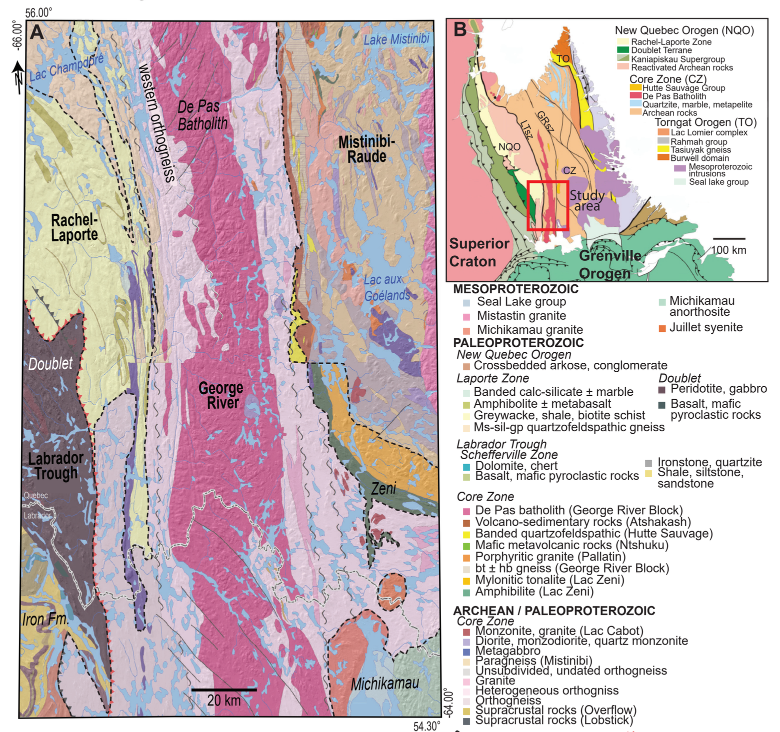


Figure 2. (A) Simplified bedrock geology of the study area (Modified from Sanborn-Barrie, 2016; Corrigan et al., 2018). The major tectonic blocks (see Figure 3) have been outlined in black dotted lines. (B) Simplified bedrock geology of the Core Zone and surrounding geology (modified from James et al. 2003).

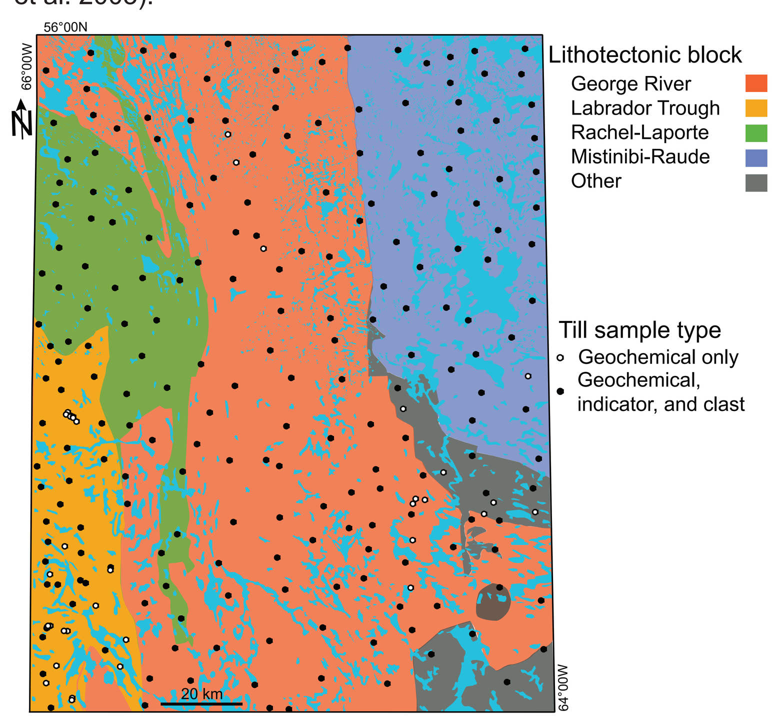


Figure 3. The five main lithotectonic blocks of the study area with till sample locations indicated as black dots.

Location

The study area straddles the Quebec and Labrador border, northeast of Schefferville.

Bedrock

The bedrock geology of the study area consists of five main lithotectonic blocks: The Mistinibi-Raude in the northeast, the George River, which centres the study area, the Rachel-Laporte in the northwest, the Labrador Trough in the southwest, and other smaller groups mainly in the southeast of the study area.

Glacial

The study area is within the heart of the Q-L sector of the LIS. Previous regional surficial studies have identified five ice-flow phases within the current study area (Rice et al., 2023). Previous work also identified the subglacial conditions (Rice et al., 2020) throughout these ice-flow phases from oldest to youngest:

1. Northeast ice flow: oldest flow, it was a widespread, warm-based flow that likely originated from the Quebec Highlands (Klassen and Thompson, 1993).

2. Northwest ice flow: warm-based conditions confined to a small region in the northwest correlated to Ungava Bay ice streams and the establishment of the ice divide somewhere to the east.

3. East/northeast ice flow: a warm-based flow, confined, it is correlated with multiple east-oriented ice streams, followed by ice divide migration to the west.

4. South flow: warm-based, it was confined to the area west of De Pas batholith and was regionally topographically controlled.

5. Various directions: late-deglacial ice flow, possibly from smaller ice caps, locally topographically controlled.

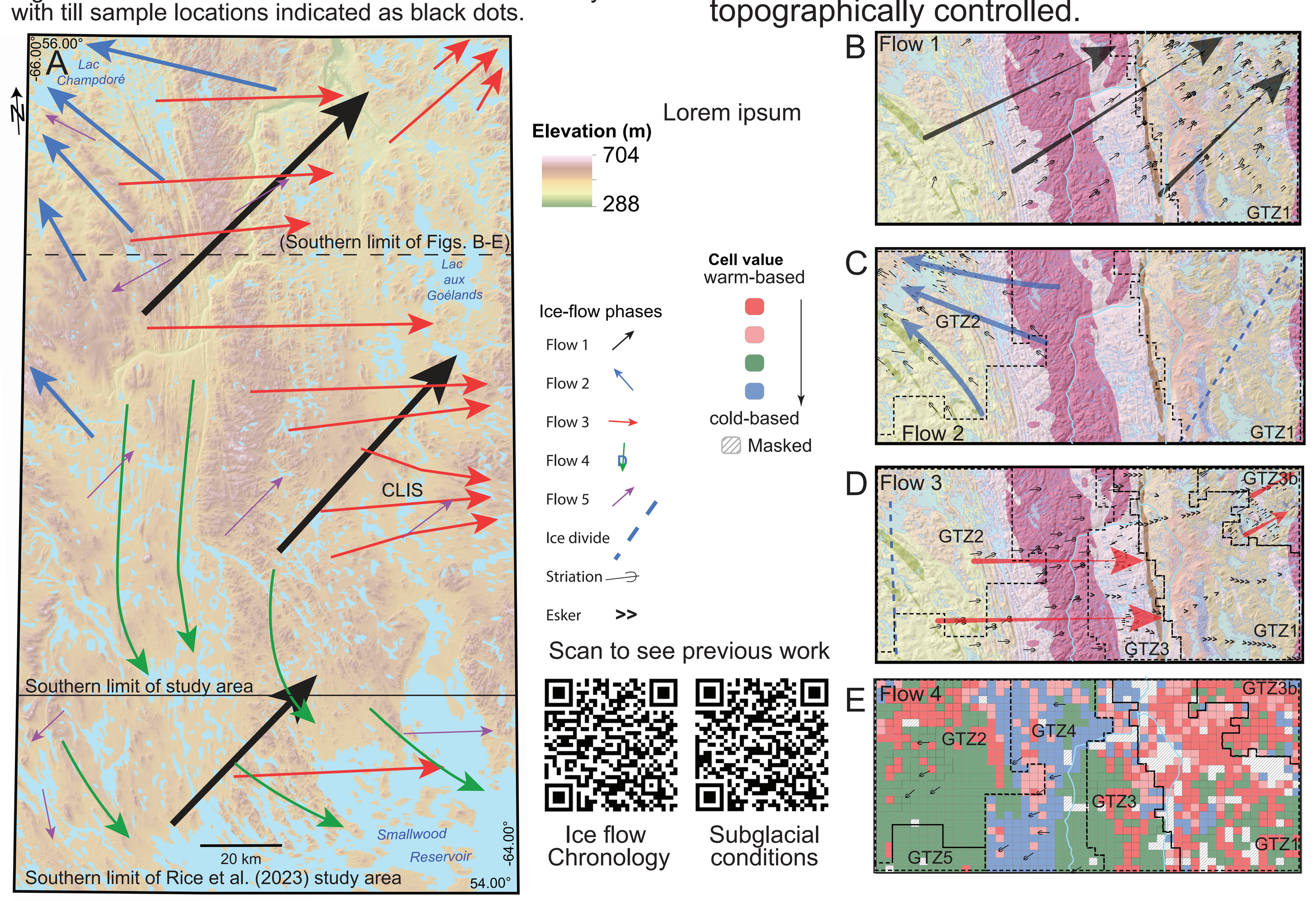


Figure 4. (A) Relative ice flow chronology of Rice et al. (2023) showing 5 ice-flow phases. The current study area is a smaller section of Rice et al. (2023)'s study. Note the Cabot Lake Ice Stream (CLIS). (B, C, and D) The glacial terrain zone (GTZ) evolution correlated to the ice-flow history of the northern third of the study area as identified by Rice et al. (2020) with bedrock geology identical to Figure 2A. (E) The resulting estimated subglacial conditions for all GTZs determined by Rice et al. (2020).

Methods and results

Samples were collected from frost boils (where present; Figure 5A) or from hand-dug pits in non-permafrost terrain. Sampling protocols and quality control and quality assurance procedures established by the Geological Survey of Canada (McClenaghan et al. 2020) were followed.

Pebbles were collected from 210 sample sites for clast lithology analysis. Clasts were categorized based on their lithology and then grouped based on which of the five lithotectonic domains they were sourced.

Bulk (10-15 kg) till samples were collected from the same 2010 sites, from which indicator minerals were separated. Results were then correlated with bedrock geology (Figure 6).

A total of 243 samples (including 23 archived samples) were submitted to the GSC's Sedimentology Laboratory for grain size analysis (Figure 7A) and to Bureau Veritas for till matrix geochemistry analysis.

The till matrix geochemistry analysis results were used for Principal component analysis (PCA). A centre-log ratio transformation was applied to account for the issue of data closure. K-means clustering was used to identify unique relationships between elements and their spatial association.

The first three PC scores were brought into Oasis Montaj®, where the results were rigged using 500 m^2 cells (Figure 8). These three results were then superimposed to create a composite image. The colours on the maps reflect the association of each cell to the PC scores, as indicated by the accompanying ternary diagram, where PC1 is red, PC2 is green, and PC3 is purple.

The results from the clast lithology classification, indicator mineral analysis, and geochemical analysis with PCA analysis were then placed in the context of the established ice-flow chronology and subglacial dynamics for the study area.

Pebble counts (> 2.0 mm)

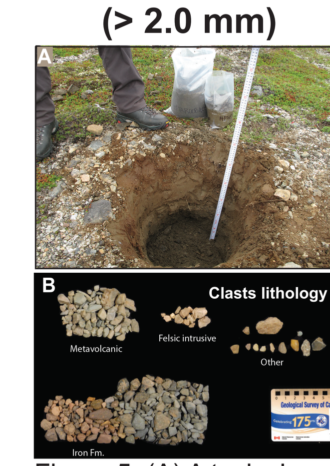
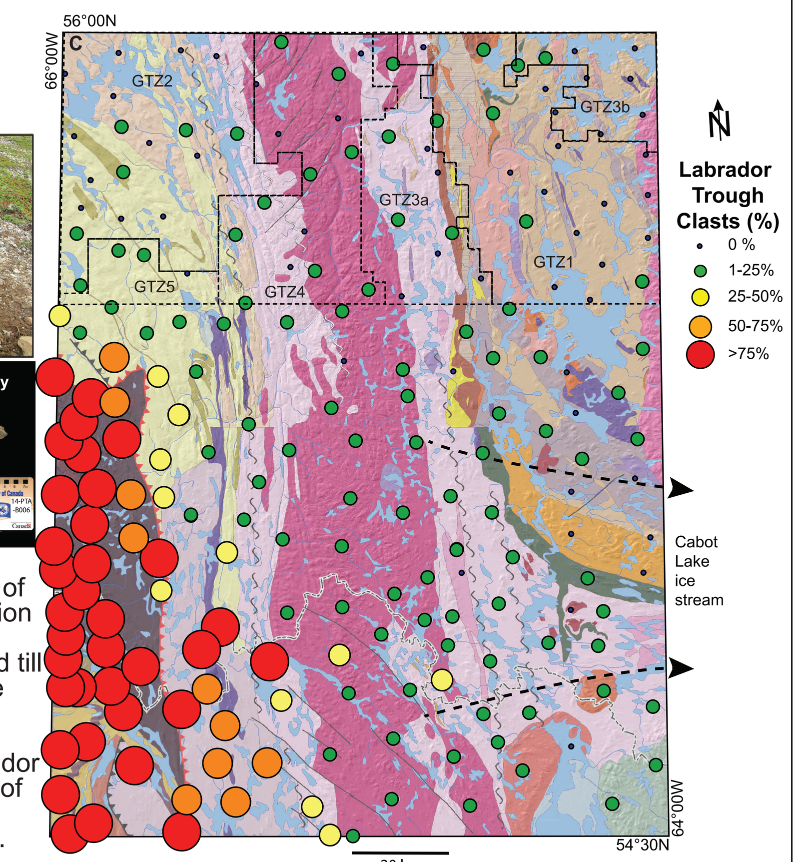


Figure 5. (A) A typical sample site. (B) Results of clast lithology classification for a single sample. (C) Results from all collected till samples from across the study area for iron formation clasts. The source is from the Labrador Trough in the southeast of the study area, where abundances are highest.



Indicator Minerals (< 2.0 mm)

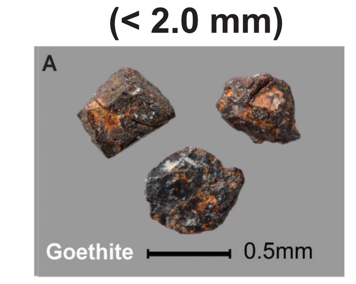
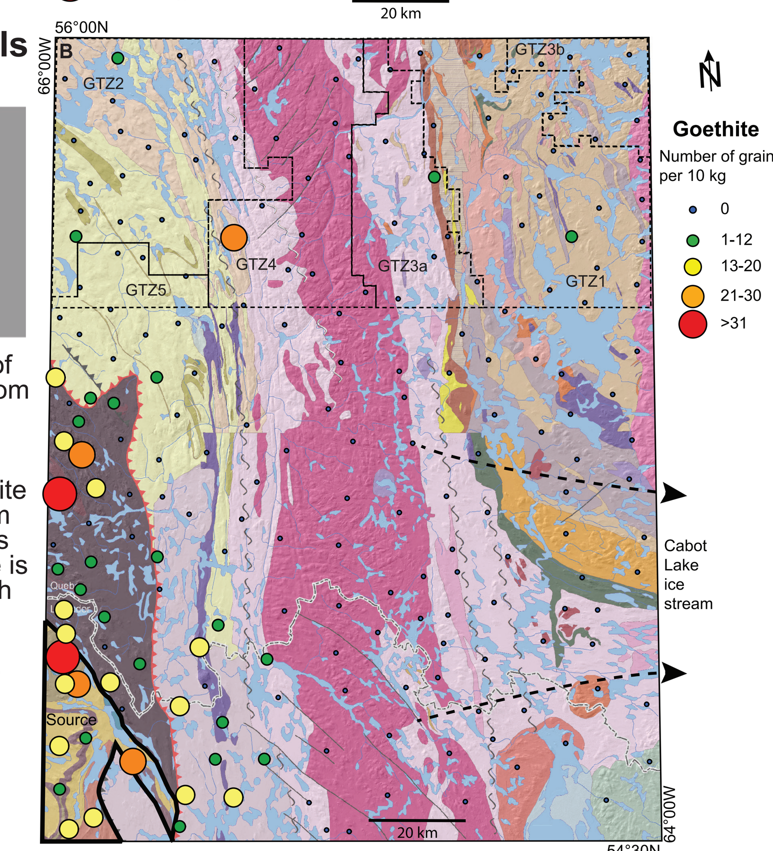


Figure 6. (A) Examples of goethite grains picked from a single sample (photograph courtesy of Michael Bainbridge). (B) The abundance of goethite grains in till samples from across the study area. As with Figure 5, the source is from the Labrador Trough in the southeast of the study area, where abundances are highest.



Till matrix geochemistry (<0.063 mm) & k-means clustering and PCA

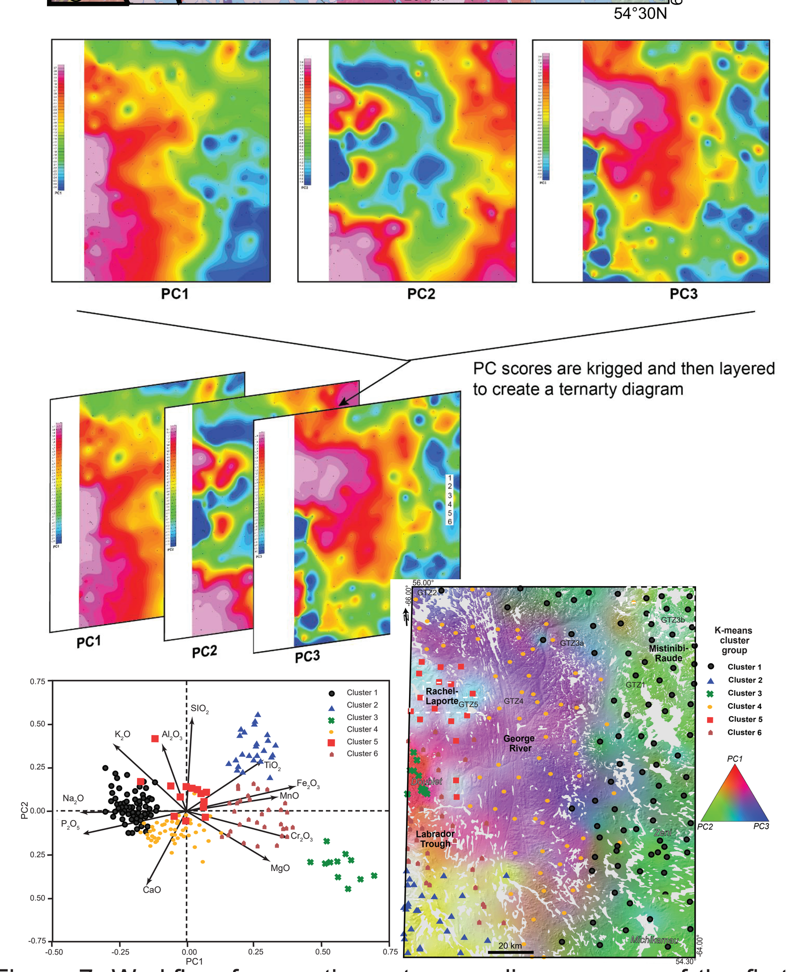
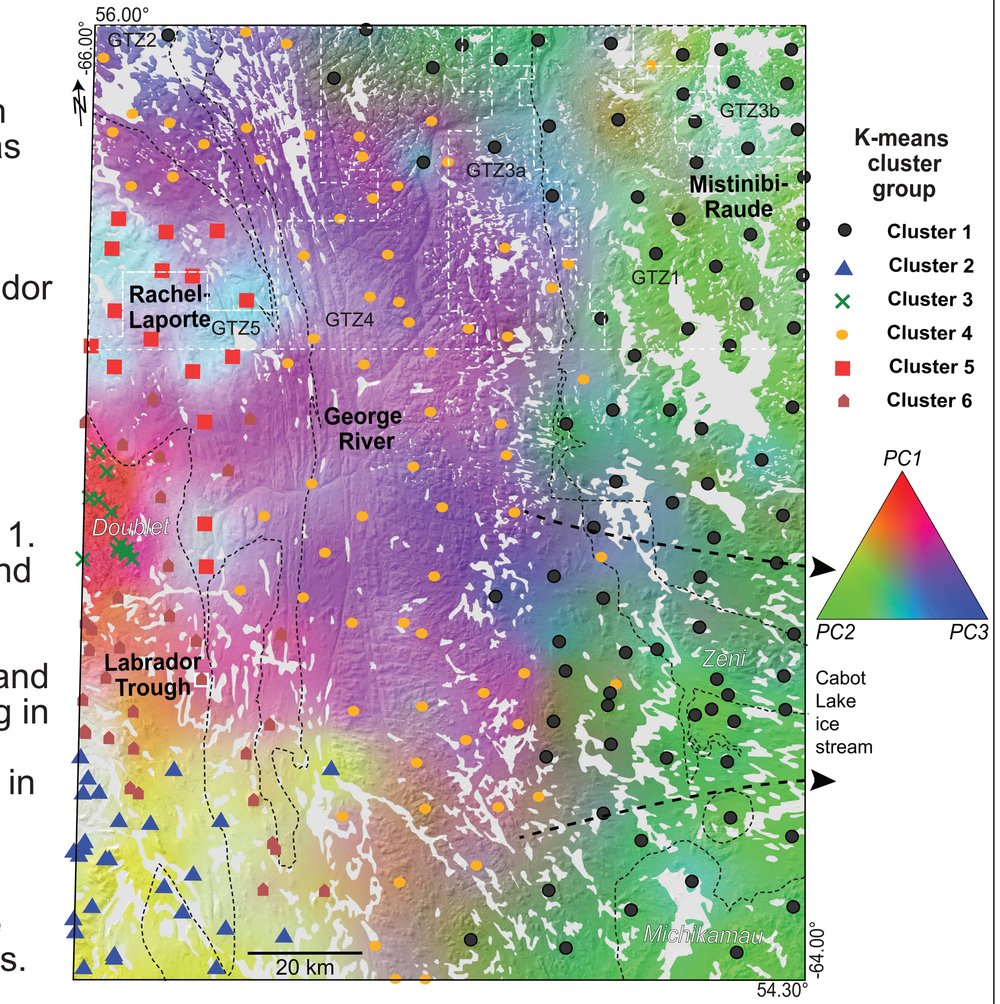


Figure 7. Workflow for creating a ternary diagram map of the first three PC scores for the study area. (Lower left): A biplot of principal component analysis PC1 vs. PC2 for the major oxides determined from till matrix geochemistry grouped by k-means cluster group.

Discussion



Ice-flow phase 1

The identification of Flow 1 in the geomorphological record was initially based on northeast-trending erosion indicators and landforms. It was uncertain whether material from the Labrador Trough was dispersed beyond what was previously suggested. GTZ1 contains most of the evidence for this ice-flow phase. Labrador Trough clasts and goethite grains in GTZ1 provide evidence of dispersal from Flow 1. Between the dispersal source and GTZ1, there was limited glacial erosion in the central highlands (GTZ4), possibly due to harder and more resistant bedrock, resulting in sluggish ice associated with reduced quarrying and abrasion in those areas.

Ice-flow phase 2

Flow 2 initiated the start of more restricted warm-based conditions. As a result, it was limited to the northwest part of the study area (GTZ2), and orthopyroxene dispersal patterns show a strong reworking to the northwest from the centre of the study area. Additionally, the k-means cluster 1 group, which is most associated with the Mistinibi-Raude, shows some westward dispersal in the northern part of the study area. However, it is difficult to confidently define Flow 2's dispersal beyond its geomorphological record due to its limited spatial footprint within the study area.

Ice-flow phase 3

As Flow 2 evidence was preserved in the western part of the study area, there was a transition to warm-based conditions in the east. This transition from sluggish ice to warm-based ice in the east of the study area resulted in the re-entrainment of Flow 1 patterns and potential new eastward dispersal during Flow 3. The extent of Flow 3's contribution to dispersal patterns is unclear, as there is an overlap between k-means clusters of different lithotectonic blocks and the influence of early northeast Flow 1. Orthopyroxene dispersal suggests an eastward direction for Flow 3 beyond its geomorphological footprint, indicating the expansion of warm-based conditions. The presence of other paleo-ice streams, like the Kogaluk River ice stream, also influenced the study area.

Ice-flow phases 4 and 5

Dispersal from Flow 4 was mainly restricted to the western edge of the central upland and a single bedrock block, making it challenging to assess the associated dispersal train. However, evidence suggests southeastern dispersal from the Labrador Trough unit into the George River, supported by k-means clustering, Labrador Trough clasts, and goethite grains. No discernible dispersal patterns were identified for Flow 5 due to its short duration, low erosive conditions, and topographical constraints.

Implications

- The Laurentide Ice Sheet transitioned from widespread warm-based conditions to more polythermal conditions, influenced by regional ice streams within the study area.
- Sediment transport from older ice flow phases, especially Flow 1, involved long-distance transport of glacial clasts.
- Limited long-distance dispersal patterns defined by major oxide geochemical signatures make it difficult to determine the ice flow phase responsible for dispersal.
- The findings reveal a complex subglacial evolution, indicating a more polythermal ice sheet compared to regions with sustained cold-based conditions.

Acknowledgments

This research was funded by the Geological Survey of Canada (GSC) Geo-Mapping for Energy and Minerals II (GEM2) Program (2013-2020) with support from the Polar Continental Shelf Program (PCSP GEM-2 01514, 05915, 06016) under the Core Zone Surficial Activity (Hudson-Ungava Project) and a Research Affiliate bursary to the first author. Generous funding was also provided by the Northern Scientific Training Program (NSTP) and by the Ontario Government through the Ontario Graduate Scholarship (OGS) to the first author. This project also benefited from the support of the Geological Survey of Newfoundland and Labrador (Support for Heather Campbell). The authors thank Matt Pyne (GSC, Ottawa) and GSC summer students Emilie Rufiange, Allan Lion and Grant Hagedorn for their enthusiastic field assistance. Brad Harvey (GSC, Ottawa) is thanked for his assistance with plotting PC ternary map diagrams. (NRCan Contribution No. 20220112).

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ISBN 978-0-660-67875-7
Catalogue No. M41-11/166-2023E-PDF

2023

Publications in this series have not been edited; they are released as submitted by the author.

Permanent link: https://doi.org/10.4095/332151

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Presented at Technical Sessions - Sudbury GAC MAC
Date presented: May 2023

Recommended citation
Rice, J.M., Ross, M., Campbell, H.E., Paulen, R.C., and McClenaghan, M.B., 2023. Net evolution of subglacial sediment transport in the Quebec-Labrador sector of the Laurentide Ice Sheet, Quebec and Newfoundland and Labrador; Geological Survey of Canada, Scientific Presentation 166, 1 poster. https://doi.org/10.4095/332151

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