Field record of ice-flow indicators

The “striation” symbol appearing on regional surficial geology maps includes glacial striae and any other small-scale erosional forms on bedrock (crescentic fractures and gouges, rat tails, nailhead striae, stoss-and-lee topography, etc., e.g. McMartin and Paulen, 2009). These features provide information on direction, sense, and relative age of ice flows, and on the record of older glaciations, commonly poorly preserved in the geomorphic record. The general orientation of roches moutonnées is also represented by a different symbol on the maps and provides an additional record of the ice flow direction.

It is mentioned in Section 3.4 that “Glacial striations also provide an opportunity for reconstructing former ice flow patterns and may preserve older flow traces on bedrock outcrops where abrasion was limited during deglaciation (Kleman er al., 1990)”. However, we are concerned about the lack of consideration and integration between some of the field-based record and the remotely mapped geomorphology to inform and resolve the flowset directions and age relationships, particularly in areas with complex flow patterns during deglaciation. As mentioned in Section 2, the “understanding of ice flow dynamics … suffers from the disconnected nature of studies at varying scales”. Although the ice-flow indicator record can be very detailed locally, striations indicated on surficial geology maps are often distributed regionally and can inform on former and deglacial ice flow patterns where no landforms are preserved. Field-based ice-flow indicators can easily be extracted from surficial geology maps or Open File reports, all available in digital format (using Advanced search in https://ostrnrcan-dostrncan.canada.ca/home), and compiled at the ice sheet sector scale. Such large-scale compilations have been completed recently directly east of the studied area in the west-central Keewatin sector of the LIS (Brouard et al., 2022; Fig. 5 below) and further east along Hudson Bay (Behnia et al., 2020; McMartin et al., 2021; DataS2c below) to help constrain the regional glacial history.

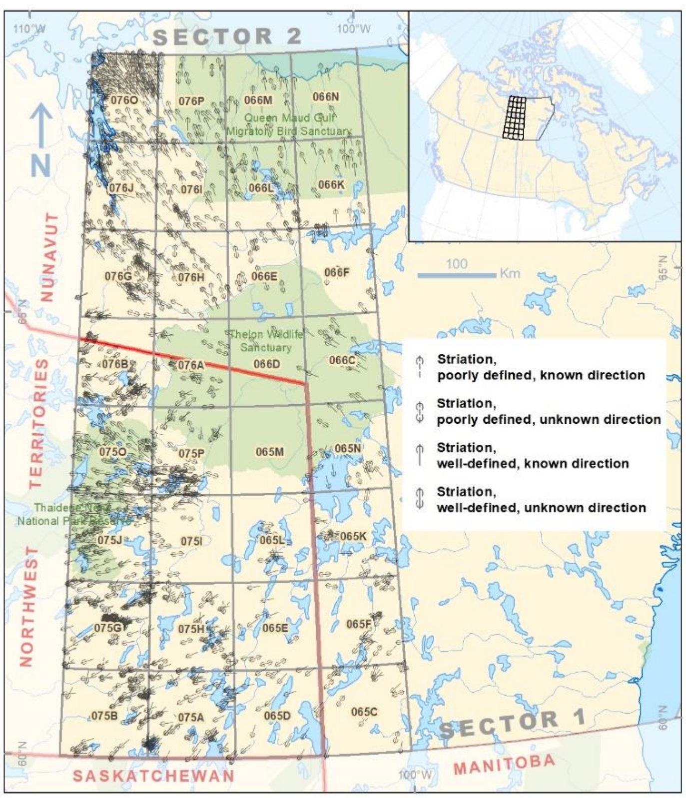
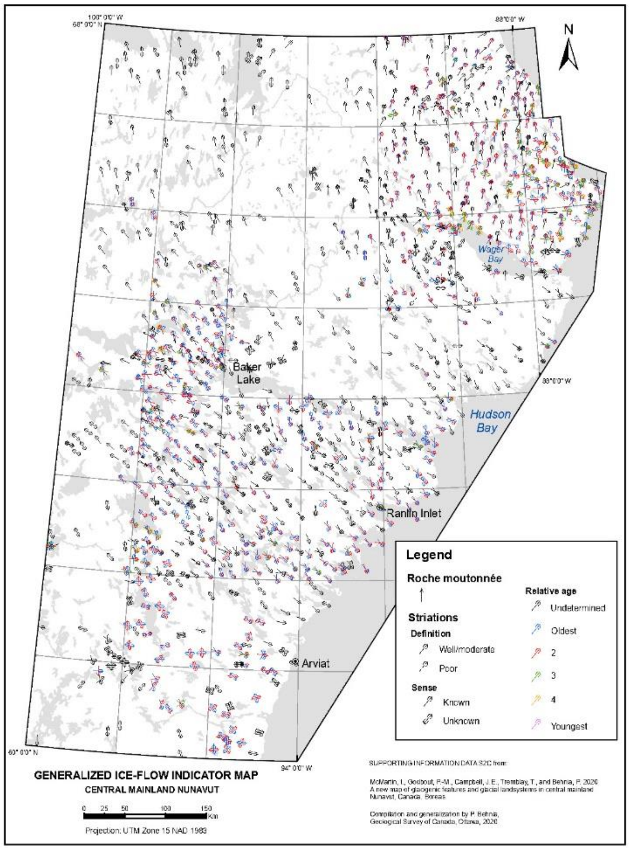


Figure 5. Location of ice-flow measurements in west-central Keewatin and their associated ice-flow orientation (From Brouard et al., 2022).



DataS2c. Generalized ice-flow indicator map, Central Mainland Nunavut (From McMartin et al., 2021).

Interpreted ice-flow indicators and glacial histories from some regional field-based studies were considered (e.g. Smoking Hills), but other available regional maps and Open File reports should also be verified in light of the proposed reconstruction. In this regard, an ice-flow data compilation in the Great Bear Magmatic Zone (Normandeau and McMartin, 2013; Fig. 4 and Appendix II) should be taken into consideration, as well as a regional deglacial history reconstruction in the northeastern Horton Plain region, particularly for the interpretation of a NE(?) flowset (Fs-230) and other relative ages of flowsets 224, 225, 231, 323 (St-Onge and McMartin, 1995 and references herein).

We also suggest a comparative analysis with Dyke and Prest (1987), the only other reconstruction offering a continental overview that shows ice-flow drainage and incorporates the extensive fieldwork data accomplished in Canada since the end of the 19th century. This comparison could provide a richer context for this study, especially in contrast to works primarily based on remote mapping. While the cost-effective approach outlined in this study is certainly practical, a more thorough integration of fieldwork data might offer a comprehensive perspective, reducing the reliance on subjective interpretations, particularly regarding the provision of relative chronology through striations.

Regional stagnation to the east of the studied area

In section 6.2.3, it says "Therefore, we suggest that widespread stagnation had not begun for the northwestern LIS margin to the west of 210°W but may have occurred further to the east, as documented by Sharpe et al. (2021)." First, it should probably be 110°W instead of 210°W, and in the Conclusions on page 47 again: “If widespread stagnation of the margin occurred, we suggest that it must have occurred after the LIS retreated to the east of 110°W.”

More importantly, no basis for the assumption that widespread stagnation may have occurred further east of the studied area is provided, other than what is presented in Sharpe et al. (2021). Recent and current high-resolution geomorphic mapping using ArcticDEM and extensive field-based studies from east of 108°W to the Hudson Bay coast does not support or indicate widespread stagnation (Campbell and Eagles, 2014; Campbell et al., 2016, 2018, 2019, 2020; Lauzon and Campbell, 2018; Livingstone et al., 2020; McMartin et al., 2021; Brouard et al., 2022, 2023; Dyke and Campbell, 2022; Vérité et al., 2024). In contrast, numerous evidence for a sequential, time-transgressive retreat is presented in these publications. If the authors of this study have not mapped east of 110°W, they should not assume or propose that a widespread stagnation characterized ice retreat east of their studied area unless a proper discussion with alternative views is presented.

<u>Ice streams on the Canadian Shield</u>

At Line 961, it says: “While hard-bed conditions are known to exert a stabilising influence on ice flow, large ice streams are observed across the Canadian Shield.” Yes, further east in Keewatin over the Shield, large ice stream footprints have been reconstructed from geomorphic mapping (including high-resolution mapping with ArcticDEM), including not only the Dubawnt Lake ice stream (e.g. Stokes and Clark, 2003, 2004) but several other large ice streams (Margold et al., 2015, 2018; McMartin et al., 2021) and not necessarily involving glacial lakes (i.e. marine-terminating ice streams).

At Line 965, it says that “The development of the ice-marginal Dubawnt Lake to the east of our study is hypothesised to have triggered the Dubawnt Lake Ice Stream… (Stokes and Clark, 2003, 2004)”. This is incorrect. Stokes and Clark conclude that “As the ice margin retreats back, early glacial lakes form in the Thelon and Back River drainage basins. These early glacial lakes in the Thelon River basin increased in size and deepened, triggering the Dubawnt Lake ice stream.” They further suggest that “This results in widespread thinning of the ice sheet and produces a large glacial lake to the south of the ice stream, dammed by the Dubawnt Lake ice stream lobe “. This glacial lake is west of Dubawnt Lake (Stokes and Clark, 2004; Fig 8).

Another point concerns the influence of crystalline bedrock on ice-margin stability. The absence of ice-flow landforms on the Canadian Shield could be attributed to several factors. 1) The scarcity of sediments associated with harder-to-erode crystalline bedrock may hinder landform production. Thus, the absence of ice-flow landforms on crystalline bedrock does not imply the absence of ice streaming (especially on the eastern part of McConnell Lake); it merely indicates that no landforms were preserved. 2) Because crystalline bedrock is more challenging to erode, ice-flow landforms that directly record bedrock are generally smaller and likely too small to be noticed at the scale mapped. Utilizing ArcticDEM at a more detailed scale, such as 1:20,000 or 1:10,000, might have revealed these features.

<u>ArcticDEM and high-resolution mapping</u>

While discussing the benefits of high-resolution data for understanding glacial history, the authors did not actually map at the highest spatial resolution provided by ArcticDEM (2 m). Instead, they mapped at scales ranging from 1:50,000 to 1:100,000 (Dulfer et al., 2023) to cover as much area as possible. This mapping scale is similar to, or even lower in resolution than that in studies that used aerial photographs (1:15,000 to 1:60,000). The advantage of ArcticDEM lies in its complementary data, which enable the production of hillshades at a higher resolution than previously available (about 20-30 m resolution). While we understand the necessity of cost-effective methods, it appears there was an aim to produce a regional-scale product with supposedly high-resolution data, yet the execution was only partially completed. The authors should be cautious with their claims of using high-resolution data, as their practice does not match their assertion.

Uncertainties

Furthermore, the authors acknowledge a 1000-year uncertainty commonly associated with cosmogenic (^{10}Be) ages, which is foundational to the study's framework for ice-margin retreat. While this initial recognition is valuable, a more thorough discussion on how this uncertainty influences subsequent interpretations, particularly regarding suggested peak ice-stream activity at the onset of the Bølling-Allerød interstadial, would greatly enhance the narrative's robustness. Given the acknowledged uncertainties and the inherently subjective nature of both the approach and Dalton's ice-margin reconstruction, a more detailed exploration of these aspects could help strengthen the study's conclusions. While we agree with the authors' assertion that the Bølling-Allerød warming significantly influenced ice sheet melt and dynamic changes, further elucidation on how these uncertainties were navigated in reaching such conclusions would provide clearer insight into the analytical rigor applied throughout the study.

References

Behnia, P., McMartin, I., Campbell, J.E., Godbout, P.-M., and Tremblay, T. (2020). Northern Canada glacial geomorphology database: part 1 — central mainland Nunavut; Geological Survey of Canada, Open File 8717 (ver. 2020), 1 zip file, https://doi.org/10.4095/327796.

Brouard, E., Campbell, J.E., McMartin, I., and Godbout, P.M., 2022. Compilation of surficial geology field data for the west-central Keewatin Sector of the Laurentide Ice Sheet (Northwest Territories and Nunavut); Geological Survey of Canada, Open File 8915, 9 p, https://doi.org/10.4095/330559.

Brouard, E., Campbell, J.E., McMartin, I., Godbout, P.-M., and Roy, M., 2023. Ice-flow reconstruction and deglacial patterns in the west-central Keewatin Sector of the Laurentide Ice Sheet (Northwest Territories and Nunavut, Canada). INQUA, Rome, Italy, 1 poster.

Campbell, J.E., and Eagles, S., 2014. Report of 2014 activities for the geologic and metallogenic framework of the south Rae Craton, southeast Northwest Territories: reconnaissance surficial and bedrock fieldwork in the GEM 2 South Rae project area; Geological Survey of Canada, Open File 7701, 7 p., https://doi.org/10.4095/295463.

Campbell, J.E., Lauzon, G., Dyke, A.S., Haiblen, A.M., Roy, M. 2016. Report of 2016 activities for the regional surficial geological mapping of the south Rae Craton, southeast NWT: GEM 2 South Rae Quaternary and Bedrock Project. Geological Survey of Canada, Open File 8143, Natural Resources Canada, 1-16, https://doi.org/10.4095/299391.

Campbell, J.E., Normandeau, P.X., Godbout, P.M., and McMartin, I. 2018. GEM-2 Glacial Synthesis Project: highlights of 2018 field activities in the Healey Lake area, Northwest Territories and Nunavut. In:

Irwin, D., Gervais, S.D., and Terlaky, V. (compilers), 2018. 46th Annual Yellowknife Geoscience Forum Abstracts; Northwest Territories Geological Survey, Yellowknife, NT. YKGSF Abstracts Volume 2018, p. 8. https://www.nwtgeoscience.ca/forum/session/gem-2-glacial-synthesis-project-highlights-2018-field-activities-healey-lake-area

Campbell, J.E., McMartin, I, Normandeau, P.X., and Godbout, P-M., 2019. Report of 2018 activities for the GEM-2 Rae Project glacial history activity in the eastern Northwest Territories and the Kitikmeot and Kivalliq Regions, Nunavut; Geological Survey of Canada, Open File 8586, 16 p., https://doi.org/10.4095/314741.

Campbell, J.E., McCurdy, M.W., Lauzon, G., Regis, D. and Wygergangs, M., 2020. Field data, till composition and ice-flow history, south Rae craton, NWT: results from the GEM2 South Rae project - Surficial Mapping activity; Geological Survey of Canada, Open File 8714, 40 p., https://doi.org/10.4095/327218.

Dyke, A.S., and Campbell, J.E., 2022. Surficial geology, Abitau Lake, Northwest Territories, NTS 75-B; Geological Survey of Canada, Canadian Geoscience Map 350, scale 1:100 000, https://doi.org/10.4095/330072.

Lauzon, G., and Campbell, J.E., 2018. Surficial geology, Wholdaia Lake south, Northwest Territories, NTS 75-A south; Geological Survey of Canada, Canadian Geoscience Map 342, scale 1:100 000, https://doi.org/10.4095/306373.

Livingstone, S.J., Lewington, E.L., Clark, C.D., Storrar, R.D., Sole, A.J., McMartin, I., Dewald, N., and Ng, F., 2020. A quasi-annual record of time-transgressive esker formation: implications for ice-sheet reconstruction and subglacial hydrology; The Cryosphere 14(6), 1989–2004, https://doi.org/10.5194/tc-14-1989-2020.

Margold, M., Stokes, C.R., Clark, C.D., and Kleman, J., 2015. Ice streams in the Laurentide Ice Sheet: a new mapping inventory; Journal of Maps 11 (3), 380-395, https://doi.org/10.1080/17445647.2014.912036.

Margold, M., Stokes, C.R., and Clark C.D., 2018. Reconciling records of ice streaming and ice margin retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice Sheet; Earth-Science Reviews 143, 117-146, https://doi.org/10.1016/j.quascirev.2018.03.013.

McMartin, I., and Paulen, R.C., 2009. Ice-flow indicators and the importance of ice-flow mapping for drift prospecting. In: Paulen, R.C., McMartin, I. (Eds.), Application of Till and Stream Sediment Heavy Mineral and Geochemical Methods to Mineral Exploration in Western and Northern Canada; Geological Association of Canada, Short Course Notes 18, Geological Association of Canada, 15-34.

McMartin, I., Godbout, P.-M., Campbell, J.E., Tremblay, T., and Behnia, P., 2021. A new map of glacigenic features and glacial landsystems in central mainland Nunavut, Canada; Boreas 50(1), 51-75, https://doi.org/10.1111/bor.12479.

Normandeau, P.-X. and McMartin, I., 2013. Composition of till and bedrock across the Great Bear magmatic zone: Quaternary field database and analytical results from the GEM IOCG-Great Bear Project; Geological Survey of Canada, Open File 7307, 22 p., https://doi.org/10.4095/292560.

St-Onge, D.A. and McMartin, I. 1995. Quaternary geology of the Inman River area, Northwest Territories. Geological Survey of Canada, Bulletin 446, 59 p., https://doi.org/10.4095/203578.

Stokes, C.R., and Clark, C.D., 2003. The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behaviour on the Canadian Shield and insights regarding the controls on ice-stream location and vigour; Boreas 32(1), 263-279, https://doi.org/10.1080/03009480310001155.

Stokes, C.R., and Clark, C.D., 2004. Evolution of late glacial ice-marginal lakes on the northwestern Canadian Shield and their influence on the location of the Dubawnt Lake palaeo-ice stream; Palaeogeography, Palaeoclimatology, Palaeoecology 215(1-2), 155-171, https://doi.org/10.1016/j.palaeo.2004.09.006.

Vérité, J., Livingstone, S.J., Ravier, E., McMartin, I., Campbell, J., Lewington, E.L.M., Dewald, N., Clark, C.D., Sole, A.J., and Storrar, R.D., 2024. Conceptual model for the formation of bedforms along subglacial meltwater corridors (SMCs) by variable ice-water-bed interactions; Earth Surface Processes and Landforms 49(1), 170-196, https://doi.org/10.1016/j.epsl.2023.118510.