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Abstract

A new glacial geomorphology map covers approximately 415,000 km^2 in a core region of the Laurentide Ice Sheet in Nunavut. The compilation builds on recent and legacy maps and is supplemented by visual digitization of glacigenic features using high-resolution digital elevation (ArcticDEM) and Landsat 8 images. From this unprecedented, detailed inventory of >156,000 features and >14,000 field observations, we identify various glacial landsystems, many of which are entirely new and others that are significantly modified or updated. These include ice streams, palimpsest ice flows, and areas where basal ice thermal regimes fluctuated between cold-based and warm-based. The GIS data comprise glacial features mapped at original and generalized scales, standardized field datasets and interpreted glacial landsystems. These comprehensive georeferenced datasets can be used to reconstruct the glacial history in the interior portion of the Laurentide Ice Sheet in Nunavut and Northwest Territories and to identify distinct glacial sediment transport paths for applications to mineral exploration.

Résumé

Une nouvelle carte de la géomorphologie glaciaire couvre environ 415 000 km^2 dans une région centrale de l'Inlandsis Laurentidien au Nunavut. La compilation s'appuie sur des cartes récentes et anciennes et est bonifiée par la numérisation visuelle d'éléments glaciogéniques à partir d'un modèle numérique d'élévation haute résolution (ArcticDEM) et d'images Landsat 8. À partir de cet inventaire inégalé et détaillé de plus de 156 000 éléments glaciaires et 14 000 observations de terrain, nous identifions divers systèmes de terrain glaciaires, dont plusieurs sont entièrement nouveaux et d'autres qui sont considérablement modifiés ou mis à jour. Ceux-ci incluent des courants de glace, des écoulements glaciaires palimpsestes et des zones où les régimes thermiques de la glace fluctuaient entre une base froide et une base chaude. Les données SIG comprennent les éléments glaciaires cartographiés aux échelles originales et généralisées, les observations de terrain standardisées et les systèmes de terrain glaciaires interprétés. Ces ensembles de données géoréférencées peuvent être utilisés pour reconstituer l'histoire glaciaire dans la partie intérieure de l'Inlandsis au Nunavut et dans les Territoires du Nord-Ouest et pour identifier des patrons caractéristiques du transport glaciaire pour les applications à l'exploration minérale.

1. INTRODUCTION

Recently available high resolution digital elevation models (DEMs) have generated unparalleled images of glacial and associated landforms and transformed geomorphological mapping in glaciated terrains (e.g. Putkinen et al., 2017; Clark et al., 2018). The 2-m spatial resolution ArcticDEM was recently made available for the entire landmass area north of 60˚ in the Northern Hemisphere (Porter et al., 2018). The Keewatin region, where one of the largest ice dome of the Laurentide Ice Sheet (LIS) was located, has one of the least constrained paleo-ice dynamics history and ice margin chronology due to incomplete mapping of the glacial geomorphology, uneven distribution of field observations and the scarcity of dated surface materials (e.g. Dyke et al., 2003; Stokes et al., 2012). As part of the Rae Glacial Synthesis project completed under the Geoscience for Energy and Minerals (GEM) Program, high resolution imagery was used for mapping new glacial features and recognizing coherent patterns of landform development (landsystems) in the Keewatin region. The new mapping builds on digitally converted published surficial geology maps (Kerr et al., 2022) and reunites large volumes of ground-based surface geology datasets acquired as part of government surficial surveys, including those collected as part of recent GEM-1 and GEM-2 surficial geological mapping projects. These comprehensive datasets are used to interpret glacial landsystems and can help to reconstruct glacial histories and to identify distinct glacial sediment transport paths.

The project area covers an extensive region of mainland Nunavut west of Hudson Bay between latitude 60°N (Manitoba border) and 68°N, east of longitude 100°W (Fig. 1). The mapping in this region is the first phase of new glacial geomorphological mapping in Keewatin (Fig. 1, Sector 1). A second phase is planned to continue the geomorphological compilation in the Northwest Territories (NWT) and Nunavut between longitudes 100°W and 108°W (Sector 2). The study area encompasses the entire central region of the Keewatin Sector of the LIS during the Wisconsin Glaciation (e.g. Prest, 1970) and includes various glacial landsystems such as paleo-ice stream tracks (e.g. Dyke and Prest, 1987a, b; Stokes and Clark, 2003; Margold et al., 2018), relict landscapes of unknown ages (McMartin et al., 2015a, b; Campbell et al., 2019), a migrating ice divide (McMartin and Henderson, 2004), and major end moraine systems (Dyke, 2004). This publication provides an historical review of previous glacial geomorphological mapping in the GEM project areas (Sectors 1 and 2), and summarizes the mapping methods and outputs for Sector 1 published in Behnia et al. (2020) and McMartin et al. (2021).

2. AN HISTORICAL REVIEW OF SURFICIAL MAPPING AND DEVELOPMENT OF QUATERNARY GEOLOGY IN KEEWATIN

Field mapping in Keewatin has always been constrained by remoteness, high logistical costs and short field seasons with highly challenging weather. Nevertheless, there is a long history of Quaternary research in this region.

The early observations

Mapping of striations along rivers first led Tyrrell (1897) to suggest a migrating 'Keewatin Glacier' that served as one of several ice dispersal centres around Hudson Bay. In the early to mid 1950's, equipped with newly available airphotos and topographic maps, the Geological Survey of Canada (GSC) completed aircraft-supported reconnaissance field mapping projects covering roughly 480,000 km^2 of central mainland Nunavut and NWT (Wright, 1967): Operation Keewatin (1952), Operation Baker (1954) and Operation Thelon (1955). The resulting maps of glacigenic landforms provided the first major, regional interpretation of ice sheet dynamics in the Keewatin region (Lord, 1953; Wright, 1955; Lee, 1959; Craig and Fyles, 1960; Craig, 1964). The Keewatin Ice Divide (KID) was recognized and defined as the zone occupied by the last glacial remnants of the LIS west of

Hudson Bay (Lee et al., 1957). Meanwhile, a misinterpretation of striae and streamlined landform orientations, i.e. a westward ice flow from Hudson Bay into Keewatin, came to support the single ice dome theory of Flint (1943) during the last glacial maximum of the LIS (e.g. Bird, 1951, 1953; Dean, 1953; Downie et al., 1953), an illustration of the continental-scale implications of Keewatin geomorphology. Taylor (1956) found evidence in the middle Back River region for a sequence of cross-cutting ice movements and superimposed streamlined landforms, and reconstructed an early southwest phase across Keewatin from Foxe Basin/Baffin Island, phases of ice expansion from Hudson Bay during the last glaciation, and deglacial phases from a residual ice sheet west of Hudson Bay. The Geological Association of Canada, under the direction of J. Tuzo Wilson, published the first Glacial Map of Canada (Falconer et al., 1958) showing ice-movement features, in which drumlins, striations and eskers indicated ice flows radiating from an approximate position of the "controversial" Keewatin Ice Divide.

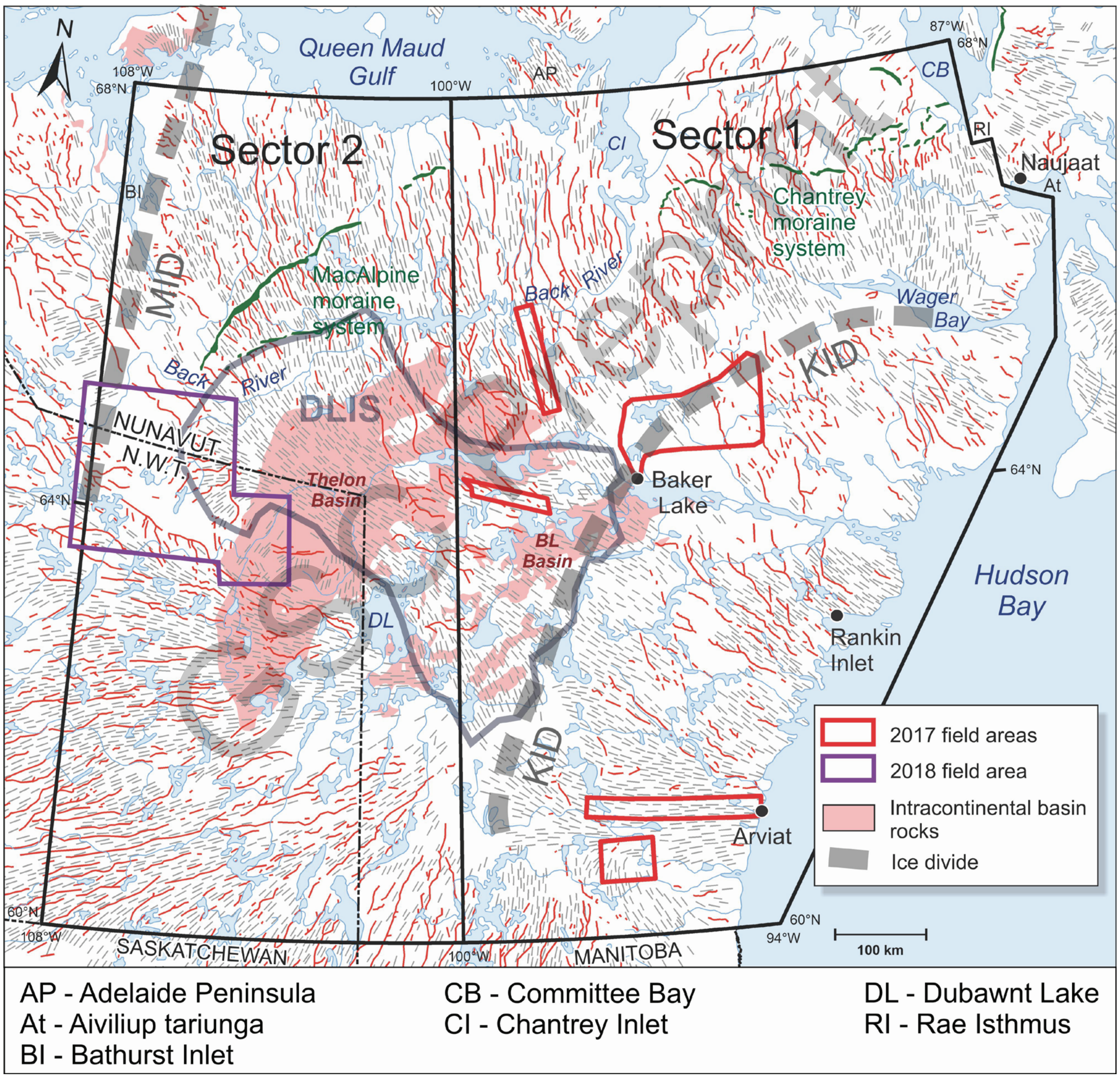

Figure 1. *Location map of the GEM-2 Rae Glacial Synthesis project area in Nunavut and NWT with Sector 1 and Sector 2, and targeted 2017 and 2018 field areas. Generalized glacial lineations (grey), eskers (red) and moraines (green) from Prest et al. (1968), last position of the Keewatin Ice Divide (KID) from McMartin et al. (2017) and presumed location of the M'Clintock Ice Divide (MID) at LGM from Dyke and Prest (1987b). The Thelon and Baker Lake (BL) intracontinental basins are from Wheeler et al. (1997). Approximate limit (navy blue) of Dubawnt Lake ice stream (DLIS) footprint is from Stokes and Clark (2003).*

Craig (1961), as part of Operation Back River in 1960 west of Chantrey Inlet, mapped major end moraine ridges at the northeastern end of an end moraine complex mapped by Blake (1963) during Operation Bathurst, later named MacAlpine Moraine System by Falconer et al. (1965). As part of Operation Wager west of Committee Bay, Craig (1965) recognized segments of morainal ridges extending into Chantrey Inlet. The integration of the GSC work from the 1950s and 1960s on the second Glacial Map of Canada (Prest et al., 1968) showed geomorphic subdivisions, limits of glaciation, and the location and orientation of glacial features in greater detail than the map produced ten years earlier. The KID was confirmed as a late ice dispersal centre of the LIS but its origin and initial development remained conjectural (Prest, 1970).

First regional mapping and development of concepts

The area between longitude 98°W and the Hudson Bay coast north of the Manitoba border was the focus of extensive surficial mapping field programs at 1:125 000 and 1:250 000 scales in the 1970s by the GSC, either to assist mineral exploration in Keewatin, or in support of infrastructure, such as a proposed natural gas pipeline route through the central Arctic. Ice-movement indicators demonstrating pervasive ice flow towards Hudson Bay and a long glacial dispersal train of red siliciclastic and volcanic rocks of the Dubawnt Supergroup extending to the Hudson Bay coast implied a long and stable Keewatin Ice Divide (e.g. Shilts and Boydell, 1974; Shilts et al., 1979; Kaszycki and Shilts et al., 1979). These authors mapped the KID as a curvilinear, northeast-oriented zone in Keewatin, depicted as the 8.4 ^{14}C ka Keewatin Ice Divide in Dyke and Prest (1987b). Evidence for an earlier southward ice flow across Keewatin was recognized from striations and southward transport of erratics (e.g. Shilts, 1973; Cunningham and Shilts, 1977).

Based on limited field-based mapping in the western part of the study area (Sector 2), a north-south oriented ice divide was proposed in the region (M'Clintock Ice Divide: MID), extending from a dome centred just east of the East Arm of Great Slave Lake to the M'Clintock Channel. The MID was portrayed as a major ice divide during the height of the last glacial episode (see Fig. 1) and although its position remained vaguely known in northern Keewatin, it was shown to have migrated eastward during deglaciation, as far as the west side of Adelaide Peninsula in Sector 1 (e.g. Dyke et al., 1982; Dyke, 1984; Dyke and Prest, 1987a, b). Between Dubawnt Lake and Bathurst Inlet, a large area of relict, southwest-oriented ice-flow indicators on the Glacial Map of Canada was taken as evidence of an LGM MID, because that flow appeared to pre-date the much more pervasive deglacial flows linked to the KID (Dyke et al., 1982).

Using published maps, airphoto interpretation and ground observations collected by the GSC in the early years and in the 1970's, Aylsworth and Shilts (1989) compiled landforms and surface materials at 1:1 million scale between Hudson Bay and the western limit of the Canadian Shield and determined concentric glacial landform assemblages around the Keewatin Ice Divide based on the distribution of eskers, ribbed moraines and streamlined landforms. This general pattern of glacial landforms, in addition to dispersal patterns of distinctive rock types, and striations, was used to suggest a limited southeastward migration of the KID, by no more than 100 km (Aylsworth and Shilts, 1989). In contrast, Dyke and Dredge (1989) summarized the Quaternary history of the northwestern Canadian Shield region by showing migration of domes, saddles and regional ice divides (Ancestral Keewatin, M'Clintock, KID), in addition to flowlines, the presence of ice streams and ice retreat patterns. Several important discussions continued during that period which impacted the reconstruction of the glacial history and understanding of glacial dynamics in Keewatin: a) the minimum-maximum debate about LGM ice extent (e.g. Dyke et al., 1982; Dyke and Prest, 1987a; Dyke and Dredge, 1989; Vincent, 1989); b) the stability of the Wisconsinan ice cover in Hudson Bay (e.g. Shilts, 1982; Andrews et al., 1983; Dredge and Thorleifson, 1987); and c) the location of ice divides and saddles radiating from central domes (e.g. Shilts, 1980, 1985; Dyke et al., 1982). The timing of the giant radial esker system in Keewatin was also debated, as either synchronous and a reflection of the surface drainage pattern and massive stagnation of the ice sheet (e.g. Shilts, 1985), or as time-transgressive and formed by near ice margin processes, reflecting the pattern of ice retreat (Dyke and Dredge, 1989).

Framework mapping and consolidation of models

Subsequent field-based research in central-mainland Nunavut focused on understanding the complex ice-movement chronology (e.g. McMartin and Henderson, 2004), and on defining the final position of the Keewatin Ice Divide (e.g. Nadeau and Schau, 1979; Klassen, 1995; Little, 2001). Based on surface and sub-surface till composition near Baker Lake, Klassen (1995, 2001) showed evidence for southeastward dispersal under the Keewatin Ice Divide area, hence supporting the southeastward migration of the divide to its last position. The mapping of cross-cutting striations and superimposed streamlined landforms in a large area of central Nunavut, together with superimposed till sheets of different provenance near Baker Lake, indicated a mobile, warm-based ice divide, which migrated by up to 500 km between ice-flow phases (McMartin and Henderson, 2004; McMartin et al., 2006). The magnitude of these shifts was significantly more than what was proposed by previous workers, and twice as much as the distance covered during the migration of the Ancestral Keewatin Ice Divide (LGM) to the KID (final deglaciation; Dyke and Prest, 1987b). The idea of major, regional shifts in the location and orientation of the KID was supported by Hodder et al. (2016) who documented a complex till stratigraphy in the Keewatin core region of the LIS in Nunavut, implying considerable till production during the migration of the KID and possibly reflecting deposition during northward ice streaming toward Chantrey Inlet.

In contrast to the relict warm-based landscape observed near Baker Lake, weathered terrain and the lack of evidence for glacial erosion in upland areas under the ice divide near Wager Bay were thought to reflect cold-based ice conditions prior to deglaciation (McMartin and Dredge, 2005; Dredge and McMartin, 2007). Smith (1990) did not recognized this relict weathered terrain around Wager Bay but brought to light a complex late glacial history based on the mapping of till landforms, some of them thought to have been preserved in "frozen" valleys, and nested meltwater channels which indicated a retreat towards small remnant ice masses north of Wager Bay. Further north on the west side of Committee Bay, several surficial geology mapping and drift prospecting studies recorded ice advances and retreats based on surficial materials distribution and ice-movement indicators (e.g. Ozyer and Hicock, 2002, 2006; Little et al., 2002, 2003; McMartin et al., 2003a, b). An orderly retreat of the ice margin to the south is marked by a series of moraines related to the Chantrey Moraine System, and supported by a clear northward direction of glacial transport. In addition, corridors with irregular and transverse hummocks associated with eskers were recognized and interpreted as late stage glaciofluvial accumulations related to north-flowing subglacial meltwater discharges (Utting et al., 2002, 2009).

The remote imagery mapping phase

In the early 1990s, a number of large-scale compilations of glacial lineations and selective glaciogenic features were produced by glacial geomorphologists, benefitting from the release of free remote sensing data, especially Landsat satellite images. Boulton and Clark (1990a, b) and Clark (1993, 1997) used Landsat TM7+ mapper over North America to map cross-cutting glacial lineations in the area of the Keewatin Ice Divide, and to infer mobility of outflow centres within the LIS throughout the last glacial cycle(s). Using a similar but more systematic approach, as well as integrating ice-flow measurements published on surficial maps compiled by the Geological Survey of Canada, De Angelis (2007) produced a glacial geomorphology map of the east-central Canadian Arctic by mapping generalised glacial features to achieve a good representation of the landform patterns. The compilation formed the basis of palaeoglaciological reconstructions of this portion of the LIS (De

Angelis and Kleman, 2005, 2007, 2008); landform assemblages were recognised (i.e. ice stream, event and wet-based deglaciation swarms, frozen-bed zones) to provide a glaciologically plausible picture of ice-stream evolution for northern Keewatin (De Angelis and Kleman, 2005). Mega-scale glacial lineations (MSGLs) and other glacially streamlined landforms continued to be mapped in Keewatin from satellite and digital elevation images and were recognized as evidence for paleo-ice stream tracks (Ozyer, 2011; Ross et al., 2011; Margold et al., 2015a, b; Storrar and Livingstone, 2017), specially over the well-documented Dubawnt Lake Ice Stream (DLIS) bed (Kleman and Borgström, 1996; Stokes and Clark, 2003, 2004; Stokes et al., 2008, 2013; Ó Cofaigh et al., 2013). Eskers were compiled from Landsat satellite imagery (Storrar et al., 2013) and were interpreted in Keewatin to reflect a time-transgressive formation at the ice margin during a stable, gradual retreat (Storrar et al., 2014). Ribbed moraines, glacial lineations and eskers were mapped in south-central Keewatin by Wagner (2014) using a combination of Landsat 7, SPOT 4/5 and Canadian Digital Elevation Dataset. In addition to providing the basis for the reconstruction of the LIS during the last glaciation, the mapping of glacial landforms with remote imagery in Keewatin also documented the pre-LGM paleo-ice sheet history of the sector. For example, the preservation of "old landforms" (i.e. "Aberdeen" and "Garry" swarms), and transverse bedforms of extreme size, was used to infer a dome in northern Keewatin and a cold-based thermal regime prior to ice sheet build-up (Kleman et al., 2002, 2010; Greenwood and Kleman, 2010).

The expansion of mapping and ideas through the GEM program

Recent surficial mapping projects as part of the GEM initiative, including graduate student research with collaborating universities, have benefited from targeted field work and the provision of high-resolution satellite imageries (i.e. LANDSAT-8, Radarsat 2, SPOT) and digital elevation models (e.g. ArcticDEM). Table 1 summarizes the nature of the work accomplished as part of the GEM field-based projects located within the Rae Glacial Synthesis project area (Fig. 2). The recent work has significantly increased the coverage and accuracy of surficial geological and geomorphological mapping in Keewatin. New mapping based on stereoscopic analysis of airphotos with minimal legacy field information has also occurred throughout the project area under the GEM initiative (see Kerr et al., 2022, for a complete list of references). The maps and field-based information completed as part of these projects were integrated in the Sector 1 compilation presented in Behnia et al. (2020) and discussed in McMartin et al. (2021). Below is a summary of key ideas on regional aspects of the surficial geology developed as a result of GEM mapping in the Rae Glacial Synthesis project area.

Wager Bay area

The deeply weathered terrain previously reported in upland areas under the ice divide south of Wager Bay (e.g. McMartin and Dredge, 2005) was thoroughly documented, and terrestrial cosmogenic nuclide (TCN) studies were conducted for the first time (McMartin et al., 2015b, 2016, 2017, 2019a), contributing to an enhanced understanding of basal ice thermal regimes and glacial erosion processes in northern landscapes of mainland Nunavut (e.g. Tremblay et al., 2016). The relict landscape, expanded to the north of Wager Bay (McMartin et al., 2015a), was assigned a pre-LGM age and is thought to have been preserved under a non-erosive cold-based ice regime under portions of the KID (McMartin et al., 2019a). Detailed mapping of striations, eskers and glacial lineations refined the last position of the KID between Baker Lake and the outer portions of Wager Bay (McMartin et al., 2013b, 2015a, b, 2016, 2017) and helped to determine glacial transport directions and till provenance, useful in surface mineral exploration (McMartin et al., 2013b, 2015a, 2019a). In addition, the ^{14}C age and exotic composition of marine shell-bearing till near Repulse Bay (McMartin et al., 2019b), deposited by an ice stream that flowed north across Rae Isthmus into Committee Bay and the Gulf of Boothia (e.g. Dredge, 2002; Tremblay and Lamothe, in press), raised potential implications for ice-free configurations in

Hudson Bay during MIS 3, a recurring debate in the Quaternary community (e.g. Dalton et al., 2019; Miller and Andrews, 2019). Detailed striation mapping documented several late deglacial ice-flow reversals in the Wager Bay area as a result of drawdown into the opening marine waters, including towards Repulse Bay and into Wager Bay (McMartin et al., 2015a, 2019a). Detailed marine limit mapping and age determinations contributed to refine the ice margin retreat chronology south of Wager Bay (Randour et al., 2016; Randour, 2018).

Table 1. *List of GEM-1 and GEM-2 surficial geology field-based projects and nature of work completed within both sectors of the GEM-2 Rae Glacial Synthesis project area. The list of references is provided in Appendix 1. An overview of the surficial geochemistry and indicator mineral surveys completed as part of all GEM projects, including those listed in this table, is presented in McClenaghan et al. (2022).*

Project name	Nature of work	Major outputs	Thesis
GEM-1			
North Wager Bay	Regional mapping at 1:100 000 and RPM; till composition, ice flow indicators; glacial history reconstruction	Campbell et al., 2013a-d; Wityk et al., 2013; Campbell and McMartin, 2014; McMartin et al., 2015a-b, 2017a, 2019a; Dredge et al., 2016; Randour et al., 2020	Wityk, 2014
Uranium-Thelon Basin	RPM; till composition	LaRocque et al., 2012; Robinson et al., 2014, 2016	Robinson, 2015
Operation GEM (Geo-Mapping Frontiers)			
Tehery-Cape Dobbs	Regional mapping at 1:100 000; till composition, ice flow indicators	Dredge et al., 2013a-c; McMartin et al., 2013a	
Chantrey	Regional mapping at 1:125 000; till composition, ice-flow indicators	Dredge and Kerr, 2013; McMartin et al., 2013b; St-Onge and Kerr, 2013	
Mary Frances Lake – Whitefish Lake – Thelon River	Till composition, ice-flow indicators	Kjarsgaard et al., 2013, 2014; Knight et al., 2013; Sharpe et al., 2014	
GEM-2			
Tehery-Wager	Regional mapping at 1:100 000 and RPM; till composition, ice-flow indicators; glacial history reconstruction, marine limit extent and chronology	Byatt et al., 2015; Randour et al., 2016; McMartin et al., 2015c, 2016, 2019b; Randour and McMartin, 2017; Byatt et al., 2019a-b	Byatt, 2017; Randour, 2018
South Rae	Regional mapping at 1:100 000 and RPM; till composition, ice-flow indicators; glacial history reconstruction	Pehrsson et al., 2015; Campbell and Eagles, 2014; Campbell et al., 2016; 2020; Latifovic et al., 2018; Lauzon and Campbell, 2018	Lauzon, in press
Thelon-Chantrey	Till composition, ice-flow indicators	McMartin, 2017; McMartin and Berman, 2015; McCurdy and McMartin, 2017	
Rae Glacial Synthesis	Glacial geomorphology mapping; detailed mapping; till composition, ice flow indicators; glacial landsystems mapping and glacial history reconstruction	Boulianne-Verschelden et al., 2019*; McMartin et al., 2017b; Campbell et al., 2019; Behnia et al., 2020; de Bronac De Vazelhes et al., 2021*; McMartin et al., 2021; Campbell et al., 2021	de Bronac De Vazelhes, 2019*; Boulianne-Verschelden, in prep*; Mendizabal, 2022*

**Research projects completed as part of NSERC—Agnico Eagle Industrial Research Chair in Mineral Exploration at Université Laval with some GEM support.*

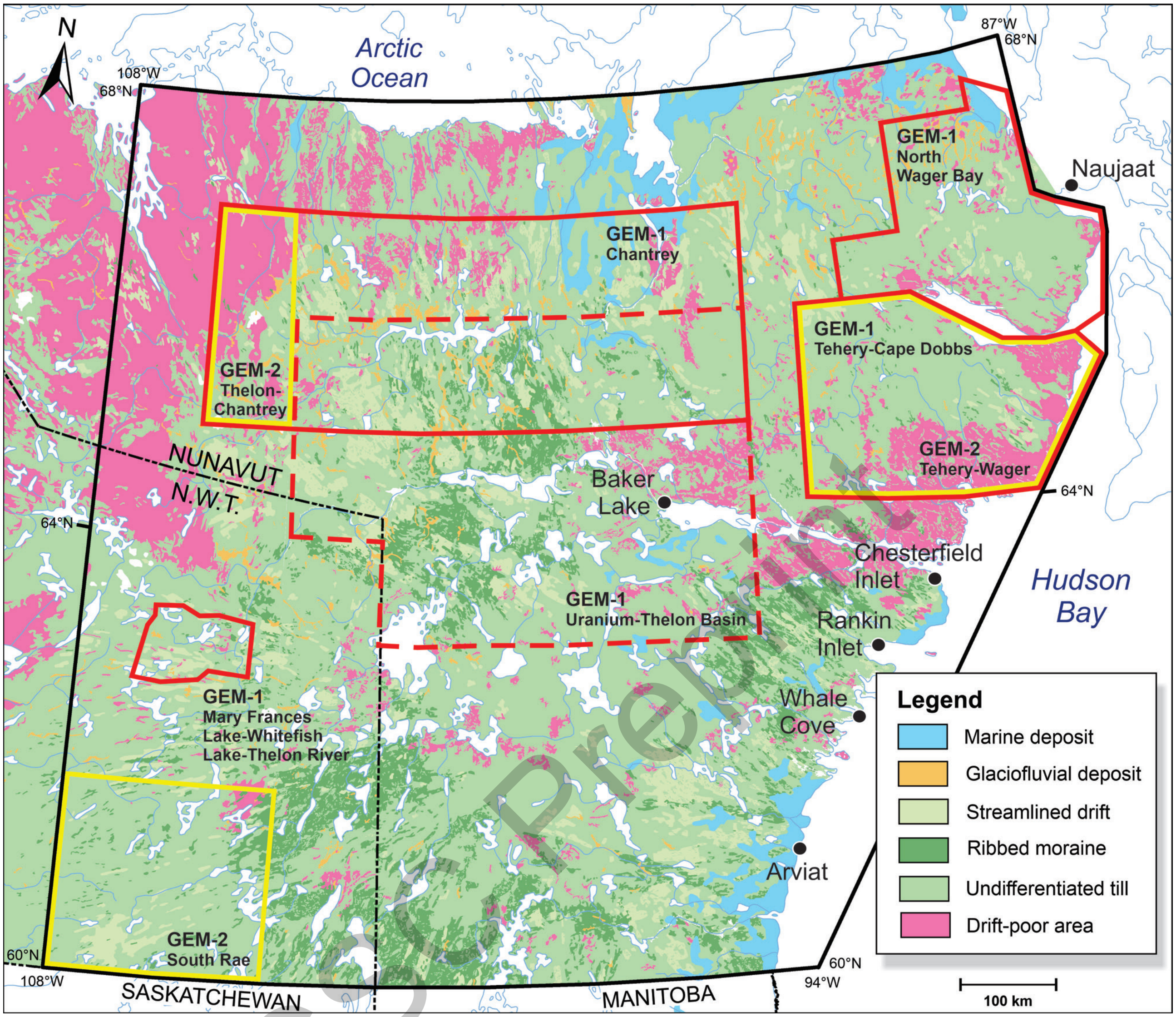

Figure 2. Location of GEM-1 (red outline) and GEM-2 (yellow outline) surficial geology field-based projects completed within the GEM Rae Glacial Synthesis project (see Table 1 for complete list of projects). Landform-sediment assemblages from Aylsworth and Shilts (1989) and marine deposits from Fulton (1995).

Northwest Keewatin

In Keewatin, the distribution of red Dubawnt erratics is key to the reconstruction of ice flow history and ice divide migration (e.g. Shilts, 1980), and their southeastward glacial dispersal into Hudson Bay is well recognized (i.e. Kaszycki and Shilts, 1979; McMartin and Henderson, 2004). However, the extent of their glacial dispersal directly north and west of the Thelon Basin remained largely unknown until GEM-related work along a transect immediately north of the Thelon Basin indicated extensive northward glacial dispersal of Dubawnt clasts, as far as 200 km north of the closest known source (McMartin et al., 2013a). This clast dispersal pattern on the northwest side of the Keewatin Ice Divide was attributed to a northward ice flow from an early, east-west ice divide position in Keewatin (McMartin and Henderson, 2004 - their phase B). Kjarsgaard et al. (2014) used till geochemistry data (wt% SiO_2) from the Operation GEM project and adjacent Thaidene Nene MERA area as a proxy for westward glacial transport of quartz-rich sandstone rocks for potentially as far as ~230 km from the Thelon Basin. A similar westward glacial transport pattern was reported in Kerr et al. (2013) based on the distribution of buff-colored Thelon Basin sandstone pebbles in till and esker samples collected within the proposed Thaidene Nene National Park Preserve (see also Sharpe et al., 2017).

The location of the M'Clintock Ice Divide, believed to have impinged over the Arctic Ocean mainland coast as a north-south trending ice divide (e.g. Dyke et al., 1982; Dyke, 1984), could not be verified by recent ice-flow indicator mapping or glacial transport studies in Sector 2 (McMartin and Berman, 2015; McMartin, 2017; Campbell et al., 2019). On the other hand, new GEM mapping in the Aylmer–Healey lakes area in 2018 (Campbell et al., 2019; see Figure 1) identified relict and palimpsest glacial terrains, the north-south trending extension of the MacAlpine Moraine System, and defined the western extent of the DLIS.

Another contribution of GEM research in this area was the evaluation of fast ice stream flow on sediment transport over the DLIS footprint (McMartin, 2017). Results showed major changes in till composition across the terminus of the DLIS that coincided with a former ice retreat position at the MacAlpine Moraine System: till composition within the DLIS showed a distal provenance, rich in undeformed Dubawnt Thelon Basin Barrenlands Grp sandstone debris, relatively clay-rich, SiO_2-rich, and depleted in most trace and major elements (except SiO_2); beyond the ice stream, till composition indicated a more local provenance, derived from the underlying crystalline basement rocks. A ratio of total versus partial contents of Sr in till was found to be a meaningful proxy to evaluate glacial dispersal from the Thelon Basin in this area. Additional till sample transects were completed across various paleo-ice stream tracks, relict landscapes and ice divides as part of other GEM-2 Rae projects (Pehrsson et al., 2015; McMartin et al., 2017, 2019a; Campbell et al., 2016, 2019). These transects will help evaluate the influence of glacial landscapes on sediment transport and the impact on surface exploration methods in the Rae geological Province of the Canadian Shield (Godbout et al., in prep.), and constrain glacial dynamics and ice-sheet reconstructions.

South Rae

GEM-2 surficial investigations in the previously unmapped region of South Rae, NWT, identified a complex glacial landscape (Pehrsson et al, 2015; Campbell et al. 2016, 2017; Lauzon and Campbell, 2018; Campbell et al., 2020) and provided an insight into the paleo-ice dynamics and deglacial history of this region. Systematic mapping of ice-flow indicators revealed multiple phases of ice flow. An old (pre-LGM?) SSE/NNW ice flow was recorded at several sites. Well-defined indicators in cross-cutting relationships revealed a regional clockwise rotation in ice-flow direction evolving from an early southward (LGM) flow to dominant SW and SSW flows, and a late deglacial westward ice flow. A mosaic of glacial landsystems reflecting poly-phased glacial dynamics was recognized such as palimpsest landscapes, and adjacent areas of streamlined and non-streamlined terrains indicating regions of fast and slow (sticky spots) ice flow respectively (e.g. Stokes et al., 2007; Trommelen and Ross, 2014). Southwest trending subglacial meltwater corridors and connecting esker systems formed an integrated subglacial drainage system across the region allowing release of meltwater during late deglaciation. Proglacial lakes, impounded between enclosed topography and the retreating ice front, were more extensive in this area than previously thought (Pehrsson et al. 2015; Campbell et al., 2016). Short-lived ice-marginal lakes existed in the western part of the region while a more extensive, enduring proglacial lake covered most of the northeastern region.

Dubawnt Supergroup (Barrenlands Grp sandstone and Wharton Grp Pitz Fm) clast dispersal patterns in the South Rae cannot be solely explained by the dominant SW ice flows (Campbell et al., 2020). While SW, SSW and W glacial transport patterns are observed in till over the northernmost part of the area, the presence of sandstone and Pitz Fm clasts in the south is consistent with a sustained transport and dispersal of glacial debris by the older southward flow, followed by re-entrainment and dispersal by subsequent and overprinting ice flows. This interpretation contrasts with the idea that the ~250 km westward glacial transport from the Thelon Basin suggests a lack of evidence of widespread older or pre-existing sediment dispersal from the Thelon Basin (i.e. Sharpe et al., 2017). In the northeast corner of the study area closer to the Thelon Basin, where there is an abundance of quartz entrained in the regional till, elevated SiO_2 contents characterise the chemical composition of the till and effectively dilute the local elemental signatures. The ratio of SiO_2:Al_2O_3 can be used as a proxy for the quartz sandstone component and to model glacial transport from the Thelon Basin (Campbell et al., 2020), while the raw geochemical data can be "normalised" to SiO_2 to remove the effects of the dilution (Bern, 2009; Kjarsgaard et al., 2014).

3. OUTLINE OF MAPPING METHODS FOR SECTOR 1

Our new mapping of glacial landscapes in Keewatin started with the compilation of selected geomorphological features and field datasets from existing maps. A total of 66 Geological Survey of Canada surficial geology maps at various scales (1:50 000 to 1:250 000), converted to the Surficial Data Model (SDM – see Deblonde et al. 2019), were used to build the glacial geomorphological map. Recent Canadian Geoscience Maps (CGM) compiled as part of GEM formed the rest of the map contributions (n=17). Visual, computer-based new mapping and verification of previously mapped features was completed with high-resolution remote images, principally 2-m resolution (resampled to 5 m) ArcticDEM (Porter et al., 2018) and 30-m resolution (pansharpen to 15 m) Landsat 8 (https://earthexplorer.usgs.gov/). The overlay of a transparent (40-60%) Landsat 8 mosaic over the hillshaded ArcticDEM (45˚ or 315˚ azimuth) was used to map the glacigenic landforms. An integrated field information database was completed; it comprises 14 153 field stations with observations on the nature of surface materials and landforms, 4677 ice flow measurements, and 8266 locations of surface samples collected for Quaternary studies. Recent mapping initiatives as part of the GEM Program provided uniform digital field data collection that followed well-developed surficial sediment sampling protocols (McClenaghan et al., 2013). However, a large number of the earlier published sources provided minimal information, including 17% of field stations with no information other than their locations appearing on legacy GSC maps.

Data comprised of glacial geomorphological features were individually identified (lines and points) or regrouped in generalized areas (polygons). Information (metadata) was stored in attribute tables for each mapped feature, including feature type, subtype (if distinguished), and original map data source. To assure consistency in the mapping process, ambiguous features were cross-validated by two mappers and linear landforms were digitized at a maximum display scale of approximately 1:40 000. A list of all mapped feature types and field datasets are provided in Table 2.

4. SUMMARY OF PRODUCTS IN SECTOR 1

All glacial geomorphological features and field datasets were compiled in a GIS geodatabase (Behnia et al., 2020: https://doi.org/10.4095/327796) with a scalable map in ArcGIS 10.0 mxd format where one can then zoom in an out in a selected area for a better visualization, without losing any information. The database includes an unprecedented number of geomorphological features (>156,000), namely glacially streamlined and crag-and-tail landforms mapped to scale, major morainic ridges, esker ridges, subglacial meltwater corridors, the post-glacial marine limit, deltas, and areas of De Geer moraines, minor morainic ridges and till plumes. Figure 3 shows the map of linear features using a colour code for the different data layers. To improve map presentation and readability, the mapped glacial features were generalized at both 1:5 million (Fig. 4) and 1:1 million scales and provided as PDF files (Behnia et al., 2020) using a semi-automated generalization method

(”GeoScaler”: Huot-Vézina et al., 2009). Coherent glacial landsystems (i.e. Evans, 2003) were compiled based on identification and grouping of mapped glacial features, together with supporting field datasets. A full description is in McMartin et al. (2021: https://doi.org/10.1111/bor.12479), and the georeferenced overlay polygon and line features are in Behnia et al. (2020). Seven glacial landsystem types were recognized including ice streams (Fig. 5A, B), palimpsest streamlined landscapes, relict cold- to warm-based terrains (Fig. 5C, D), preserved warm-based terrains and cold-based retreat landscapes.

Table 2. *List of mapped features and field datasets; with number of features (from Behnia et al., 2020).*

Feature Type	Feature Type Subset	Count
Mapped features		
Major moraine ridge	End, Lateral, Interlobate, Lateral shear	1102[a]
Ice front retreat position		375
Ice-flow direction (in glacial trough)		127
Streamlined landform	Sense: Known, Unspecified	94601
Crag-and-tail landform	Pre-crag (if indicated)	26361
Esker ridge	Sense: Known, Unknown	22768[a]
Subglacial meltwater corridor		3252[b]
Lateral meltwater channel	Lateral up hill left, right, undefined	2500
Marine limit		1714[a]
Ice-contact delta	Marine, Glacial lake	331
Delta	Marine, Glacial lake	350
Till plume, visible	Carbonate, Non-carbonate	13
De Geer moraine area		43
Minor moraine ridge area		143
Field information		
Field station	Observation type	14153
Ice-flow indicator	Indicator type	4677
Sample location	Sample type	8266
[a] Counts represent segments of line features		
[b] Counts represent segments of line features (both sides of corridors)		

This unparalleled, detailed inventory of glacial features in central mainland Nunavut provides new coverage where no- or low-density maps existed, and permitted the consolidation, scaling and harmonisation of existing maps (McMartin et al., 2021). Glacial landsystems were first recognized, significantly modified or updated; they can be used for the reconstruction of paleo-ice sheet dynamics or for the interpretation of glacial transport patterns. Compilation, integration and standardization of both remote and ground observations acquired during years of government mapping will also facilitate the use of field-based datasets in empirically-based LIS reconstructions, numerical ice-sheet modelling and mineral exploration using glacial history and sediment provenance.

The next phase of this compilation for Sector 1 will include the integration of field-based ice-flow indicator measurements with glacial lineations into ice flowsets, and the synthesis of ice divide location and migration paths. A continuation of the glacial geomorphological mapping is planned to the west of Sector 1 in NWT and Nunavut between longitudes 100° and 108° W. The interpretation of new geochronological data on surface materials (TCN, IRSL, 14C) in both Sectors will help evaluate the significance of inheritance for glacial erosion and provide an update on ice margin retreat positions and marine limit chronology. The net effect of the complex ice flow dynamics and changing basal ice thermal regimes on the nature of glacial transport in Keewatin is also under examination and will contribute to increase our understanding of sediment provenance in key regions of the Canadian Shield covered by glacial sediments.

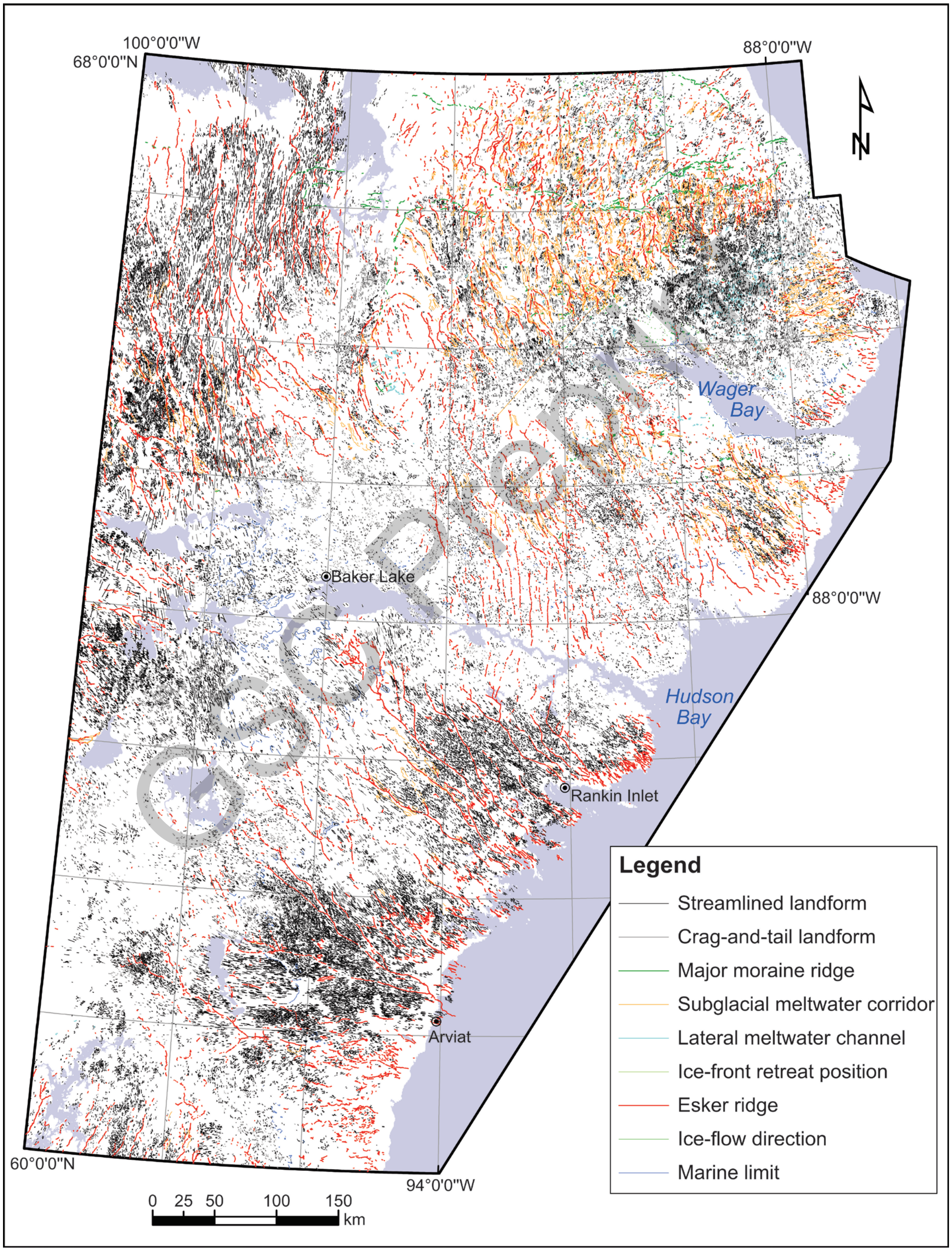

Figure 3. *Linear glacial features within Sector 1 of the GEM-2 Rae Glacial Synthesis project. All data layers are available for downloading in Behnia et al. (2020: https://doi.org/10.4095/327796).*

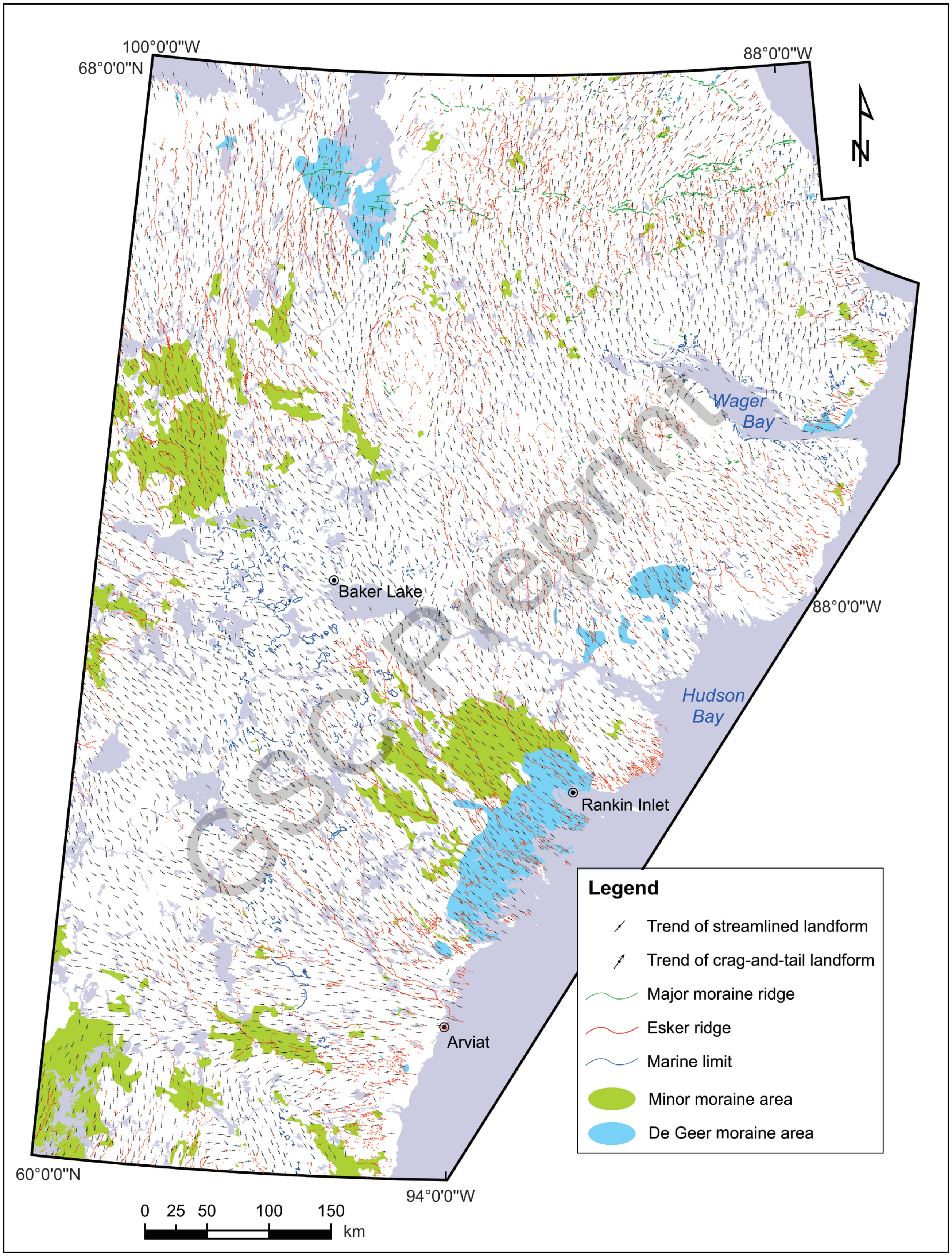

Figure 4. *Selected glacial features generalized at 1:5 000 000 scale within Sector 1 of the GEM-2 Rae Glacial Synthesis project (modified from McMartin et al., 2021).*

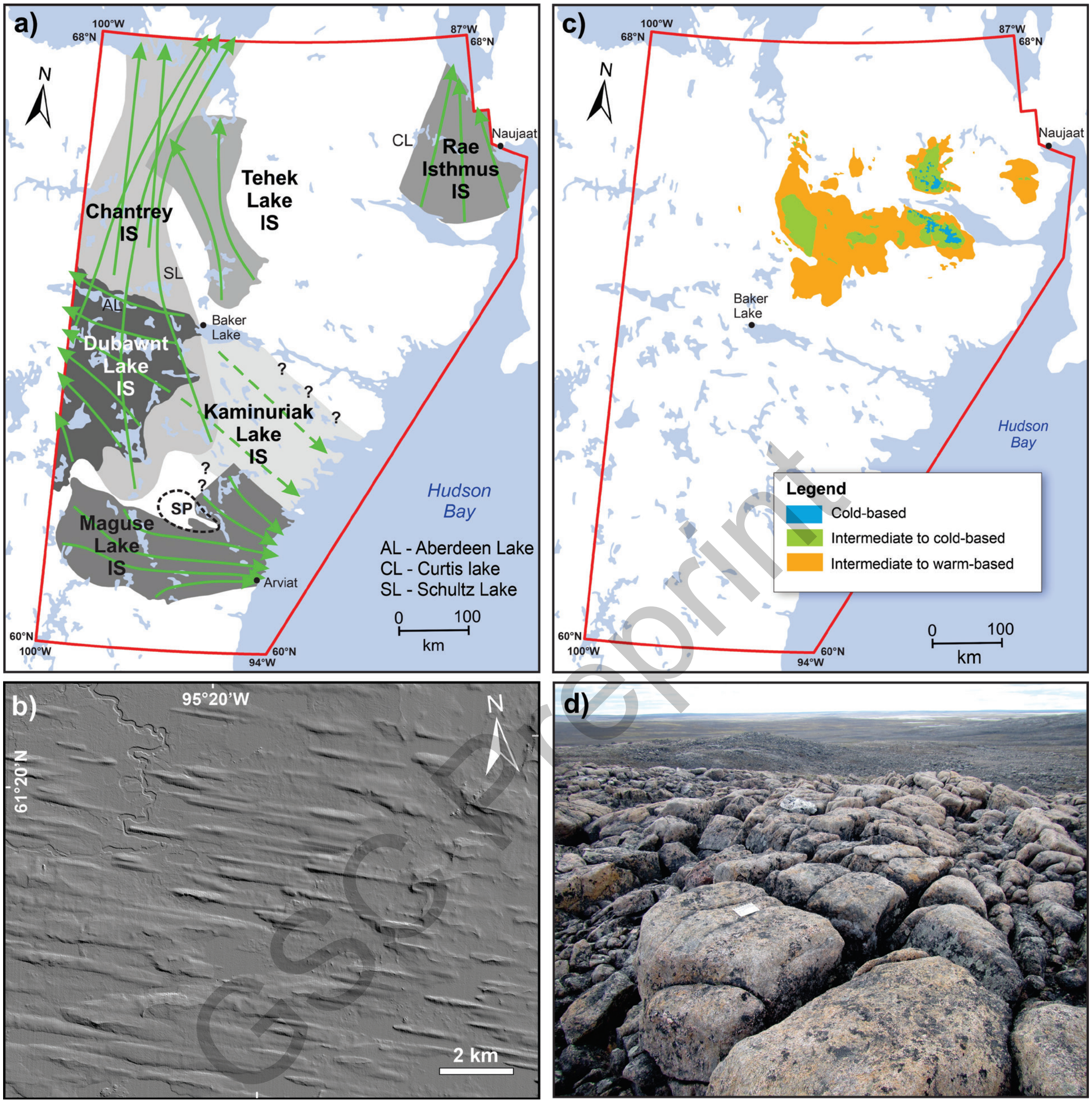

Figure 5. *Maps and images of selected glacial landsystems within Sector 1 of the GEM-2 Rae Glacial Synthesis project: A. Map of ice streams with ice flow directions (green arrows); B. ArcticDEM image of MSGLs within the Maguse Lake Ice Stream; C. Map of relict terrains including cold-based, intermediate to cold-based, and intermediate to warm-based glacial landsystems; D. Weathered bedrock in the uplands south of Wager Bay (cold-based landsystem). The glacial landsystem overlays are discussed in McMartin et al. (2021) and available for downloading in Behnia et al. (2020). IS = ice stream; SP = short streamlined landform pattern.*

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Appendix 1. List of References for Table 1*

**Note from the Volume editor: Previously included in prep and in press references were updated (as of September 12, 2022)*

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