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Critical review
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Abstract: The composition of glacial sediments across the Dubawnt Lake ice stream in central mainland Nunavut was examined to assess the potential influence of fast ice flow on sediment transport. Major changes in clast content, texture, and geochemical composition are observed in till collected over and beyond the ice-stream footprint. These changes coincide with an ice-front position at the southern segment of the MacAlpine moraine system. The till composition over the ice stream reflects a distal provenance, rich in undeformed Dubawnt Supergroup sandstone debris from the Thelon basin, relatively clay-rich, SiO_2-rich, and depleted in most trace and major elements (except SiO_2). Although giving an indication of the long glacial-transport distance of exotic quartz sandstone from the Thelon Basin (~80 km), the SiO_2 content in the matrix (<0.063 mm) is not entirely appropriate to reflect the Thelon Basin component in the till because of the abundance of quartz-rich rocks in the local crystalline basement. The ratio of total versus partial concentrations of Sr in till is a better suited proxy in the Thelon tectonic zone region; Sr ratios below ~10 characterize till composition within the Dubawnt Lake ice stream. Beyond the ice stream, till composition reflects a more local provenance, derived from the underlying Thelon tectonic zone rocks, and Sr ratios increase up to ~24. Furthermore, atypical clay contents in till, related to changes in till facies or stratigraphy rather than a change in provenance, can have a significant influence on till composition and may complicate the interpretation of till geochemistry. The work has implications for mineral exploration in the Rae geological province of the Canadian Shield.

Résumé : Nous avons examiné la composition des sédiments glaciaires laissés par le courant glaciaire de Dubawnt Lake, dans la partie continentale du Nunavut, afin d'évaluer l'influence que pourrait exercer un écoulement glaciaire rapide sur le transport des sédiments. À l'intérieur de la trace laissée par le courant glaciaire et au-delà de celle-ci, nous relevons d'importants changements dans le contenu en clastes, la texture et la composition géochimique du till. Ces changements coïncident avec la position d'un front glaciaire qui se manifeste par le segment sud du complexe morainique de MacAlpine. La composition du till à l'intérieur de la trace du courant glaciaire de Dubawnt Lake révèle une provenance distale des matériaux. Le till est riche en débris de grès non déformés du Supergroupe de Dubawnt provenant du bassin de Thelon, relativement riche en argiles, riche en SiO_2 et présente des concentrations diminuées de la plupart des éléments majeurs ou en traces (à l'exception de SiO_2). Bien qu'il fournisse une indication du transport glaciaire sur de longues distances de débris de grès quartzeux exotique en provenance du bassin de Thelon (env. 80 km), le contenu en SiO_2 de la matrice (<0,063 mm) n'est pas un reflet adéquat des constituants issus du bassin de Thelon, en raison de l'abondance de roches riches en quartz dans le socle cristallin des environs. Le rapport entre la concentration totale et la concentration partielle de Sr dans le till constitue un meilleur indicateur indirect dans le secteur de la zone tectonique de Thelon; des rapports de Sr inférieurs à ~10 caractérisent la composition du till à l'intérieur de la trace du courant glaciaire de Dubawnt Lake. Au-delà de la trace du courant glaciaire, la composition du till indique une provenance davantage locale, où les débris proviennent des roches sous-jacentes de la zone tectonique de Thelon et les rapports de Sr peuvent grimper jusqu'à ~24. De plus, l'existence de contenus en argiles atypiques dans le till, associés à des changements dans les faciès ou la stratigraphie du till plutôt qu'à une modification de la provenance des matériaux, peut avoir une influence importante sur la composition du till et rendre plus complexe l'interprétation de la géochimie du till. Les présents travaux ont des incidences sur l'exploration minérale dans la province géologique de Rae du Bouclier canadien.

INTRODUCTION

Till provenance and landform-sediment relationships in terrains formerly covered by ice streams are still poorly understood. Yet, ice streams are thought to be key agents of glacial dispersal and till deposition (e.g. Dyke and Morris, 1988; Smith et al., 2012), and known to carry up to 90% of ice discharging from the Antarctic Ice Sheet (Bamber et al., 2000; Rignot et al., 2011). Several paleo-ice stream footprints have been identified over the Laurentide Ice Sheet area in the recent decades (i.e. Winsborrow et al., 2004; De Angelis and Kleman, 2005; Margold et al., 2015), including the northwest-flowing Dubawnt Lake ice stream in central mainland Nunavut (e.g. Kleman and Borgström, 1996; Stokes and Clark, 2003). This terrestrially terminating, continental, paleo-ice stream was reconstructed based on regional-scale mapping of glacial landforms using satellite imageries (Stokes and Clark, 2003; Stokes et al., 2013), but little is known about the sediment characteristics and glacial dispersal patterns within the ice stream footprint (i.e. McMartin et al., 2006; Stokes et al., 2008; O'Cofaigh et al., 2013). To acquire information on till provenance, with a focus on glacial transport in areas of rapidly flowing ice, the Geological Survey of Canada recently completed a targeted till sampling survey along two 100 km transects crossing the terminal zone of the Dubawnt Lake ice-stream bed southeast of Bathurst Inlet, parallel to the predominant northwest ice-flow direction and perpendicular to the western end of the MacAlpine moraine system (McMartin and Berman, 2015). The survey was completed as part of the GEM-2 Thelon tectonic zone Rae Project over parts of the Thelon tectonic zone and adjacent Slave Craton in mainland Nunavut within NTS 76-H and 76-I (Berman et al., 2015a, b, 2016). The main goal of the till survey was to document surface geochemical anomalies identified in 2012 (McCurdy et al., 2013; McMartin et al., 2013), and to characterize the regional glacial composition (provenance) across major geological and glaciological features. This paper provides a preliminary discussion on the composition of till across the ice-stream terminus, and examines the potential influence of ice streaming on sediment transport and the impact on surface exploration methods in the Rae geological Province of the Canadian Shield. Additional till sample transects are planned as part of other GEM-2 Rae projects across various paleo-ice stream tracks, relict landscapes and ice divides (Pehrsson et al., 2015; McMartin et al., 2015, 2016; Campbell et al., 2016).

REGIONAL CONTEXT

The study area is covered by variable thicknesses of Quaternary sediments in an area of continuous permafrost, and lies immediately north of Thelon Game Sanctuary (Fig. 1). Physiography is characterized by broad, level to gradually sloping uplands draining toward the Arctic Ocean via the Ellice and Back rivers (Fig. 1). Local relief is low and characterized by gently rolling hills and upland plateaus, interspersed by shallow linear valleys that connect with the two main river valleys. McMartin and Berman (2015) provide an overview of the bedrock and Quaternary geology of the study area, which is summarized below.

The till sample transects span the boundary between the eastern Slave Craton and the Thelon tectonic zone on the western flank of the Rae Craton (Fig. 2). The Thelon tectonic zone comprises a series of pronounced, north- to north-northeast-striking magnetic anomalies that extend approximately 500 km from the MacDonald fault to Queen Maud Gulf (Berman et al., 2015a, 2015b, 2016). Three main magnetic highs represent ca. 2.0 Ga metaplutonic rocks (Berman et al., 2016) which have been postulated to represent a continental arc built on the western flank of Rae Craton and subsequently intensely deformed during collision with, and indentation of, the Slave Craton (Hoffman, 1988). The eastern Slave Craton is dominated by metasedimentary and metavolcanic rocks of the Yellowknife Supergroup intruded by 2.61 to 2.58 Ga granitoids (Frith, 1982; Thompson et al., 1986; Bleeker and Hall, 2007). The western Rae Craton consists largely of Mesoarchean upper amphibolite- to granulite-facies granitoid rocks of the Queen Maud block (Fig. 2). The easternmost belt of ca. 2.0 Ga metagranitoid rocks (Davis et al., 2014) separates a Mesoarchean crustal domain (Duggan Lake domain; Fig. 2) that correlates with the Queen Maud block (Berman et al., 2016). Distinct, nondeformed rocks of the Proterozoic Dubawnt Supergroup lie immediately southeast of NTS 76-H (Thelon Basin), over 30 km from the beginning of the two transects. These include predominantly poorly indurated Thelon Formation quartz sandstone and conglomerate of the Barrensland Group, minor sub-Thelon weathered regolith, and Pitz Formation rhyolite of the Wharton Group (Rainbird et al., 2003).

Reconnaissance-scale surficial-geology maps largely based on airphoto interpretation, together with field observations collected as part of the GEM-1 Geo-mapping Frontiers' Chantrey Project and the current GEM-2 mapping activity, indicate that the area is covered by widespread till veneers and streamlined till blankets east of Ellice River, interspersed by discontinuous areas of low bedrock outcrops and linear glaciofluvial corridors (Dredge and Kerr, 2013; St-Onge and Kerr, 2013; McMartin et al., 2013; McMartin and Berman, 2015). Clusters of eskers lead up to a discontinuous series of prominent end moraines forming the most northern splay of the arcuate MacAlpine moraine system (MM1; Figures 1 and 3)(Blake, 1963; Falconer et al., 1965). Large expanses of pro-glacial outwash fans and ice-contact deltas occur in front of the moraines. A more subtle ice margin position to the south (MM2; Figure 3) is marked by eskers terminating at coalescing pro-glacial outwash plains and terraces, and minor end moraines. This southern splay has been correlated with the inferred terminus of the Dubawnt Lake ice stream which is characterized by a divergent flow pattern at its distal end (i.e. Stokes and Clark, 2003).

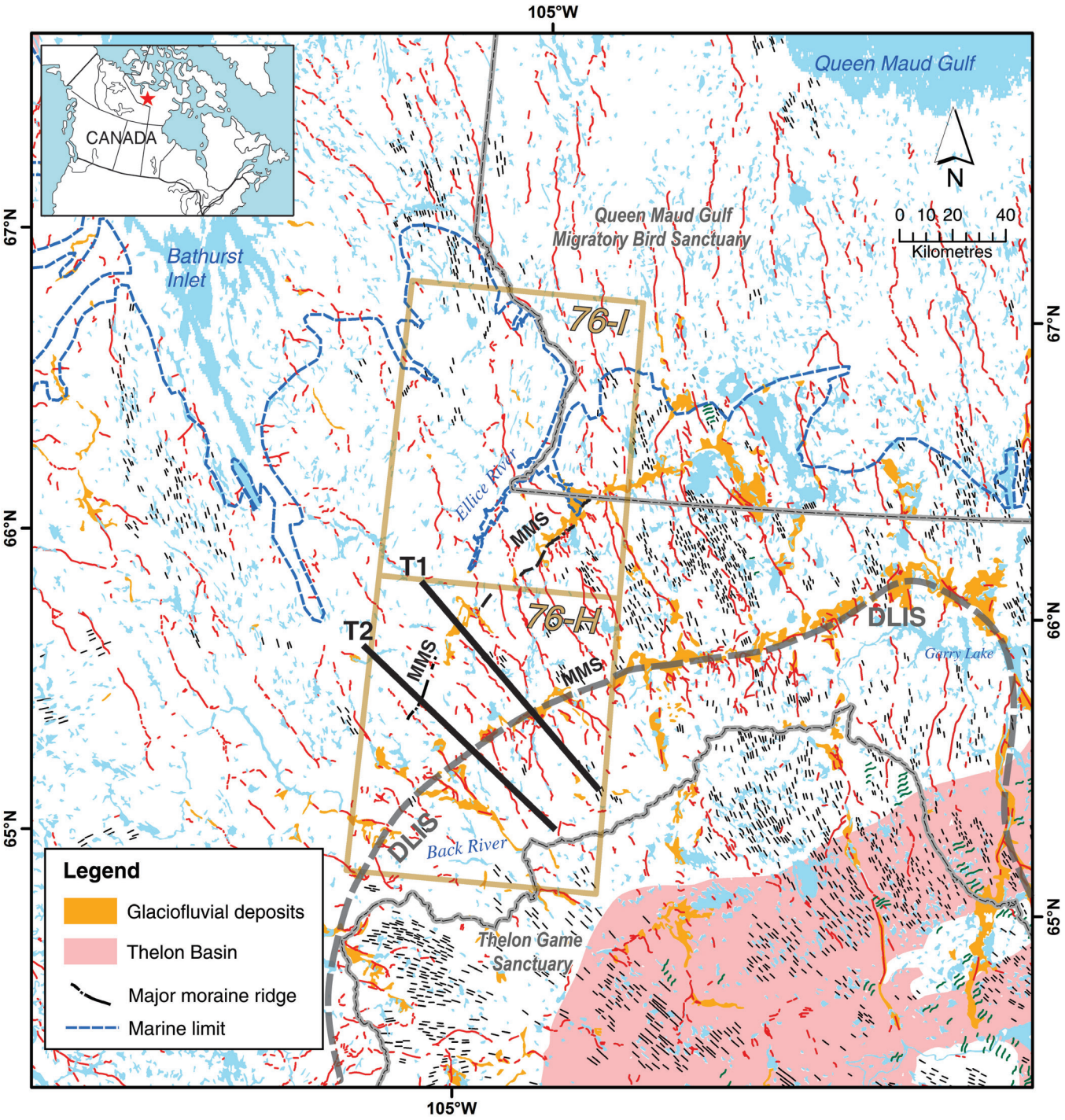

Figure 1. Location of till transects in mainland Nunavut (T1 and T2) and location of Thelon Basin. Regional Quaternary map (from Aylsworth and Shilts, 1989) shows glaciofluvial deposits and major glacial features. Esker ridges (red), streamlined landforms (black) and ribbed moraine ridges (green) are also shown. Approximate location of marine limit is modified from Prest et al. (1968). MMS: MacAlpine moraine system; DLIS: approximate limit (dashed grey) of Dubawnt Lake ice stream landscape (from Stokes and Clark, 2003).

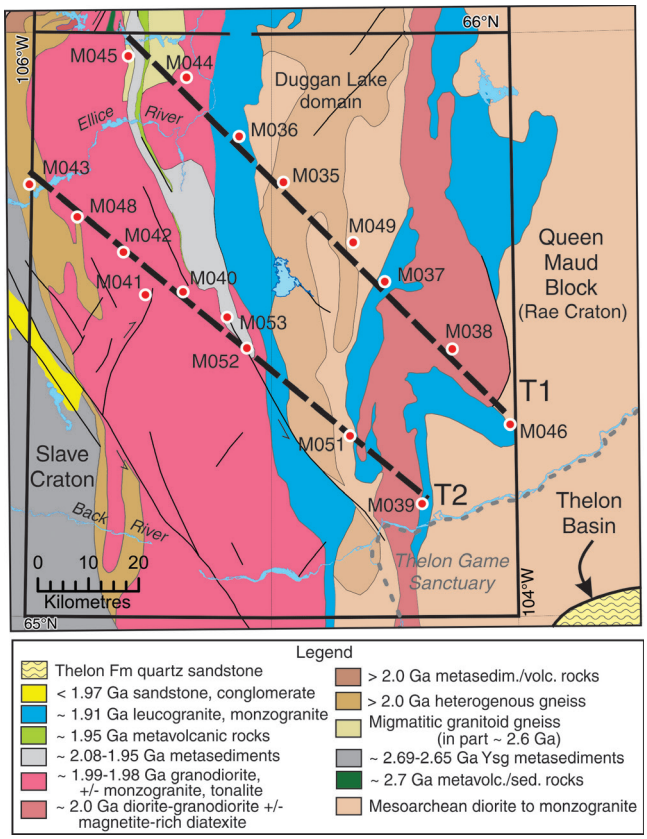

Figure 2. Simplified bedrock compilation map of the Thelon tectonic zone on the western flank of the Rae Craton (incorporating modifications of Frith, 1982 and Thompson et al., 1986), showing till sample locations (red dots) along T1 and T2 till transects (*updated from* Berman et al., 2016). Ysg: Yellowknife Supergroup.

Consistent striae, glacially moulded bedrock surfaces, and streamlined landforms indicate the predominant regional ice flow was toward the north to northwest from the Keewatin Ice Divide during the Late Wisconsin glaciation (St-Onge and Kerr, 2013; McMartin and Berman, 2015). During deglaciation, ice flow shifted to the northwest as recorded by crosscutting fine striae and subparallel streamlined landforms. As the ice front paused at major ice-recessional positions marked by MM1 and MM2, the ice flow shifted progressively to the west-northwest. The end moraines were assigned to the interval 8.2 to 8.0 ka BP by Dyke (2004) and are thought to represent stabilizations or readvances related to major climatic events.

METHODS

Surficial geology observations and till samples were collected at 17 sites along two approximately 100 km long transects (T1 and T2: Fig. 2 and 3) within NTS 76-H. For each transect, three sites are located within the known Dubawnt Lake ice-stream tract, three beyond the ice stream between MM1 and MM2, and the rest down-ice from MM1 (Fig. 3). The closest sites from the known margin of the Thelon Basin are located 43 and 34 km down-ice (northwest) along T1 and T2 respectively; the furthest sites are located 146 (T1) and 131 (T2) km down-ice of the basin margin. Samples were carefully collected at the top of streamlined landforms from active frost boils (Fig. 4) at an average depth of 35 cm and analyzed for Munsell colour, texture, clast composition (8–30 mm), matrix geochemistry (<0.063 mm: silt + clay-sized fraction; modified aqua regia 1:1 HNO3:HCl by ICP-MS; 4-acids by ICP-MS; lithium borate fusion by ICP-ES/MS), and gold grain and potential indicator mineral counts. Three samples from each transect were selected for the examination of the mineralogy of the clay-sized fraction by X-ray powder-diffraction analyses. The detailed field and analytical methods and the complete results of the till survey are available in McMartin and Berman (2015).

RESULTS

Physical characteristics

Samples collected along T1 and T2 transects consist of a silty sand diamicton, characterized by a massive and compact matrix, and the occurrence of striated clast facets and stoss-and-lee clasts, typical of subglacial traction tills (e.g. Evans et al., 2006). Sampling surfaces have a low boulder cover and show no sign of post-glacial erosion, reworking, or winnowing, other than periglacial up-heaving and churning (Fig. 4). The surface material is fresh and unaltered with most samples taken from Cy-horizon soils. Matrix colour varies between predominantly light grey to pale red and brown (Fig. 4). In a down-ice direction, clay content decreases from the highest values at 5% (T1) and 9.5% (T2) within the known ice stream footprint to below 3% beyond the ice stream (Fig. 5); in contrast, sand (mean = 59%) and silt (mean = 39%) contents do not show any systematic variations along the direction of ice flow (*see* complete data sets in Appendix 5 of McMartin and Berman, 2015). The relatively clay-rich till matches the ice-stream bed location where particularly large frost boils have developed (Fig. 4d). The clay-sized fraction is rich in quartz (46–68 wt %) with subordinate plagioclase feldspar (11–20 wt %) and K-feldspar (12–15 wt %); quartz contents (semiquantitative) tend to decrease along the ice-flow direction. Amphibole-group minerals (2–5%), chlorite (2–6%), kaolinite (1–6%), and illite/mica (1–3%) occur in minor amounts and do not show any systematic variations along the ice flow path.

Clast composition

Clasts lithologies identified in the 8 to 30 mm fraction of till (max counted is 200, average 181) include mainly plutonic and high-grade metamorphic rocks (granitic and gneissic rocks, paragneiss and paramigmatite, metapelite/psammite/quartzite, metachert and iron formation, metagabbro, amphibolite, quartz veins and tectonite), supracrustal

rocks (metasedimentary and metavolcanic), and unmetamorphosed Proterozoic Dubawnt Supergroup rocks. Dubawnt lithologies consist essentially of unoxidized and slightly oxidized pink Thelon Formation quartz-rich sandstone, and very minor red Pitz rhyolite (Fig. 4). Dubawnt clast content clearly decreases in a down-ice direction from the highest values at 27.0 (T1) and 20.9% (T2) to 0.0 and 0.5% at the end of the transects beyond the most northern morainic position (MM1) (Fig. 5). Along T1, values decrease rapidly from 27.0 to 5.6% within the ice stream footprint at ~80 km from the Thelon Basin margin, and continue to decrease more slowly to below 2% after 120 km of glacial transport from the margin. Along T2, values also decrease rapidly from 20.9 to 2.4% within the known ice-stream bed, and vary slightly below 4% beyond ~80 km (MM2) to attain 0.5% after 131 km of glacial transport down-ice from the basin margin.

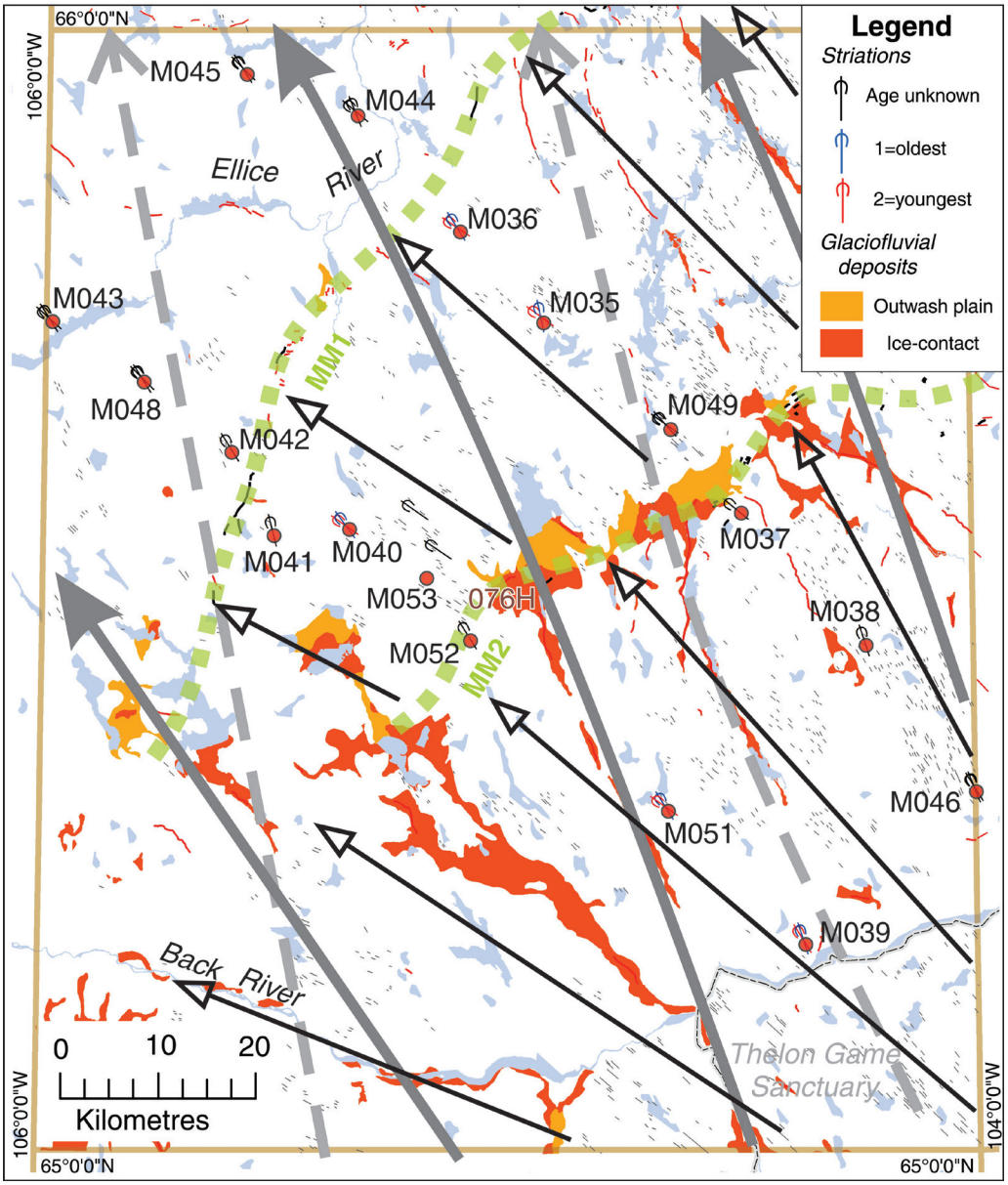

Figure 3. Map of field-measured ice-flow indicators (mainly striations) showing trends and relative ages at each site. Generalized trend of glacial flow directions is also shown (dashed grey = oldest; grey = second oldest; thin black = retreat to MM1 and MM2 – MacAlpine Moraine positions shown as dashed green). Esker ridges (red), streamlined landforms (dark grey), morainic ridges (thick black) and glaciofluvial deposits are derived from St-Onge and Kerr (2013). Till sample locations are shown as red dots.

Figure 4. a) Field photographs of sample sites along T1 till transect. 2017-016–2017-023; **b)** Field photographs of sample sites along T2 till transect. 2017-024–2017-032; **c)** Streamlined till terrain within Dubawnt Lake ice stream footprint. 2017-033; **d)** Large frost boils developed in streamlined till. 2017-034; **e)** Thelon Formation quartz-rich sandstone clasts recovered from till sample M039. 2017-035; **f)** Pitz Formation rhyolite recovered from till sample M039. 2017-036

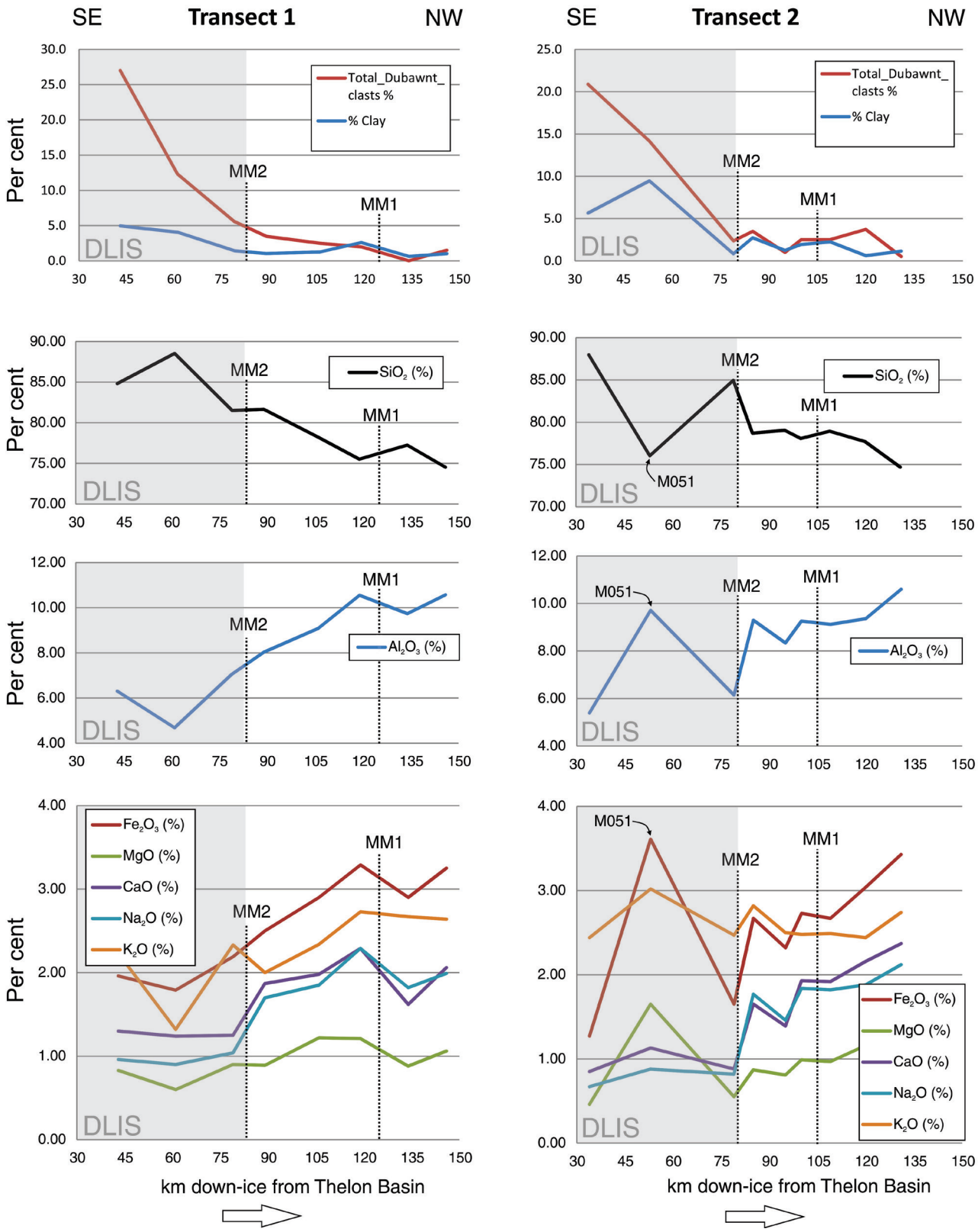

Figure 5. Dubawnt clasts (8–30 mm), clay (% weight of the <2 mm fraction) and major-element (<0.063 mm; lithium borate fusion, ICP-ES) contents along the two till transects. MM1 and MM2 indicate location of MacAlpine moraine positions; shaded areas show the extent of the Dubawnt Lake ice-stream footprint in its terminus zone (DLIS).

Matrix geochemistry

Major elements

Major elements analyzed by ICP-ES after a lithium borate fusion of the <0.063 mm fraction reflect the near-complete destruction of resistive and labile minerals, hence, similar to pebble counts, may indicate regional trends related to provenance, i.e. Thelon basin vs crystalline basement (Fig. 5). Results show that SiO_2 contents generally decrease in a down-ice direction from maximum values of 88.5% (T1) and 88.0% (T2) over the ice stream bed to below 75% at the furthest sites along the two transects. Although values decrease regularly along T1, values are more erratic along T2, namely at site M051 within the ice stream bed where the SiO_2 content is unusually low (~76%). Till collected at this site has the highest clay content (9.5%) of the data set. Most of the other major elements tend to increase in content by approximately 1.5 to 3x in a down-ice direction, particularly beyond the ice stream bed. The elevated clay content noted in sample M051 collected along T2 is reflected with increased Al_2O_3, FeO_3, and MgO concentrations, which significantly deviate from the regional increasing trend along the down-ice direction.

Trace elements

Trace elements analyzed after partial (modified aqua regia), near-total (-acids) and "total" (lithium borate fusion) digestions of the <0.063 mm fraction can be compared to help interpret the varying host minerals of the samples and infer variation in provenance (Fig. 6). Two elements are examined here, Sr and Zn, as they both reflect significant trends related to provenance, with some effects from mineral and physical partitioning, and are similar to many associated elements.

Strontium concentrations are similar, but slightly higher, with the total digestion method compared with the near-total digestion; both leaches indicate *increasing* concentrations in the down-ice direction by up to 2x along T2. In contrast, Sr concentrations analyzed after the partial leach are substantially lower (average of 17x and 13x lower for T1 and T2) than Sr analyzed after the total leach. This is true for many elements held in minerals not completely dissolved after a partial leach (i.e. Ba, Mn, Ni, Co, Na, Zr). In addition, the Sr content after the partial leach *decreases* by about half in the down-ice direction, suggesting the dispersal and/or incorporation of Sr-host minerals having various resistivity to chemical leaches. The ratio of Sr values after the total leach versus those after the partial leach increases from below ~10 within the ice-stream bed up to ~24 beyond the ice stream (Fig. 6).

Similar to Sr concentrations, Zn contents with the total and near-total digestion methods indicate increasing concentrations in the down-ice direction. Several trace elements follow the same trend (i.e. Cr, V, La, Pb, Cd, Bi), as well as most REEs. In contrast, Cu, Ag, As, Mo, Sb have more erratic distributions along both transects and even decreasing concentrations along T2 (i.e. As, Sb; *see* complete data sets in Appendix 4 of McMartin and Berman, 2015). The effects of a high clay content are visible once more in sample M051 with maximum Zn concentrations attained at that site along T2, departing from the down-ice increasing trend. Unlike Sr however, the Zn content using the lithium borate fusion gives similar but slightly *lower* Zn values than with the -acid leach. This is uncommon for the trace elements, except for Co, and may reflect an incomplete leach with the lithium borate fusion for Zn and Co. Although generally more erratic, Zn and many trace elements that have clear increasing concentrations using the total and near-total leaches along the glacial transport direction, also increase with values derived from the partial leach. Ratios of near-total to partial leach values remain stable for Zn, unlike Sr results.

DISCUSSION

Till texture, specifically sand and silt content, does not significantly differ along the ice-flow path. However, till collected up-ice of the southern splay of the MacAlpine moraine system (MM2), corresponding with the inferred ice-stream terminus, has relatively higher clay contents. Elevated clay contents in surface till over the Dubawnt Lake ice stream is likely related to higher proportions of comminuted clay-sized quartz particles and clay minerals from poorly-indurated and clay-cemented Thelon Formation quartz-rich sandstone transported long distances (~80 km) to the northwest. In addition to Thelon Formation sandstone, sub-Thelon weathered regolith may have provided clay-rich material as reported by McMartin et al. (2006) in clayey till derived from Thelon Formation rocks south of Schultz Lake. The physical characteristics of the till and associated striated bedrock surfaces suggest basal-sliding flow mechanisms were important subglacial till forming processes; under the ice stream, the more clayey till may also have contributed to the presence of a pervasively deforming subglacial layer enhancing the flow of the ice stream. Based on the study of four stratigraphic sections in the middle of the Dubawnt Lake ice stream over Thelon Basin rocks, O'Cofaigh et al. (2013) also suggested that diamictons in mega-scale glacial lineations (MSGLs) formed by a combination of subglacial sediment deformation and lodgement. However, these authors inferred short glacial-transport distances (<1–2 km) in the till components, in contrast to the long glacial-transport distances reported here in the terminus zone of the Dubawnt Lake ice stream.

A regional correlation between Dubawnt clast contents and a red-coloured matrix was found in surface till southeast of the Keewatin ice divide and interpreted to reflect the long-distance glacial transport of red-coloured debris from the Baker Lake Basin (Kaszycki and Shilts, 1980; McMartin et al., 2006; Robinson et al., 2014). In the Thelon tectonic

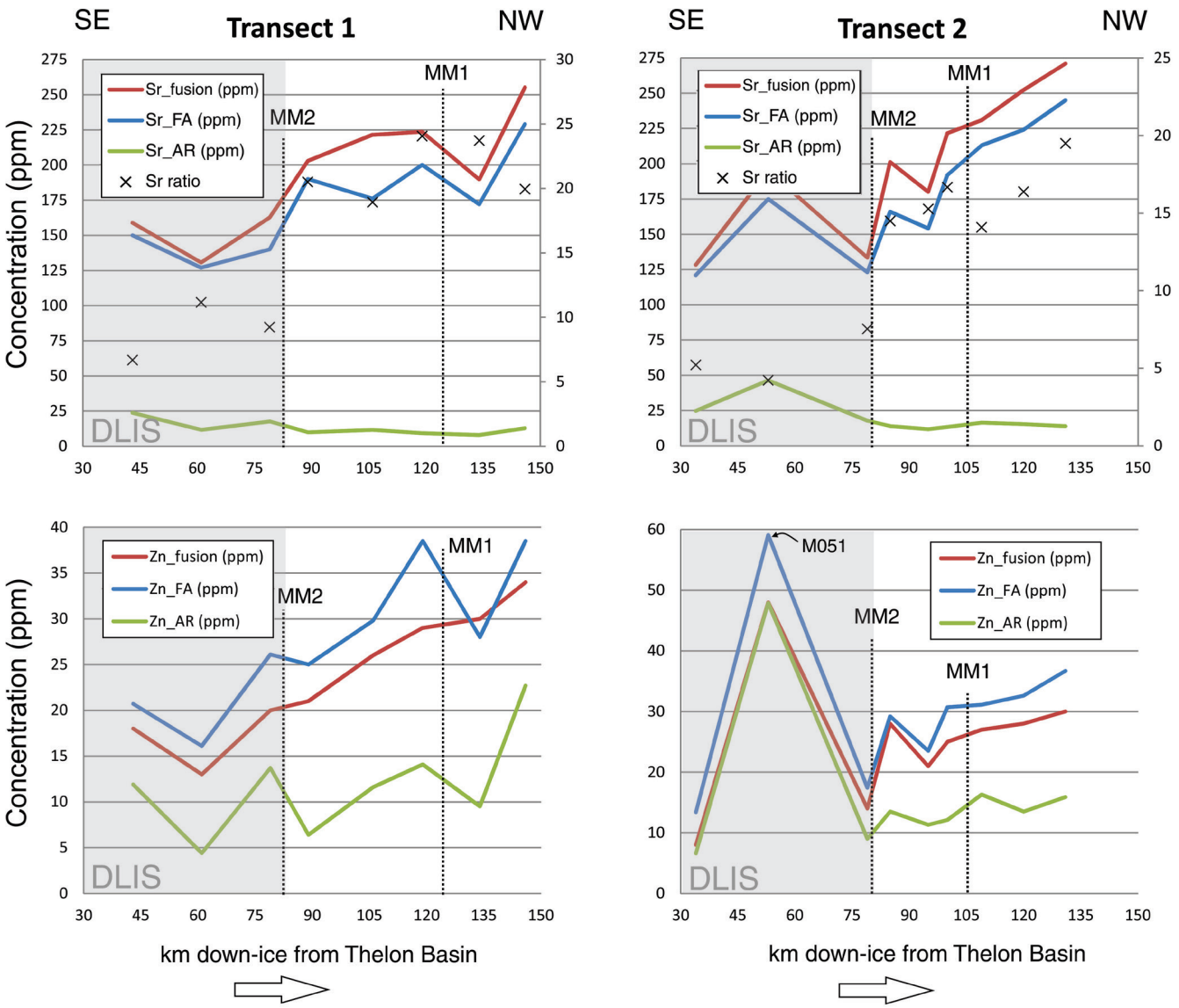

Figure 6. Sr and Zn concentrations along the two till transects (<0.063 mm; fusion:lithium borate fusion by ICP-MS; FA:four acids by ICP-MS; AR: modified aqua regia by ICP-MS). MM1 and MM2 indicate location of MacAlpine moraine positions; shaded areas show the extent of the Dubawnt Lake Ice Stream (DLIS). Sr ratios refer to the ratio of Sr contents after the borate fusion versus aqua regia digestion (scale on left axis).

zone area, the till-matrix colour does not vary significantly with Dubawnt clast or clay contents. Pinkish colours are somewhat more dominant in the tills within the ice stream terrain; the predominance of pale pink to buff-coloured Thelon sandstone in the Thelon Basin, much paler and less distinctive than red to purple Pitz and Christopher Island volcanic rocks, red Amarook Formation sandstones and Kazan Formation arkose in the Baker Lake Basin, reduces the typical relationship observed elsewhere between the till matrix colour and the Dubawnt clast content. Only two clasts of Pitz Formation rhyolite were observed at one site along the two transects (Fig. 4f).

The significant decrease in Dubawnt clast content in till located beyond MM2 (~80 km from Thelon Basin margin) suggests a change from a distal provenance to a more local provenance, and confirms that the inferred terminus of the Dubawnt Lake ice stream footprint lies close to the most southern splay of the MacAlpine moraine system (Fig. 3). The boundary of the exotic debris dispersal is fairly sharp at MM2; beyond MM2 (>80 km), the Dubawnt clast content continues to slowly decrease along T1; and along T2, the contents are low but erratic. Concentrations below 4% in streamlined terrain beyond the ice-stream footprint, and further north of the transect in NTS 76-I (*see* McMartin et al., 2013 and McMartin and Berman, 2015), may be related to the tail end of an exponential decay characteristic of glacial

dispersal by a normally sustained regional flow, or to previous ice streaming events. Note that the counter-clockwise rotation of ice flow during deglaciation, shifting from northwest to west-northwest as the ice front receded progressively to MM1 and MM2, suggests the possibility of palimpsest dispersal trains or fans, within a 60° lateral spread. As a result, the transect orientation and the sample spacing (>10 km) may not reflect entirely the nature of debris transport from the Thelon Basin. In addition, potential for buried outliers of Thelon Formation outcrops cannot be completely ruled out.

The decreasing SiO_2 contents in the <0.063 mm fraction of till along the ice-flow path may, to a certain extent, reflect a decrease in the quartz-rich sandstone Thelon Basin component, as suggested by Kjarsgaard et al. (2014) for westward dispersal patterns in tills west of the Thelon Basin. However, the correlation between SiO_2 matrix content and Thelon Formation clast content is not particularly strong in the Thelon tectonic zone (R2 = 0.3824; Fig. 7a) and hence cannot be used as a direct proxy for provenance. The presence of many local quartz-rich bedrock sources in the crystalline basement of the Thelon tectonic zone, namely within the Queen Maud Block and Duggan Lake Mesoarchean domain and other metagranitic rocks of the zone (Berman et al., 2015b), complicates the correlation. Although the clay content is highest in the quartz-sandstone-rich till over the ice stream bed, the increase in the other major elements (Al_2O_3, FeO_3, CaO, Na_2O, and MgO) beyond the ice stream bed may reflect a relative increase in plagioclase, K-feldspar, amphibole, and illite/mica components across the Thelon tectonic zone, as suggested by the decrease in quartz content of the clay-sized fraction. Inversely, the increase of these components, and clear inverse relationship with SiO_2, particularly for Al_2O_3 and FeO_3 (Fig. 7b), also indicates that the major-element data are "closed," that is, they sum up to a constant (100%) (i.e. Buccianti et al., 2006). Notwithstanding this difficulty in inferring relationships in compositional data, the suppressed SiO_2 content in sample M051, and corresponding increase in Fe_2O_3 and Al_2O_3, points to an increase in clay minerals in this sample (no XRD data available for that sample). The unusually high clay content in the otherwise sandy silty material at site M051 is in agreement with the field observation of a contorted clayey lens in the pit, and incorporation into the matrix through cryoturbation, rather than a change in provenance. As seen below, a rise in phyllosilicates may further complicate the interpretation of till geochemistry in clay-rich samples.

Strontium is a lithophile element known to occur in K-feldspar, plagioclase, sulphate minerals, and carbonate rocks. The increase in near-total and total Sr contents along the ice-flow path reflects the incorporation and glacial dispersal of resistant silt-sized Sr-bearing silicates from the various granitic rocks of the Thelon tectonic zone. In contrast, the glacial dispersal of Sr-rich minerals, soluble in relatively weaker acid (i.e. sulfates), from Thelon Basin rocks is a likely source of higher strontium over the Dubawnt

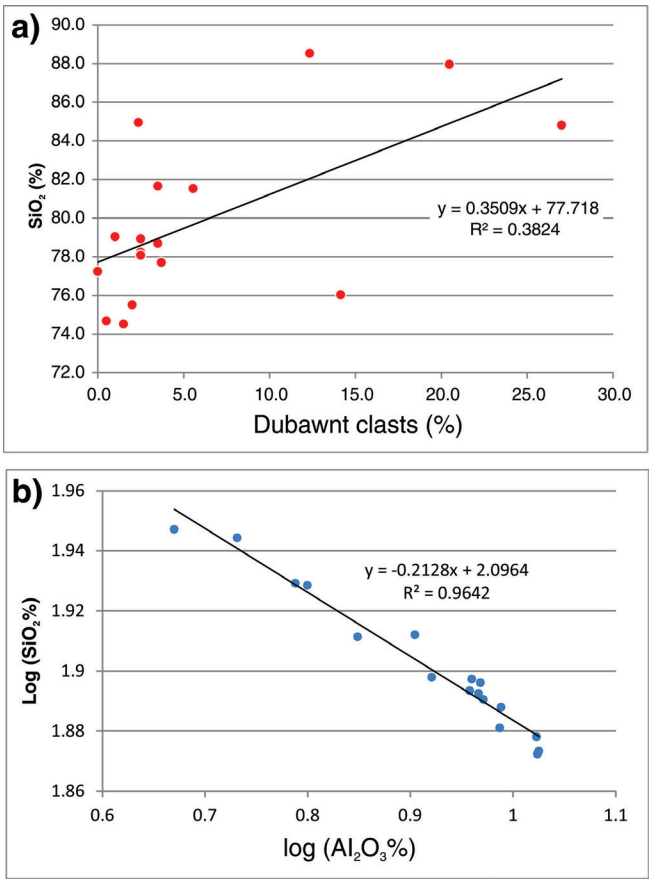

Figure 7. Biplots for all samples along the two transects: **a)** SiO_2 (<0.063 mm; lithium borate fusion, ICP-ES) vs Dubawnt clast contents (8–30 mm); **b)** log-transformed SiO_2 vs Al_2O_3 contents (<0.063 mm; lithium borate fusion, ICP-ES).

Lake ice stream bed resulting in an increase in the ratio of total versus partial leach Sr contents in the down-ice direction (Fig. 6). Strontium distribution in till analyzed after an aqua regia leach has been linked to the northward dispersal of Sr sulphate minerals from Dubawnt Baker Lake Group rocks near Baker Lake (McMartin et al., 2006), or to southeast dispersal of Dubawnt-rich debris as far as Rankin Inlet (McMartin, 2000). Unlike in Hodder et al. (2016), for surface till located southeast of the Thelon Basin, the till enriched in Thelon Formation debris over the Thelon tectonic zone is not depleted in Rb nor enriched in B, therefore the B:Rb ratio in the silt- and clay-sized fraction cannot be used to indicate the proportion of Thelon Formation detritus in the till matrix. Similarly, Zr, Hf, P, Ba, REEs, and La concentrations, all elements used variably to indicate dispersal of Dubawnt debris in surface till (e.g. McMartin et al., 2006; Kjarsgaard et al., 2014), do not show increased concentrations in till over the ice stream bed, or consistent decreasing contents along the ice-flow path. Therefore, in the Thelon tectonic zone, the ratio Sr_{total}:$Sr_{partial}$ provides the best indicator of Dubawnt debris in surface till.

Zinc contents generally increase in a down-ice direction, with the exception of sample M051. In till located over the Dubawnt Lake ice-stream bed, the exotic metal-poor Dubawnt debris slightly depresses the geochemical signature of the local bedrock, similar to that observed and discussed for till in the Kaminak Lake, MacQuoid Lake, Baker Lake, Rankin Inlet, Schultz Lake, and Thelon River areas for many trace metals (e.g. Shilts and Wyatt, 1989; Henderson, 2000; McMartin, 2000; Klassen, 2001; McMartin et al., 2006; Kjarsgaard et al., 2014). Although till over the ice-stream bed has a relatively higher clay content, the minerals in this fraction derived from the Thelon Fm sandstone are geochemically inert (quartz and probably kaolinite); therefore, Zn concentrations are generally lower in Dubawnt-rich till (i.e. Shilts, 1984). Nevertheless, at site M051 the clay content has more influence on Zn concentrations than provenance (or nearby mineralization), unlike in the rest of the samples along the transects. At this site, Zn preferentially accumulates in the clay-sized fraction because clay minerals in this fraction have large surface area, high cation-exchange capacity and can accommodate wide ranges of ionic radii (Shilts, 1995). Physical partitioning in this sample is demonstrated by the high contents of Fe_2O_3, Al_2O_3, or MgO, and somewhat K_2O, which are the main constituents of phyllosilicates occurring in Canadian Shield rocks, mainly micas and chlorite. Down-ice of MM2 beyond the Dubawnt Lake ice-stream terrain, the increase in Zn values analyzed by all three methods reflects the incorporation of more Zn-rich debris over the Thelon tectonic zone. There, Zn concentrations show a direct correlation with Fe_2O_3 and Al_2O_3, a somewhat weaker correlation with MgO, and an inverse correlation with SiO_2.

SUMMARY

Surface till composition across the distal end of the Dubawnt Lake ice stream over the Thelon tectonic zone in central Nunavut was examined for provenance. Results show that major changes in clast content, texture, and geochemical composition occur between till collected up-ice and down-ice of an ice front position marked by the MacAlpine Moraine (southern segment – MM2). This change coincides with the terminus of the ice-stream bed which suggests that the ice stream mapped on the basis of landform distribution and size is reflected in the surface composition of the material. The till composition over the Dubawnt Lake ice stream indicates a significant distal component, high in undeformed Dubawnt debris, relatively clay-rich, SiO_2-rich, and depleted in most trace and major elements (except SiO_2). Beyond ~80 km from the Thelon Basin margin (MM2), till composition reflects a more local provenance and glacial dispersal from metamorphosed Thelon tectonic-zone rocks. Although giving a general indication of long glacial transport of quartz sandstone from the Thelon Basin, the SiO_2 content of the till matrix does not appropriately reflect the Thelon Basin component in the tectonic zone because of the abundance of quartz-rich rocks in the crystalline basement. The ratio of total versus partial contents of Sr is a better proxy to evaluate glacial dispersal from the Thelon Basin; a Sr ratio below ~10 characterizes till composition within the ice stream footprint in the Thelon tectonic-zone area. Atypical clay content in till related to changes in till facies or to other stratigraphic variations rather than to provenance, can have a significant influence on till composition which may complicate the interpretation of till geochemistry for mineral exploration.

The results from additional and future till transects within and outside the ice stream margins and in areas of sustained normal ice flows, relict terrains and ice divides will be examined southeast, north and south of the Thelon and Baker Lake basins and analyzed in terms of glacial transport, provenance, glacial dynamics and basal thermal conditions over the Keewatin Sector of the Laurentide Ice Sheet.

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REFERENCES

Aylsworth, J.M. and Shilts, W.W., 1989. Glacial features around the Keewatin Ice divide: Districts of MacKenzie and Keewatin; Geological Survey of Canada, Paper 88–24, 21 p. doi:10.4095/127320

Bamber, J.L., Vaughan, D.G., and Joughin, I., 2000. Widespread complex flow in the interior of the Antarctic ice sheet; Science, v. 287, p. 1248–1250. doi:10.1126/science.287.5456.1248

Berman, R.G., Nadeau, L., Percival, J.A., Harris, J.R., Girard, E., Whalen, J.A., Davis, W.J., Kellett, D., Jefferson, C.W., Camacho, A., and Bethune, K., 2015a. Geo-Mapping Frontiers' Chantrey project: bedrock geology and multidisciplinary supporting data of a 550 kilometre transect across the Thelon tectonic zone, Queen Maud block, and adjacent Rae Craton; Geological Survey of Canada, Open File 7698, 39 p. doi:10.4095/296202

Berman, R.G., Davis, W.J., Whalen, J.B., McCurdy, M.W., Craven, J.A., Roberts, B.J., McMartin, I., Percival, J.A., Rainbird, R.H., Ielpi, A., Mitchell, R., Sanborn-Barrie, M., Nadeau, L., Girard, É., Carr, S., and Pehrsson, S.J., 2015b. Report of activities for the Geology and Mineral Potential of the Chantrey-Thelon Area: GEM-2 Thelon tectonic zone, Montresor belt, and Elu basin projects; Geological Survey of Canada, Open File 7964, 19 p. doi:10.4095/297302

Berman, R.G., Sanborn-Barrie, M., Nadeau, L., Brouillette, P., Camacho, A., Davis, W.J., McCurdy, M., McMartin, I., Weller, O.M., Chadwick, T., Liikane, D., and Ma, S., 2016. Report of activities for the GEM-2 project "Geology and Mineral Potential of the Chantrey-Thelon Area": Thelon tectonic zone; Geological Survey of Canada, Open File 8129, 15 p. doi:10.4095/299386

Blake, W., Jr., 1963. Notes on the glacial geology, northeastern District of Mackenzie; Geological Survey of Canada, Paper 63–28, 12 p. doi:10.4095/101060

Bleeker, W. and Hall, B., 2007. The Slave Craton: geological and metallogenic evolution; *in* Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods, (ed.) W.D. Goodfellow; Geological Association of Canada, Mineral Deposits Division, Special Publication no. 5, p. 849–879.

Buccianti, A., Mateu-Figueras, G., and Pawlowsky-Glahn, V. (ed.), 2006. Compositional data analysis in the Geosciences: From theory to practice. Geological Society London Special Publication 264, 282 p.

Campbell, J.E., Lauzon, G., Dyke, A.S., Haiblen, A.M., and 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, 16 p. doi:10.4095/299391

Davis, W.J., Berman, R.G., Nadeau, L., and Percival, J.A., 2014. U-Pb zircon geochronology of a transect across the Thelon tectonic zone, Queen Maud region, and adjacent Rae craton, Kitikmeot Region, Nunavut, Canada; Geological Survey of Canada, Open File 7652, 41 p. doi:10.4095/295177

De Angelis, H. and Kleman, J., 2005. Palaeo-ice streams in the northern Keewatin sector of the Laurentide ice sheet; Annals of Glaciology, v. 42, p. 135–144. doi:10.3189/172756405781812925

Dredge, L.A. and Kerr, D.E., 2013. Reconnaissance Surficial Geology, Overby Lake, Nunavut, NTS 76-I; Geological Survey of Canada, CGM Map 143, scale 1:125 000.

Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada; *in* Quaternary Glaciations: Extent and Chronology, Part II., (ed.) J. Ehlers and P.L. Gibbard; Elsevier, Amsterdam, p. 373–424.

Dyke, A.S. and Morris, T.F., 1988. Drumlin fields, dispersal trains and ice streams in Arctic Canada; Canadian Geographer, v. 32, p. 86–90. doi:10.1111/j.1541-0064.1988.tb00860.x

Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., and Auton, C.A., 2006. Subglacial till: Formation, sedimentary characteristics and classification; Earth-Science Reviews, v. 78, p. 115–176. doi:10.1016/j.earscirev.2006.04.001

Falconer, G., Ives, J.D., Loken, O.H., and Andrews, J.T., 1965. Major end moraines in eastern and central Arctic Canada; Geographical Bulletin, v. 7, p. 137–153.

Frith, R.A., 1982. Geology, Beechey Lake-Duggan Lake, District of Mackenzie; Geological Survey of Canada, Open File 851, scale 1:125 000.

Henderson, P.J., 2000. Drift composition and Surficial geology, MacQuoid Lake area (NTS 55M/7 and 55 M/10), Kivalliq Region, Nunavut: a guide to drift prospecting; Geological Survey of Canada, Open File 3944, 189 p. doi:10.4095/211803

Hodder, T.J., Ross, M., and Menzies, J., 2016. Sedimentary record of ice divide migration and ice streams in the Keewatin core region of the Laurentide Ice Sheet; Sedimentary Geology, v. 338, p. 97–114. doi:10.1016/j.sedgeo.2016.01.001

Hoffman, P.F., 1988. United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia; Annual Review of Earth and Planetary Sciences, v. 16, p. 543–603. doi:10.1146/annurev.ea.16.050188.002551

Kaszycki, C.A. and Shilts, W.W., 1980. Glacial erosion of the Canadian Shield – calculation of average depths; Atomic Energy of Canada Limited, Technical Record TR-106, 37 p.

Kjarsgaard, B.A., Plourde, A.P., Knight, R.D., and Sharpe, D.R., 2014. Geochemistry of regional surficial sediment samples from the Thelon River to the East Arm of Great Slave Lake, Northwest Territories, Canada; Geological Survey of Canada, Open File 7649, 17 p. doi:10.4095/295195

Klassen, R.A., 2001. The interpretation of background variation in regional geochemical surveys: an example from Nunavut, Canada; Geochemistry Exploration Environment Analysis, v. 1, p. 163–173. doi:10.1144/geochem.1.2.163

Kleman, J. and Borgström, I., 1996. Reconstruction of palaeo-ice sheets: the use of geomorphological data; Earth Surface Processes and Landforms, v. 21, p. 893–909 doi:10.1002/(SICI)1096-9837(199610)21:10%3c893::AID-ESP620%3e3.0.CO%3b2-U.

Margold, M., Stokes, C.R., and Clark, C.D., 2015. Ice streams in the Laurentide Ice Sheet: Identification, characteristics and comparison to modern ice sheets; Earth-Science Reviews, v. 143, p. 117–146. doi:10.1016/j.earscirev.2015.01.011

McCurdy, M.W., Berman, R.G., Kerr, D.E., and Vaive, J.E., 2013. Geochemical, Mineralogical and kimberlite indicator mineral data for silts, heavy mineral concentrates and waters, Duggan Lake Area, Nunavut (NTS 76H and 76I South); Geological Survey of Canada, Open File 7471, 22 p. doi:10.4095/293044

McMartin, I., 2000. Till composition across the Meliadine Trend, Rankin Inlet area, Kivalliq region, Nunavut; Geological Survey of Canada, Open File 3747, 330 p. doi:10.4095/211793

McMartin, I., Byatt, J., Randour, I., and Day, S.J.A., 2015. Report of 2015 activities for regional surficial mapping, till and stream sediment sampling in the Tehery-Wager GEM 2 Rae Project area; Geological Survey of Canada, Open File 7966, 14 p. doi:10.4095/297440

McMartin, I. and Berman, R.G., 2015. Till composition across the MacAlpine Moraine System: results from the GEM-2 Thelon tectonic zone project, Nunavut (NTS 76-H and NTS 76-I); Geological Survey of Canada, Open File 7910, 21 p. doi:10.4095/296833

McMartin, I., Dredge, L.A., Ford, K.L., and Kjarsgaard, I.M., 2006. Till composition, provenance and stratigraphy beneath the Keewatin Ice Divide, Schultz Lake area (NTS 66A), mainland Nunavut; Geological Survey of Canada, Open File 5312, 81 p. doi:10.4095/222246

McMartin, I., Berman, R.G., Normandeau, P.X., and Percival, J.A., 2013. Till composition of a transect across the Thelon tectonic zone, Queen Maud block, and adjacent Rae craton: results from the Geo-Mapping Frontiers' Chantrey project; Geological Survey of Canada, Open File 7418, 26 p. doi:10.4095/292801

McMartin, I., Day, S.J.A., Randour, I., Roy, M., Byatt, J., LaRocque, A., and Leblon, B., 2016. Report of 2016 activities for surficial mapping and sampling surveys in the Tehery-Wager GEM-2 Rae Project area; Geological Survey of Canada, Open File 8134, 16 p. doi:10.4095/299385

O'Cofaigh, C., Stokes, C.R., Lian, O.B., Clark, C.D., and Tulacyzk, S., 2013. Formation of mega-scale glacial lineations on the Dubawnt Lake Ice Stream bed: 2. Sedimentology and stratigraphy; Quaternary Science Reviews, v. 77, p. 210–227. doi:10.1016/j.quascirev.2013.06.028.

Pehrsson, S.J., Campbell, J.E., Martel, E., McCurdy, M.W., Agosta-Gongora, P., Theissen, E., Jamieson, D., Lauzon, G., Buller, G., Falck, H., and Dyke, A.S., 2015. Report of 2015 Activities for the Geologic and Metallogenic Framework of the South Rae Craton, Southeast Northwest Territories: GEM 2 South Rae Quaternary and Bedrock Project; Geological Survey of Canada, Open File 7958, 24 p. doi:10.4095/297387

Prest, V.K., Grant, D.R., and Rampton, V.N., 1968. Glacial map of Canada; Geological Survey of Canada, Map 1253A, scale 1:5 000 000.

Rainbird, R.H., Hadlari, T., Aspler, L.B., Donaldson, J.A., Lecheminant, A.N., and Peterson, T.D., 2003. Sequence stratigraphy and evolution of the Paleoproterozoic intracontinental Baker Lake and Thelon Basins, western Churchill Province, Nunavut; Precambrian Research, v. 125, p. 21–53. doi:10.1016/S0301-9268(03)00076-7

Rignot, E., Mouginot, J., and Scheuchl, B., 2011. Ice Flow of the Antarctic Ice Sheet; Science, v. 333, p. 1427–1430. doi:10.1126/science.1208336

Robinson, S.V.J., Paulen, R.C., Jefferson, C.W., McClenaghan, M.B., Layton-Matthews, D., Quirt, D., and Wollenberg, P., 2014. Till geochemical signatures of the Kiggavik uranium deposit, Nunavut; Geological Survey of Canada, Open File 7550, 168 p. doi:10.4095/293857

Shilts, W.W., 1984. Till geochemistry in Finland and Canada; Journal of Geochemical Exploration, v. 21, p. 95–117. doi:10.1016/0375-6742(84)90037-2

Shilts, W.W., 1995. Geochemical partitioning in till; *in* Drift Exploration in the Canadian Cordillera, (ed.) P.T. Bobrowsky, S.J.Sibbick, J.M. Newell, and P.F. Matysek; British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1995-2, p. 149–163.

Shilts, W.W. and Wyatt, P.H., 1989. Gold and base metal exploration using drift as a sample medium, Kaminak Lake - Turquetil Lake area, District of Keewatin; Geological Survey of Canada, Open File 2132, 168 p. doi:10.4095/130776

Smith, A.M., Bentley, C.R., Bingham, R.G., and Jordan, T.A., 2012. Rapid subglacial erosion beneath Pine Island Glacier, West Antarctica; Geophysical Research Letters, v. 39, p. 1–5. doi:10.1029/2012GL051651

St-Onge, D.A. and Kerr, D.E., 2013. Reconnaissance surficial geology, Duggan Lake, Nunavut, NTS 76-H; Geological Survey of Canada, CGM Map 113, scale 1:125 000. doi:10.4095/292269

Stokes, C.R. and Clark, C.D., 2003. The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behavior on the Canadian Shield and insights regarding the controls on ice-stream location and vigour; Boreas, v. 32, p. 263–279. doi:10.1111/j.1502-3885.2003.tb01442.x

Stokes, C.R., Lian, O.B., Tulaczyk, S., and Clark, C.D., 2008. Superimposition of ribbed moraines on a palaeo-ice- stream bed: implications for ice stream dynamics and shutdown; Earth Surface Processes and Landforms, v. 33, p. 593–609. doi:10.1002/esp.1671

Stokes, C.R., Spagnolo, M., Clark, C.D., O'Cofaigh, C., Lian, O.B., and Dunstone, R.B., 2013. Formation of mega-scale glacial lineations on the Dubawnt Lake Ice Stream bed: 1. size, shape and spacing from a large remote sensing dataset; Quaternary Science Reviews, v. 77, p. 190–209. doi:10.1016/j.quascirev.2013.06.003

Thompson, P.H., Culshaw, N., Buchanan, J.R., and Manojlovic, P., 1986. Geology of the Slave Province and Thelon tectonic zone in the Tinney Hills-Overby Lake (west half) map area, District of Mackenzie; *in* Current Research, Part A; Geological Survey of Canada Paper 86–1A, p. 275–289.

Winsborrow, M.C.M., Clark, C.D., and Stokes, C.R., 2004. Ice Streams of the Laurentide Ice Sheet; Géographie physique et Quaternaire, v. 58, no. 2–3, p. 269–280.

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