# Preliminary Ice-Flow Indicator Mapping, Fond du Lac River Area, Southern Tantato Domain and Northern Athabasca Basin, Saskatchewan

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### *Abstract*

*Airphoto interpretation and field data collection of large-, meso-, and small-scale ice-flow indicators north and south of the Fond du Lac River were performed in order to determine a relative ice-flow chronology that would help with the interpretation of past, current and future surficial geochemical sampling programs. The detailed survey resulted in a substantial increase in the existing ice-flow-indicator dataset and the production of a relative ice-flow chronology comprising a four-flow sequence: 1) westward; 2) south and south-southwestward; 3) west-southwestward and southwestward; and 4) west-southwestward and westward.*

*In terms of drift prospecting, it is important to note that not all ice-flow directions are found throughout the area, and that the dominant ice-flow direction is not the same throughout the area. To the north of the Fond du Lac River, in the southern Tantato Domain, the dominant ice-flow direction is to the west-southwest. To the south of the river, on the northern edge of the Athabasca Basin, drumlins and megaflutings highlight a dominant ice-flow direction generally to the west.*

*An additional objective of the project was to further document the presence of a paleo–ice stream in the region (Campbell* et al.*, 2007b), which also has relevance for drift prospecting as ice streams can disperse large amounts of sediment over great distances. The mapping of westward-trending drumlins and megaflutings, as well as small-scale erosional ice-flow indicators, further confirms the presence of this paleo–ice stream. The ice stream flowed westward in the area at the end of the last glaciation and dominated a large part of the study area and beyond.*

**Keywords:** *ice-flow indicator mapping, ice-flow chronology, paleo–ice stream, Quaternary, Fond du Lac River, Tantato Domain, Athabasca Basin, drift prospecting, drumlin, megafluting*

## 1. Introduction

In 2014 and 2015, ice-flow indicator mapping was undertaken along the Fond du Lac River in northern Saskatchewan encompassing the southern part of the Tantato Domain and the adjacent northern edge of the Athabasca Basin (NTS 74O/01, /02, /07, /08, and 74P/05; Figure 1). The objectives of the ice-flow indicator mapping were two-fold.

The primary objective was to provide an ice-flow chronological framework for interpreting glacial dispersal of mineralized debris at the local scale. The area surrounding the Fond du Lac River is prospective for nickel, copper, gold and uranium (Figure 1). Magmatic nickel and copper is present in the mafic granulite of the southern Tantato

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Domain (Knox and Lamming, 2014, 2015a; Normand, *in press*). The Axis Lake deposit (Figure 1) has a historic, non-NI 43-101–compliant resource estimate of 3.8 million tons grading 0.6% Ni and 0.6% Cu (Coombe Geoconsultants Ltd., 1991); organic soil sampling in the area surrounding this deposit indicates anomalous Ni and Cu results (Saskatchewan Ministry of the Economy Assessment File 74O08-0075). In terms of gold, the area between Robillard Bay and Pine Channel (Figure 1) is of economic interest because of the presence of numerous gold occurrences (Morelli and MacLachlan, 2012) and elevated gold levels in lake sediment (Friske *et al*., 1994a, 1994b; McCurdy *et al*., 2015). Lastly, the study area is situated between the Fond du Lac uranium deposit on the south shore of Lake Athabasca (~30 km west of the study area; Figure 1), the Black Lake and Riou Lake uranium occurrences (Figure 1), and the former Nisto uranium mine on the west shore of Black lake (~30 km east of the study area; Figure 1). Measurement of ice-flow directions and reconstruction of the sequence of flow changes is thus fundamental to any future drift prospecting programs as it provides a means for interpreting glacial dispersal of lithological, mineralogical and geochemical indicators of economic mineralization in the sediment.

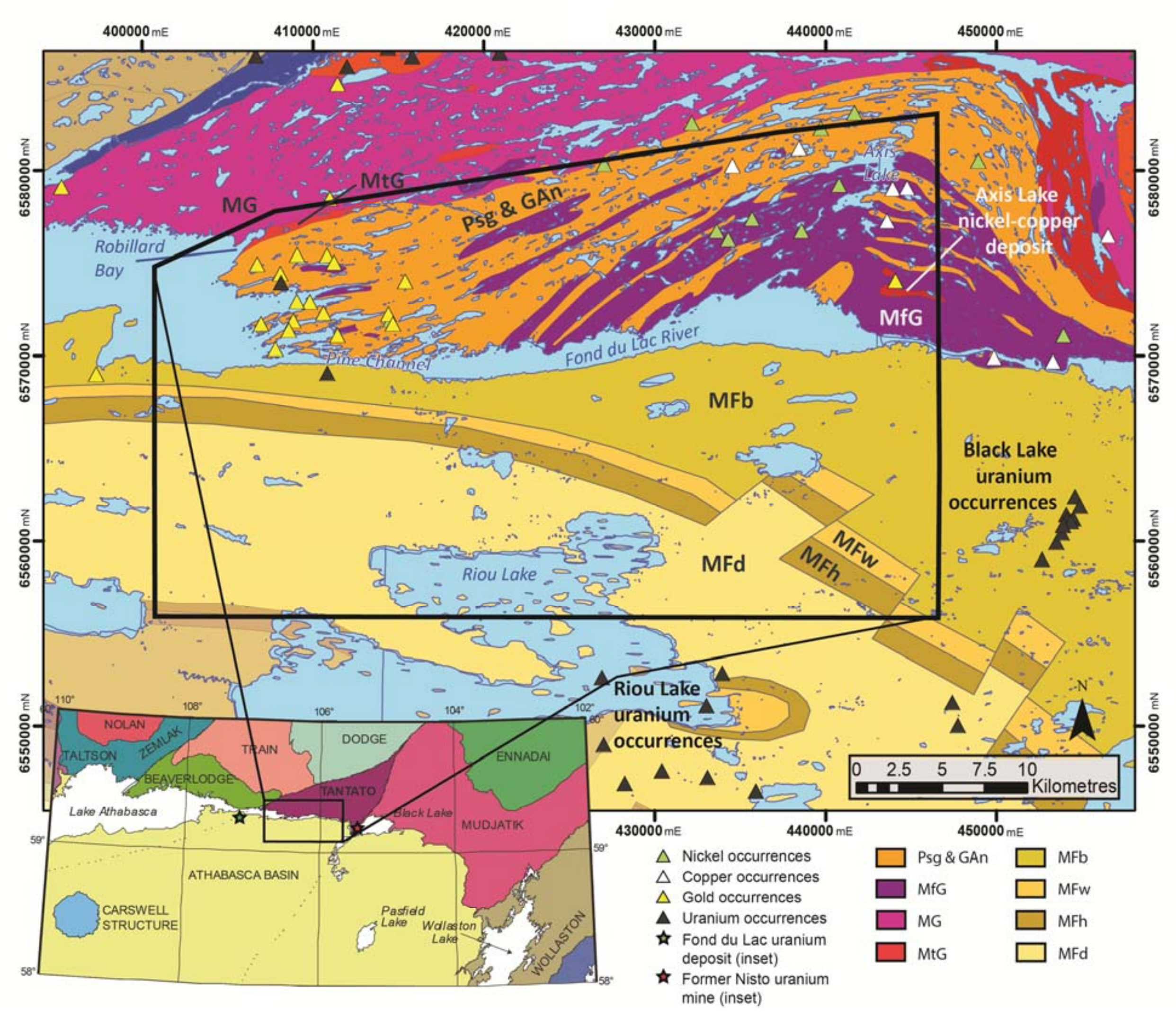


***Figure 1** – Location of the study area (black outline) within the context of the lithostructural domains of northern Saskatchewan (inset) and the simplified regional bedrock geology. Regional geology adapted from Bosman and Ramaekers (2015), Knox and Lamming (2014, 2015b, 2015c, 2015d), and Saskatchewan Geological Survey (2015). For simplicity, the legend contains only geological units that are found within the study area; for information on the units outside the study area, please refer to the Saskatchewan Geological Atlas (Saskatchewan Geological Survey, 2015). Psg: psammopelitic gneiss; GAn: garnet-bearing anatectic granite; MfG: mafic granulite; MG: Mary granite; MtG: Melby-Turnbull granite; MF: Manitou Falls Group (b: Bird Formation; w: Warnes Formation; h: Hodge Formation; d: Dunlop Formation).*

The secondary objective was to use the ice-flow chronology to contribute to a better understanding of ice sheet dynamics at a regional scale and, in particular, to document evidence for ice streaming in this region during the last glaciation (Campbell *et al*., 2006a, 2007a; Stokes and Tarasov, 2010; Hanson, 2014). An ice stream is an area of an ice sheet that flows noticeably faster (>300 metres per annum ($ma^{-1}$); Stokes and Clark, 1999) than the surrounding ice. Ice streams commonly radiate out from the interior of an ice sheet and are typically >20 km wide and >150 km in length (Stokes and Clark, 1999). Several ice streams have already been well documented in southern Saskatchewan and along the eastern margin of the Athabasca Basin (Adams, 2009; Ross *et al*., 2009; Ó Cofaigh *et al*., 2010; Margold *et al*., 2015) but only preliminary work has been done to document ice streaming in the region of the study area (Campbell *et al*., 2007b). Ice streams play important roles in glacial dynamics. They result in a substantial ice flux that can affect ice sheet configurations, including ice-divide configurations; thus their documentation is crucial to former ice sheet geometry reconstruction, as well as understanding of regional ice-flow directions. Ice streams also result in a large sediment flux, which has important implications for mineral exploration.

This paper presents a preliminary interpretation of the relative ice-flow chronology for the study area and evidence for ice streaming, and is accompanied by an ice-flow indicator map (Hanson, 2015). Concurrent to the ice-flow indicator mapping project, surficial geological mapping and a regional till sampling program were undertaken; results will be published in upcoming reports and maps. Additionally, detailed geological mapping of the gold and nickel occurrences was undertaken by Normand (2014, and *in press*, respectively) and regional geological mapping of the southern Tantato Domain was undertaken by Knox and Lamming (2014, 2015a, 2015b, 2015c, 2015d).

## 2. Previous Work

Previous regional surficial geological mapping in the area includes reconnaissance-scale mapping of streamlined glacial landforms in the south, over the Athabasca Basin, from 1:63 360-scale aerial photographs for production of a 1:250 000-scale surficial geology map (Schreiner, 1984b; Figure 2). Additional ice-flow indicator measurements were compiled from a Saskatchewan Ministry of the Economy Assessment File (74O07-0049) and from Campbell *et al*. (2007a; Figure 2).

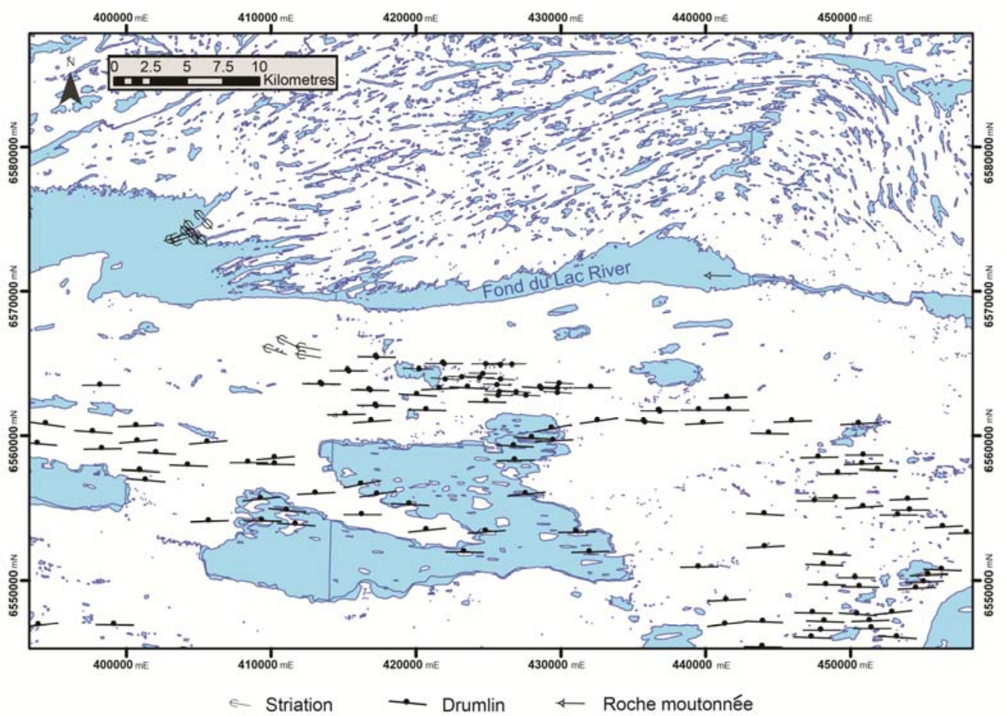


*Figure 2 – Ice-flow measurements recorded prior to this project (Schreiner, 1984b; Campbell* et al.*, 2007a; Ministry of the Economy Assessment File 74O07-0049). Note the absence of ice-flow indicators north of the Fond du Lac River.*

To the west of the study area, surficial geological mapping at a scale of 1:50 000 included detailed maps of ice-flow directions (Campbell *et al*., 2006b, 2007b) and summaries of relative ice-flow chronology (Campbell *et al*., 2006a, 2007a). Largely, there is a glaring absence of ice-flow information in the study area, particularly north of the Fond du Lac River (Figure 2); the existing information is not sufficiently detailed for interpretation of the distribution of anomalous lake sediment and soil geochemical data, or results of future till sampling programs.

## *3.* Regional Setting

### a) Bedrock Geology

The bedrock geology of the southern Tantato Domain is being mapped in detail by the Saskatchewan Geological Survey as part of this multidisciplinary project and is discussed by Knox and Lamming (2014, 2015a). Lithologic codes after rock names in this paper (*e.g.*, (unit Psg)) correspond to rock codes in Figure 1. The southern Tantato Domain is composed of garnetiferous granitic orthogneiss, psammopelitic gneiss (unit Psg) and minor derived garnet-bearing anatectic granite (unit GAn). Mafic granulite (unit MfG) intrudes these units and crosscuts the earliest structures (Figure 1). All of these units have been multiply deformed, locally mylonitized, and have undergone regional granulite facies metamorphic events at *ca*. 2.55 Ga and 1.90 Ga (Knox and Lamming, 2014), the latter of which locally produced late leucogranite.

Four subunits of the Manitou Falls Group (Figure 1) underlie glacial drift along the northern edge of the Athabasca Basin. The Bird Formation (unit MFb) is a lower conglomeratic quartz arenite; the Warnes Formation (unit MFw) is a clay intraclast–rich quartz arenite; the Hodge Formation (unit MFh) is a pebbly to coarse-grained quartz arenite containing little to no clay intraclasts; and the Dunlop Formation (unit MFcl) is a clay intraclast–rich quartz arenite (Bosman and Ramaekers, 2015).

### b) Quaternary Geology

Saskatchewan has undergone multiple glaciations throughout the Quaternary Period but it is primarily the record of the latest—the Late Wisconsinan—that has been well preserved. During the Last Glacial Maximum, 19 to 23 thousand calendar years before present (cal ka BP; Mix *et al*., 2001), most of Saskatchewan was covered by the Laurentide Ice Sheet (LIS). At maximum ice extent, the ice sheet would have had a thickness of up to 3000 m over the study area (Dyke *et al*., 2002). Widespread retreat of the LIS throughout North America was underway by 16.8 cal ka BP (Dyke, 2004). In Saskatchewan, ice retreated to the northeast and the study area was completely ice free by 9.0 cal ka BP (Schreiner, 1984a; Dyke *et al*., 2003; Dyke, 2004).

The Quaternary geology of the southern Tantato Domain will be described in an upcoming paper; the Quaternary geology of the Athabasca Basin part of the study area was preliminarily described by Hanson (2014). The surficial geology of both terrains is largely the product of erosion, deposition and modification during retreat of the LIS. North of the Fond du Lac River, bedrock exposure is abundant and the bedrock has been glacially eroded and molded; locally, subglacially deposited till can be overlain by stagnant-ice melt-out till, which has been eroded by glaciofluvial processes and/or overlain by glaciofluvial sediments. South of the Fond du Lac River, drumlins, organic plains, hummocky stagnant-ice melt-out till, and glaciofluvial outwash sediments cover the majority of the area. Late in the deglacial sequence, both terrains were inundated by proglacial Lake Athabasca, part of glacial Lake McConnell (Smith, 1994), to at least ~305 m above sea level (asl; Schreiner, 1984a; Campbell *et al*., 2006b, 2007b; Hanson, 2014). Wave and current action within the lake resulted in the winnowing, removal, and redeposition of drift, leaving a notable cobble-boulder lag covering the majority of the area (Hanson, 2014). Other areas are covered in glaciolacustrine silts and clays and littoral sands and cobbles.

### c) Regional Ice Flow

During the last glaciation, ice generally advanced toward the southwest over Saskatchewan from a dispersal centre in the Keewatin Sector of the LIS, located in Nunavut (Prest *et al*., 1968; Prest, 1984; Dyke and Prest, 1987; Dyke *et* *al*., 2002). In the study area, possibly during initial ice advance and during late retreat, a paleo–ice stream flowed westward along the Fond du Lac River into the Lake Athabasca basin, also called the 'Athabasca Low' (Figure 3; Campbell *et al*., 2007b; Hanson, 2014). This ice stream has been documented and hypothesized by Campbell *et al*. (2007b) immediately west of the study area and modelled regionally by Stokes and Tarasov (2010). A mapping inventory of LIS ice streams, however, did not include this potential ice stream (Margold *et al*., 2015). This ice stream had a significant effect on ice flow in the study area.

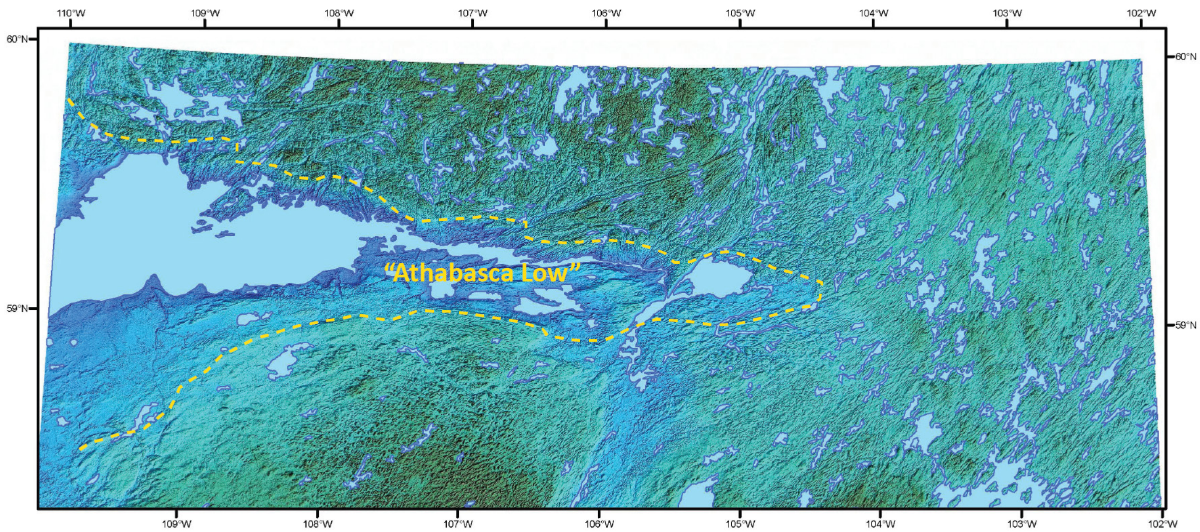


***Figure 3 –*** *Digital elevation model of northern Saskatchewan displaying the general location of the 'Athabasca Low' (after Campbell* et al.*, 2007b).*

## d) Ecoregions and Physiography

The study area north of the Fond du Lac River is part of the Tazin Lake Upland Ecoregion. The physiography is characterized by steep, generally southwest-trending ridges of crystalline basement rocks. Local relief is up to 100 m and black spruce forest dominates the terrain. The dominant soil is Brunisolic on sandy and bouldery drift; Organic and Cryosolic soils are present on poorly drained areas (Padbury and Acton, 1994; Acton *et al*., 1998). Parts of the study area were burned in 2006 and 2014.

The area south of the Fond du Lac River lies within the Athabasca Plain Ecoregion. Immediately south of the river, local relief is up to 130 m, but much of the area consists of nearly flat plateaus. Higher areas are characterized by a thin veneer of sandy glaciofluvial sediments and till covered by jack pine forest; lower areas have thicker drift deposits and extensive black spruce peatlands. Brunisolic soils are present on well-drained slopes, whereas Gleysols, Organics and local Cryosols exist in poorly drained areas (Padbury and Acton, 1994; Acton *et al*., 1998).

# 4. Methods

## a) Large-scale Landforms

Prior to fieldwork, pre-existing ice-flow indicator data was compiled from Schreiner (1984b) and Saskatchewan Ministry of the Economy Assessment File 74O07-0049 (Figure 2). Aerial photographs at 1:60 000 scale were used to identify additional large-scale streamlined landforms (drumlins and megaflutings) in the southern part of the study area and eskers throughout (Hanson, 2015). Subsequent to formation, the landforms were submerged under glacial Lake Athabasca, which eroded and subtly to drastically modified their shapes. Thus, only the landforms that were clearly recognizable were mapped and measured from the airphotos. A few minor corrections (*e.g.*, azimuth and location) were made to Schreiner's (1984b) interpretation of the streamlined landforms.

## b) Meso- and Small-scale Landforms

Prior to fieldwork, a few ice-flow indicator measurements were compiled from Campbell *et al*. (2007a) and Saskatchewan Ministry of the Economy Assessment File 74O07-0049 (Figure 2). Fieldwork focused on providing detailed information on meso- and small-scale erosional landforms. Meso-scale landforms included roches moutonnées; small-scale landforms included striations, microstriations, grooves, crescentic and lunate gouges, crescentic fractures, and chattermarks (Figure 4)[2]. A total of 1155 measurements were made at 342 sites, most of which were north of the Fond du Lac River (Figure 5).

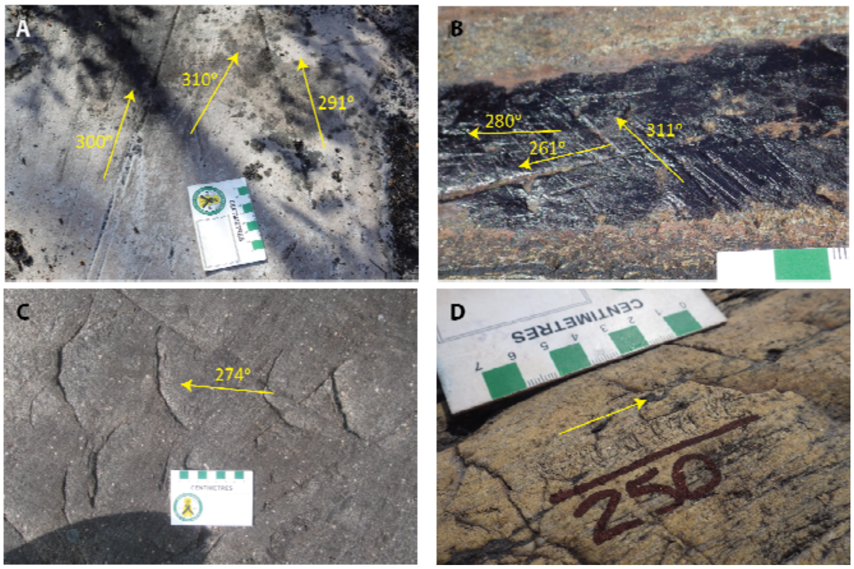


***Figure 4*** *– Examples of small-scale ice-flow indicators; arrows denote ice-flow directions. **A)** Striations in multiple directions on an outcrop of Athabasca sandstone (UTM 423903E, 6568300N). **B)** Crosscutting microstriations, highlighted with black marker, on a leucosome layer within psammopelitic gneiss (UTM 416704E, 6570036N). **C)** Four crescentic gouges on mafic granulite (UTM 411861E, 6570034N). **D)** Chattermarks on garnet-bearing anatectic granite (UTM 405573E, 6573096N).*

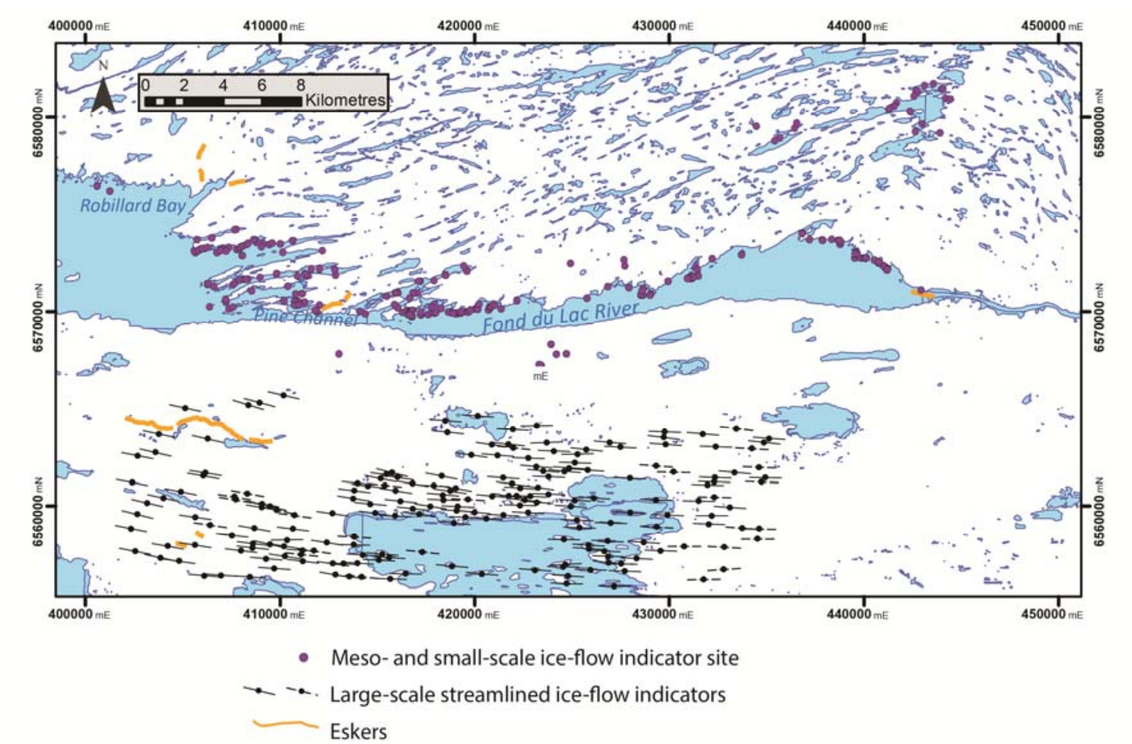


***Figure 5*** *– Distribution of ice-flow indicators measured from airphotos and in the field in 2014 and 2015.*

[2] All coordinates are in UTM Zone 13V using North American Datum NAD83.

The gneissosity and foliation of the southern Tantato Domain bedrock is commonly parallel to some of the ice-flow directions, requiring careful inspection; many potential roches moutonnées were not recorded because of this. Measurements of the azimuth of small-scale features were made on subhorizontal outcrops using an orienteering compass. Care was taken not to bias data collection by preferentially measuring sites on stoss (up-ice facing) or lee (down-ice facing) slopes. The sense of ice flow was determined from roches moutonnées, crescentic and lunate gouges, chattermarks, wedge striations, and stoss-and-lee topography. Small-scale ice-flow indicators, especially microstriations, are best preserved on fine-grained and polished leucosome layers within psammopelitic gneiss (Figure 6A), which is exposed in many places along the northern shore of the Fond du Lac River (Figure 6B). Less commonly exposed, coarser-grained mafic granulite and garnetiferous granitic gneiss do not as readily preserve ice-flow indicators due to chemical and physical weathering of the exposed surfaces, as well as to the fact that these rocks are originally more resistant to erosion than the psammopelitic gneiss. However, mafic dykes within these rocks do preserve ice-flow indicators relatively well. To the south, on the Athabasca sandstone, striations are only preserved on smooth, silicified surfaces that have not undergone spalling (Figure 6C).

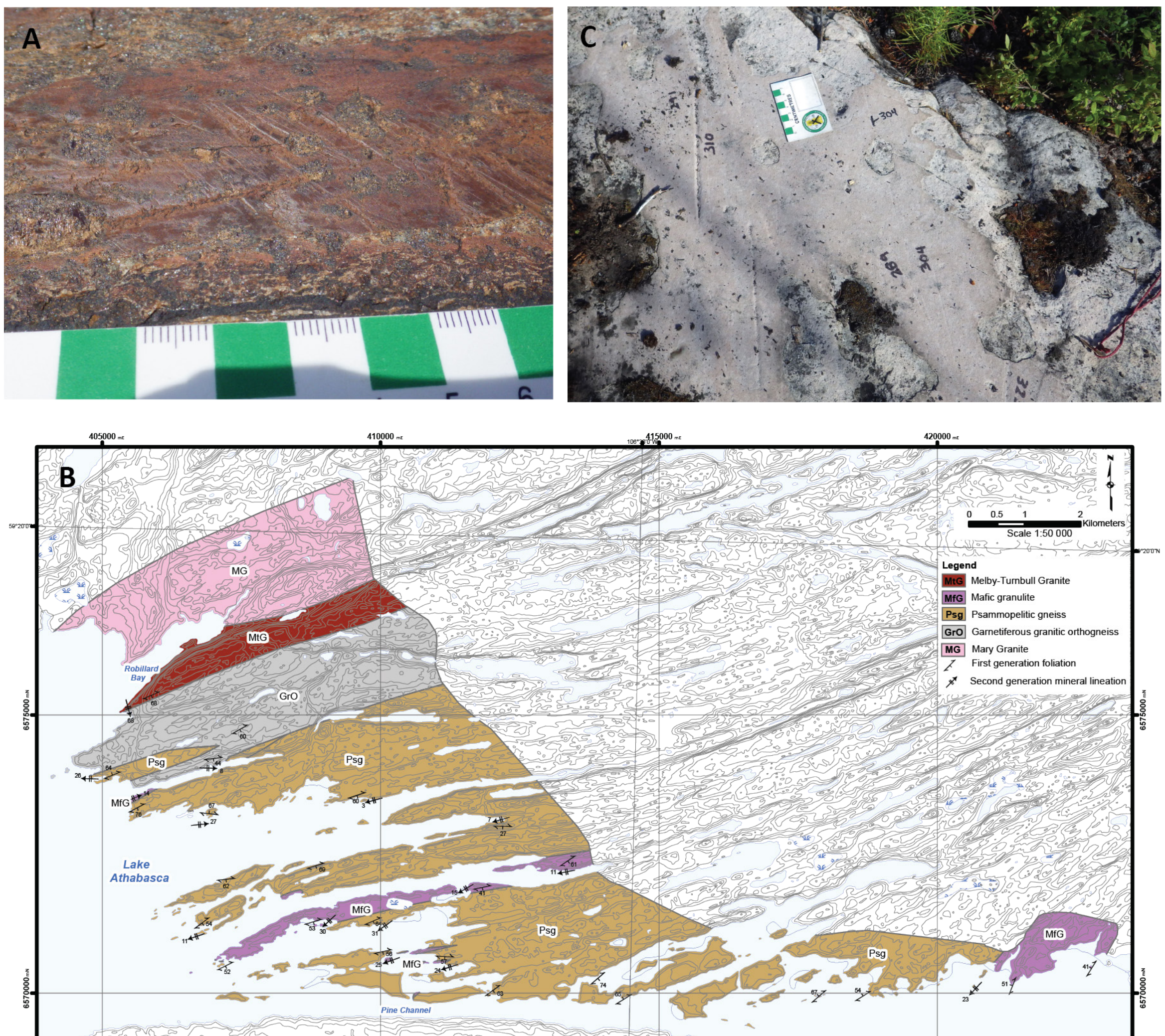


***Figure 6 – A)*** *Microstriations preserved on fine-grained leucosome layers within psammopelitic gneiss (UTM 416704E, 6570036N).* ***B)*** *Simplified 1:50 000-scale geology map from Knox and Lamming (2014). Psammopelitic gneiss (Psg) preserves small-scale ice-flow indicators very well; mafic granulite (MfG) and garnetiferous granitic orthogneiss (GrO) do not. Mary granite (MG) and Melby-Turnbull granite (MtG) were not sufficiently exposed in the study area to assess ice-flow indicator preservation.* ***C)*** *Striations preserved on smooth, silicified Athabasca sandstone; note surrounding surfaces that have been eroded (spalled) and that do not preserve striations (UTM 423903E, 6568300N).*

## c) Relative Age Determination

Criteria used to determine relative ages of ice-flow indicators in this study included:

1) crosscutting of small-scale features (Figure 4B);
2) superposition of small features (*e.g.*, striations) on top of larger features (*e.g.*, roches moutonnées), which indicates that the smaller feature is younger than the larger feature (Figure 7A);
3) stoss-and-lee topography: a set located in a lee position relative to a set in the stoss position is older because as ice flows over the stoss side of an outcrop, directions will be overwritten, but older directions can be protected and preserved in lee positions where ice flow is less vigorous or non-existent (Figure 7B; Lundqvist, 1990); similarly, a set preserved only in depressions or other protected surfaces is older (Lundqvist, 1990);
4) surface aspect: a set found only on top of an outcrop is considered to be youngest (Lundqvist, 1990); and,
5) relative size: deeper grooves and/or striations crosscut by, or adjacent to, a finer set of indicators, including microstriations, are generally older (McMartin and Paulen, 2009).

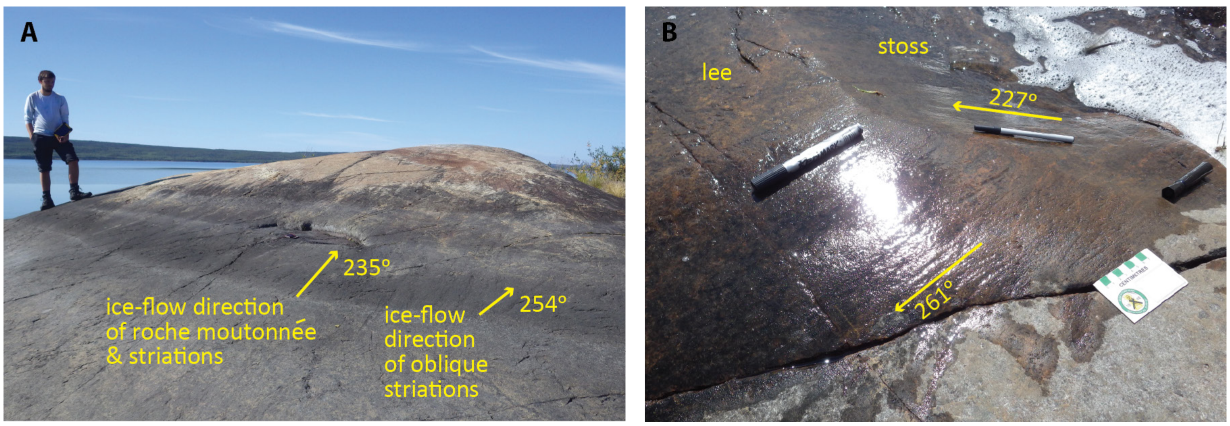


***Figure 7 –*** *Examples of some ice-flow indicator age relationships.* ***A)*** *Superposition of striations on a roche moutonnée; one set of striations is in the same direction as the roche moutonnée (235°), the other is at an oblique angle (254°) to the roche moutonnée. The obliquely angled striations are interpreted to be younger than the roche moutonnée (UTM 440110E, 6572736N).* ***B)*** *Stoss (younger) and lee (older) topography with a different ice-flow direction on each surface (UTM 419287E, 6569916N).*

# 5. Results

## a) Large-scale Landforms

Mapped large-scale ice-flow landforms include drumlins, megaflutings and eskers. In the south of the study area, drumlins and megaflutings are abundant (Figure 8). Drumlins and megaflutings are streamlined landforms aligned parallel to ice flow. The distinction between drumlins and megaflutings is based upon the elongation ratio (length/width) of the landform: both are longer than 100 m, but drumlins have elongation ratios of up to 7:1, whereas megaflutings have elongation ratios greater than 7:1 (Rose, 1987). Drumlins here range from 180 to 1470 m long and 35 to 385 m wide, with elongation ratios of 2.5 to 7.0; megaflutings range from 295 to 2125 m long and 40 to 220 m wide, with elongation ratios of 7.1 to 22.9. These landforms indicate a single flow to the west and west-northwest (266° to 287°). From east to west, the landforms swing from a westward flow to a west-northwestward flow (Figure 5), possibly representing deflection of flow by slightly higher topography to the south of the study area, but likely still representing the same ice flow. Several eskers trend in a similar direction among the drumlins and megaflutings (Figure 5), and in the eastern part of the Fond du Lac River an esker flows to the west-northwest (Figure 5). The ice-flow directions of these landforms are consistent with measurements of small-scale features north of the Fond du Lac River, although this direction is not the dominant direction there (Figure 9).

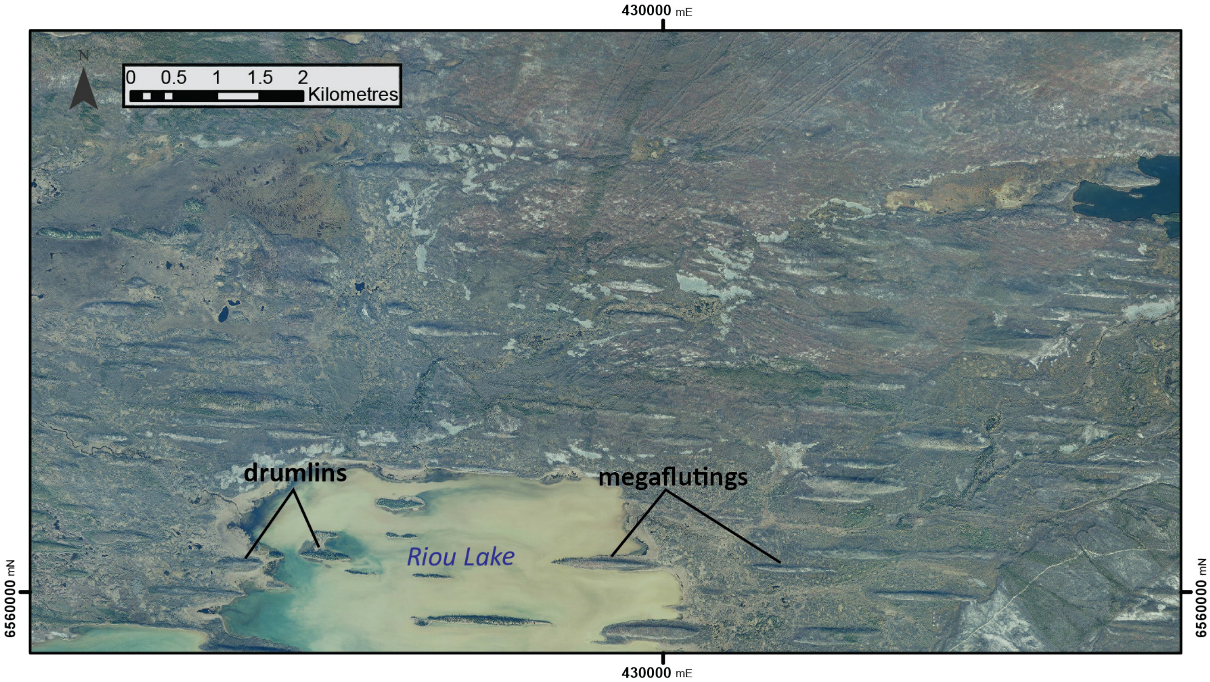


***Figure 8** – Saskatchewan Geospatial Imagery Collaborative orthophoto of part of the southern part of the study area on the Athabasca Basin showing large-scale landforms.*

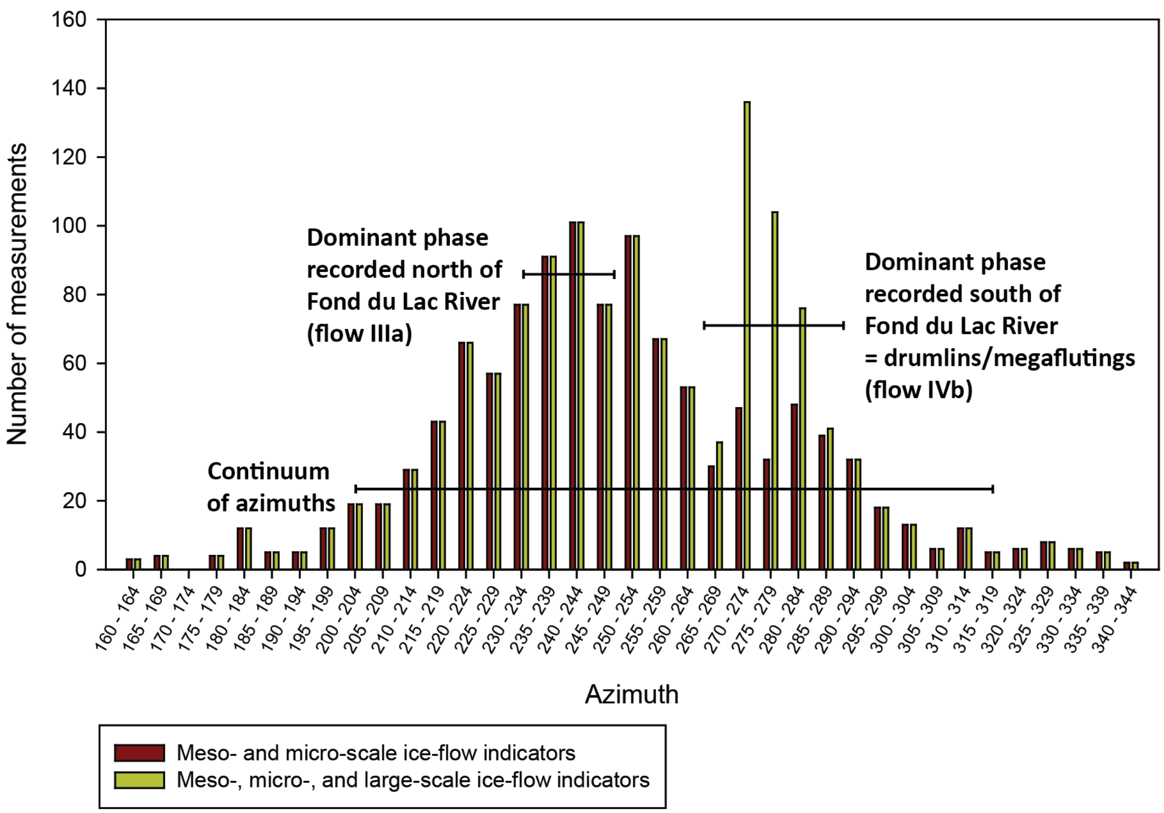


***Figure 9** – Number of measurements per azimuth. Azimuths were grouped into five degree ranges to account for human error while measuring (e.g., Stea et al., 2009). Note that not all observed indicators were measured, but that this is still likely a reasonable representation of the ice-flow directions in the area. Flow IVb is clearly distinguished by the drumlin and megafluting azimuths.*

A few other ice-flow directions were recorded by large-scale landforms. In the northwest corner of the study area, two eskers flow from the north and the east-northeast into Robillard Bay (Figure 5). Along Pine Channel, an esker flows from the north-northeast into the Fond du Lac River (Figure 5).

### b) Meso- and Small-scale Landforms

Only 11 roches moutonnées were recorded north of the Fond du Lac River during fieldwork because of the factors mentioned above (see section 4b). These features were more confidently identified in the hinge of the regional fold axis south of Axis Lake (Figure 1) as opposed to areas in which the glacial features paralleled the regional foliation in the bedrock. The abundant bedrock exposure along the Fond du Lac River allowed for easy identification and measurement of many small-scale features. Azimuths of the meso- and small-scale features range from 162° to 344°; there is a continuum of measurements between 202° and 316° (Figure 9). These measurements were divided into four different ice flows (see section 6b, below).

## 6. Discussion

### a) Evidence of Paleo–ice Streaming

Evidence of paleo–ice streaming was documented by Campbell *et al*. (2007b) immediately west of the study area, and modelled regionally by Stokes and Tarasov (2010). The drumlins and megaflutings in the study area are possibly the result of this paleo–ice stream that flowed generally westward during retreat of the LIS. Criteria that can be used to identify a terrestrial (as opposed to marine-based) paleo–ice stream include (Stokes and Clark, 1999; Winsborrow *et al.*, 2010):

1) a characteristic large shape and dimension (>20 km wide, >150 km long);
2) notably convergent flow patterns at the onset of the ice stream;
3) indications of rapidly flowing ice, such as highly attenuated landforms (drumlins, megaflutings, etc.), especially with elongation ratios >10:1, and/or the presence of deformable sediment, which can predispose an ice sheet to flow faster;
4) an erratic dispersal train that exhibits a longer dispersal train where ice was flowing faster adjacent to shorter dispersal trains of similar composition where ice was flowing more slowly;
5) sharply delineated margins marked by abrupt changes in landform pattern (*i.e.*, a sharp end to attenuated landforms) and/or lateral shear moraines;
6) topographic lows that enable focusing of the ice streaming;
7) macro-scale bed roughness: topographic highs can offer resistance to ice flow ("sticky spots"), whereas areas of low bed roughness can promote faster ice flow; and,
8) the presence of sedimentary bedrock as opposed to hard bedrock: sedimentary bedrock has the potential for greater glacial erosion, and thus greater till cover, which in turn promotes macro-scale bed smoothness and till that has a high potential to deform.

Not all of the above criteria are required for the existence of an ice stream, nor is the presence of some of the criteria on their own (*e.g.*, attenuated landforms) conclusive evidence of an ice stream (Stokes and Clark, 1999; Winsborrow *et al.*, 2010).

In the study area, 36% of the streamlined landforms measured in this study exceed the elongation ratio of 10:1 (point #3) indicating the potential for the presence of fast-flowing ice. These landforms extend ~60 km to the east, ~35 km to the west, and ~100 km to the south, which would be consistent with the size of an ice stream (point #1). The presence of the 'Athabasca Low' (point #6) would have contributed to funneling of the ice westward, especially when the ice was thin and had a low surface profile, late in the glaciation. The macro-scale topography (point #7) could also have contributed to the presence of an ice stream: the underlying topography of the Athabasca Basin, where the streamlined landforms are found, is generally flat and smooth compared to the 100-metre-high southwest-trending (*i.e.*, somewhat transverse to ice stream flow) ridges of the southern Tantato Domain where no substantial evidence supporting ice streaming has been documented. Lastly, the presence of a sedimentary basin (the Athabasca Basin; point #8) that was susceptible to glacial erosion could have produced relatively large volumes of sediment that would have enhanced basal sliding and/or till deformation to allow for fast-flowing ice. The remaining criteria (points #2, #4 and #5) have yet to be evaluated; however, preliminary indications support the presence of a paleo–ice stream that flowed westward in the study area and to the west. The presence of an ice stream has considerable impacts on drift prospecting in the area. Ice streams can move large amounts of sediment over great distances and thus their boundaries need to be properly mapped.

## b) Ice-flow Sequence

The large-scale remotely mapped landforms were combined with the detailed record of meso- and small-scale landforms observed in the field. A continuum of measurements between 202° and 316° was noted. This continuum could be the result of shifting ice divides, local bedrock topographic control and changes in ice thickness, as well as the influence of the 'Athabasca Low.' One hundred and thirty age relationships were used to construct a complex four-stage ice-flow sequence, with an additional unknown ice-flow direction (Figure 10, Table 1).

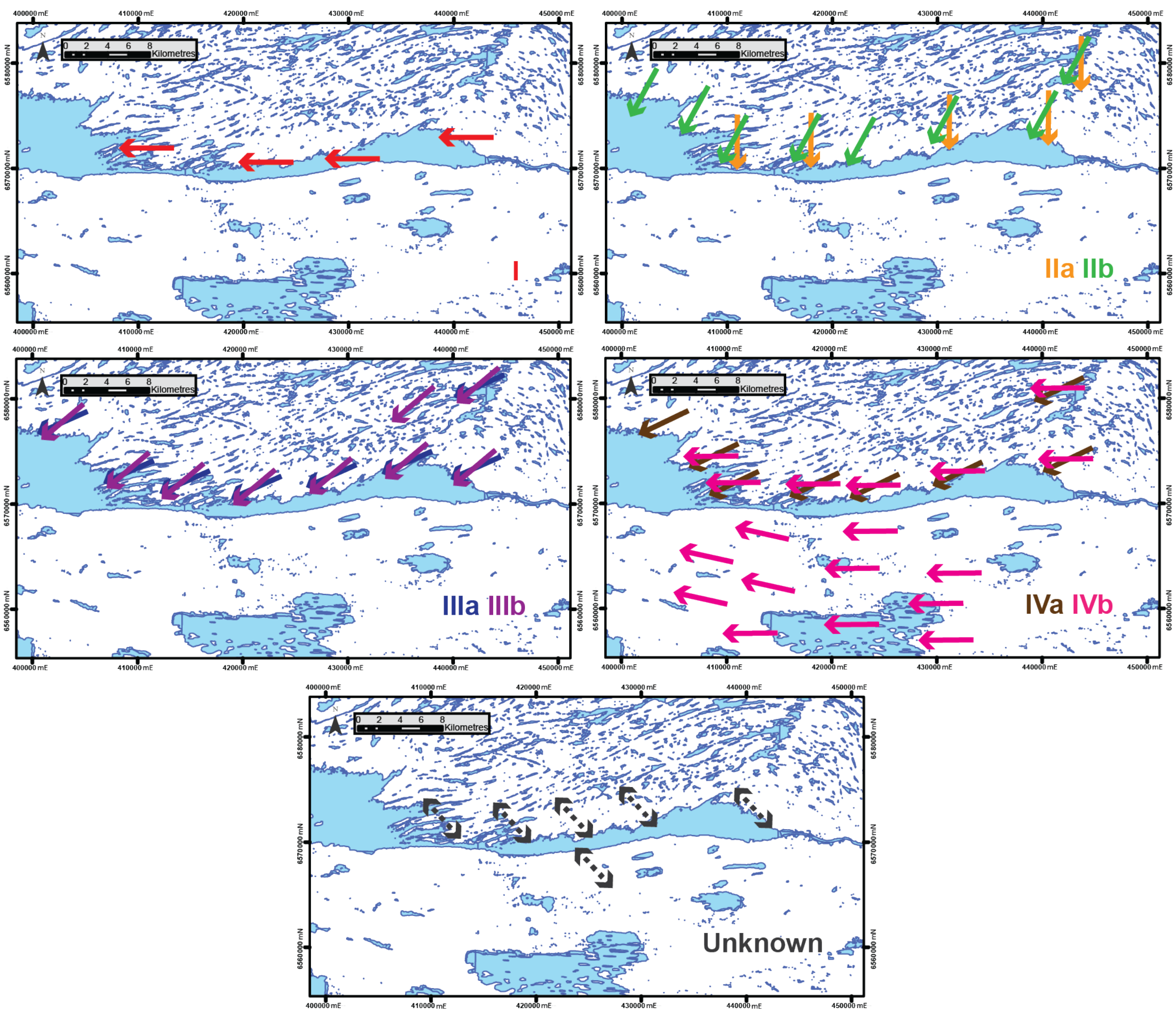


***Figure 10 –*** *Sequence of ice flows for the Fond du Lac River area. Distribution of arrows approximates spatial distribution of indicators for each flow.*

***Table 1 –*** *Comparison of ice flows determined in this study to those determined immediately to the west (Campbell* et al.*, 2006b, 2007b).*

| **This paper** | | | **Campbell *et al.* (2006b, 2007b)** | | |
|---|---|---|---|---|---|
| Flow | Direction | Azimuth | Flow | Direction | Azimuth |
| I | W | 249° – 282° | I | W | 250° – 280° |
| II a | S | 161° – 185° | II | SSE | 165° – 180° |
| b | SSW | 191° – 212° | | SSW | 195° – 208° |
| III a | WSW | 234° – 249° | III | SW | 230° – 245° |
| b | SW | 212° – 236° | | SSW | 210° – 230° |
| IV a | WSW | 249° – 260° | IV | W | 250° – 280° |
| b | W | 266° – 290° | | | |
| | | | | S | |
| Unknown | NW-SE | | Unknown | NW-SE | |

An ice-flow phase is defined as a regionally mappable and coherent set of ice-flow trends, distinguished from other trends by relative age (Stea *et al*., 2009). The ice-flow directions described below pertain to the study area only and may not reflect regional ice-flow directions in the rest of northern Saskatchewan. More work outside of the study area is required to put this ice-flow sequence into a regional context. Thus, in this paper, ice-flow directions are labelled as flows, not phases. Flows are grouped based on their interpreted relative age and extent within the study area. The flows are listed in relative chronological order, but more work is required in order to put more stringent constraints on the timing of these flows.

The ice flows described below are very similar to those described by Campbell *et al*. (2006b, 2007b) immediately west of the study area (Table 1), indicating that there is a consistent pattern in the eastern region of the 'Athabasca Low.' Campbell *et al*. (2006b, 2007b), however, did not subdivide flow IV as below, and they noted a late-glacial southward flow, attributed to drawdown into the 'Athabasca Low,' a direction that was not noted around the Fond du Lac River.

*Flow I: West*

Flow I is a westward flow (249° to 289°). Evidence of this flow in the ice-flow indicator record is sparse and is found only north of the Fond du Lac River; any evidence south of the river would have been remolded by subsequent flows or not preserved on the erodible Athabasca sandstone. This flow, and flow IVb—both westward flows—are the only two that were not found inland (north) of the Fond du Lac River. These two flows are anomalous when compared with regional ice-flow directions across northern Saskatchewan (*e.g.*, Saskatchewan Geological Survey, 2015). It is possible that flow I coincided with an ice stream (similar to flow IVb) but there is not enough evidence at this point to state this with any confidence. Campbell *et al*. (2006b, 2007b) indicate that this flow could predate the last glaciation.

*Flow II (a and b): South and South-southwest*

Flow II comprises two parts: an early flow to the south (162° to 185°) and a later flow to the south-southwest (191° to 212°). This flow possibly occurred as ice thickened in the study area, overcoming local topographic bedrock control that had helped to funnel ice westward. This direction, and subsequent ones (excluding flow IVb), coincide with regional ice-flow directions across northern Saskatchewan. In the study area, this direction was found only north of the Fond du Lac River in the southern Tantato Domain; this is likely due to the poor preservation of indicators on outcrops of Athabasca Basin sandstone.

*Flow III (a and b): West-southwest and Southwest*

Flow III encompasses a swing from the west-southwest (234° to 249°) to the southwest (212° to 236°). The west-southwest flow is the dominant regional direction north of the Fond du Lac River (Figure 9), and is the most commonly noted flow direction inland and north of the river. The dominance of this ice-flow direction implies that it was sustained for a long period of time. Several roches moutonnées coincide with the southwestward direction, indicating that it is also a relatively dominant flow in the area. Neither flow was found south of the river within the study area, likely due to the poor preservation of indicators on outcrops of Athabasca sandstone. The west-southwest flow, however, was found near the south shore of Lake Athabasca, ~30 km west of the study area on Isle Brochet (Campbell, 2005). Campbell *et al*. (2006b, 2007b) attribute these flows to the Last Glacial Maximum and much of deglaciation.

*Flow IV (a and b): West-southwest and West*

Flow IV encompasses a swing from the west-southwest (249° to 260°) to the west and west-northwest (266° to 290°). The azimuths of some roches moutonnées coincide with the first direction, indicating that it is also a somewhat dominant flow in the area. This swing from southwest to west is only found north of the Fond du Lac River, again because of varying bedrock preservation capabilities. This swing is likely caused by thinning of the ice sheet as the ice margin was retreating back toward the study area; thinning would allow for progressively more control of ice flow by local topography, hence the final westward flow. The westward flow indicates the establishment of the paleo–ice stream. Drumlins in the southern part of the study area (Figure 5) confirm that the westward and west-northwestward flow was a late dominant ice flow in the area. Any subsequent significant flow would have remolded the drumlins and megaflutings, produced superimposed streamlined landforms, and/or left erosional indicators in the sandstone. The west-northwestward flow could represent deflection of flow by slightly higher topography, as mentioned in section 5a, but it could also represent slight convergence of flow into the topographic low during ice streaming.

*Unknown Flow: Northwest–Southeast*

Multiple ice-flow indicator measurements indicate a northwest–southeast (291° to 344° or 111° to 164°) direction. Similar ice-flow directions have been noted immediately to the west (Campbell, 2005; Campbell *et al*., 2006a, 2007a) and east (Schreiner, 1984a; Saskatchewan Ministry of the Economy Assessment File 74O07-0036) of the study area, as well as farther east in the northeastern corner of Saskatchewan (Campbell, 2002).

It is difficult to determine if this flow is old or young compared to other flows in the study area. In the northeastern corner of the province, Campbell (2002) interpreted this direction as a flow that would have predated the southward flow in that area. In this study area, age relationships were found that supported this flow being both old and young. However, most of the indicators are small and faint with low preservation potential, supporting the hypothesis that they are from a young ice-flow direction that was not very vigorous. This direction is found throughout the study area, but it is noticeable that it is the only other direction, aside from flow IVb, found on outcrops of Athabasca Basin sandstone. This also implies that it represents a young ice-flow direction; if it was the oldest ice-flow direction in the area, it is unlikely that it would be preserved on these rocks without the preservation of subsequent flows. If this direction had been found only on the south shore, it could have been attributed to convergence of flow into the topographic low during ice streaming, but it is found throughout the study area.

It is also difficult to determine the direction of this flow. Out of the 120 measurements made of this flow, 71 were recorded with general slope directions. Of the 71, 31% were found on southeast-facing slopes, compared to 4% on northwest-facing slopes, and 28% on flat surfaces. If this direction is a young direction and was not from vigorous ice flow, then expectations are that it might be found mostly on stoss and flat surfaces as opposed to lee surfaces. A potential interpretation then is that because more indicators were found on southeast-facing surfaces, the southeast-facing surfaces are stoss surfaces and ice was thus flowing to the northwest. The fact that a continuum of azimuths was measured between 202° and 316° could also indicate that this flow was to the northwest. A few of the measurements, however, are crescentic gouges that contradict this interpretation as they indicate a flow direction to the southeast. Regardless of flow direction, these azimuths are difficult to reconcile with regional ice sheet dynamics.

## 7. Summary

Airphoto interpretation and field data collection of ice-flow indicators north and south of the Fond du Lac River were performed in order to produce a relative ice-flow chronology to help with the interpretation of past, current and future surficial geochemical sampling programs in the area, as well as to document paleo–ice streaming.

The detailed survey resulted in a substantial increase in the ice-flow indicator dataset and in refinement of the local relative ice-flow chronology into a four-flow sequence (west; south and south-southwest; west-southwest and southwest; west-southwest and west). This sequence is similar to the ice flows recorded immediately to the west (Campbell *et al*., 2006a, 2007a), but more work is required to determine if this ice-flow sequence is applicable beyond the boundaries of the study area.

In terms of drift prospecting, it is important to note that the dominant ice-flow direction is not the same throughout the area. To the south of the Fond du Lac River, drumlins and megaflutings highlight a dominant ice-flow direction to the west and west-northwest. To the north of the river, however, the dominant ice-flow direction is to the west-southwest, an earlier direction than the one that is dominant on the south shore. Analysis of till pebble petrography and fine-fraction till geochemistry results will further contribute to the determination of the dominant ice-flow directions, as well as their spatial distribution in the study area.

This new dataset also contributes to the continued documentation of a paleo–ice stream that existed prossibly at least twice and that extends throughout the southern part of the area and substantially beyond. Further documentation of the paleo–ice stream, in particular its extent, is crucial to the determination of regional ice flow in northern Saskatchewan as well as to understanding till-dispersal mechanisms, patterns and distances in the area.

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