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Glacial geomorphology of north-central Hall Peninsula, Southern Baffin Island, Nunavut

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1. Introduction

Canada was affected by several glaciations during the Quaternary (Ehlers and Gibbard 2004). Many ore deposits are covered by glacial sediments, which make it difficult to detect the deposits remotely. Currently, an important exploration method in Canada involves the search for distinct mineral assemblages in glacial sediments and tracing them back to their source. To use this method effectively, it is critical to understand regional past glacial dynamics and the subtleties of glacial erosion, sediment production, transportation, and deposition (Klassen 2001). Lack of such knowledge can delay major discoveries and lead to increased exploration costs.

The evolution of ice-flow systems over time has a major effect on the glacial landscape and its sediments. Maps of glacial landforms at various scales, including streamlined hills and striations and other ice flow indicators preserved on glacially abraded outcrops, are necessary to understand the glacial dynamics and ice flow history of an area. Such mapping efforts were undertaken on Hall Peninsula, Baffin Island, because available maps and data were clearly insufficient to meet the needs of mineral exploration in this prospective region. The goal of this report is to present the results of the mapping of large (kilometre scale) subglacial landforms based on remote sensing and of targeted field mapping of meso-scale (sub-kilometre) landforms and outcrop-scale glacial striae and other paleo-ice-flow indicators throughout the study area.

2. Location

The study area is located in north-central Hall Peninsula, Baffin Island. Fieldwork was restricted to a smaller area than what was mapped using remotely sensed imagery (Figure 1: The location of the field site on Hall Peninsula, Baffin Island. Focused fieldwork is shown in the red polygon and geomorphology mapping was within the largest, green polygon..

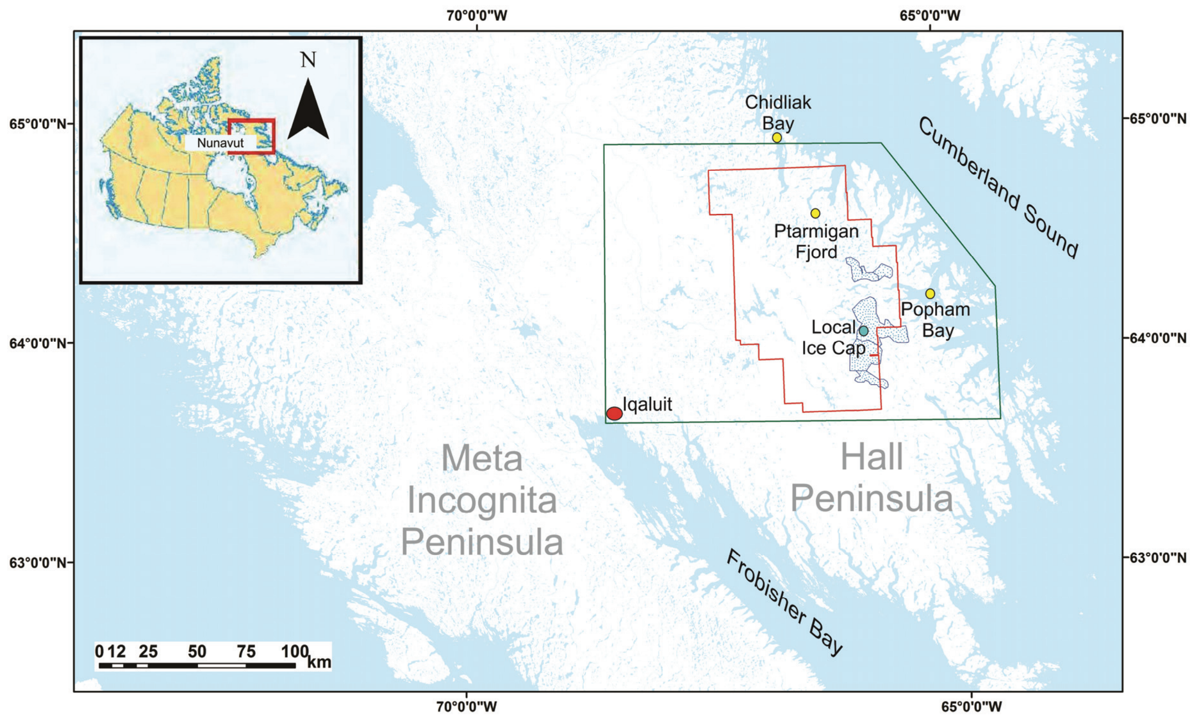


Figure 1: The location of the field site on Hall Peninsula, Baffin Island. Focused fieldwork is shown in the red polygon and geomorphology mapping was within the largest, green polygon. The larger area is approximately 25,400 km^2.

3. Physiography

Hall Peninsula is the middle of three large peninsulas of southeastern Baffin Island. It is bounded by Frobisher Bay to the south/southwest and Cumberland Sound to the north/northeast (Figure 1). The elevation ranges from 200 m asl in the southeast to 700 m asl in a central plateau decreasing towards the northwest to about 200-300 meters asl (Miller 1985). Most of central and eastern Hall Peninsula is drained via the McKeand River (Miller 1985), which cuts through the eastern portion of the study area (Pell 2011). Fjords dissect the perimeter of the peninsula, thus directing the drainage. According to the physiographic region maps by Bostock (1970) and Andrews (1989), the physiographic regions of the study area are the stepped plain or dissected upland surfaces to the north and "Baffin Surface" in the south. Baffin Surface is described as an area with few lakes (<5%) with tors and angular blockfields, suggesting that the area has not been intensely scoured by warm-based glacial ice (Andrews, 1989). The land from the coast to approximately 50 km inland consists of abundant lakes, ponds and bedrock-controlled streamlined hills. The central part of the study area is characterized by flat to rolling topography consisting of more continuous till surrounding an area of regolith, and with few ponds and lakes. The central area also contains minor glaciofluvial and lacustrine deposits.The eastern region is characterized by bedrock hills occupied by the current ice cap, valleys, and fjords.

4. Bedrock Geology

The bedrock geology of the study area is summarized by Pell (2011). The bedrock geology of Baffin Island has only been mapped at a reconnaissance scale (Jackson and Berman 2000). Hall Peninsula was mapped by Blackadar (1967) and revisited by Scott (1996). In 2006, the map was released digitally (St-Onge, Jackson, and Henderson) (Figure 2).

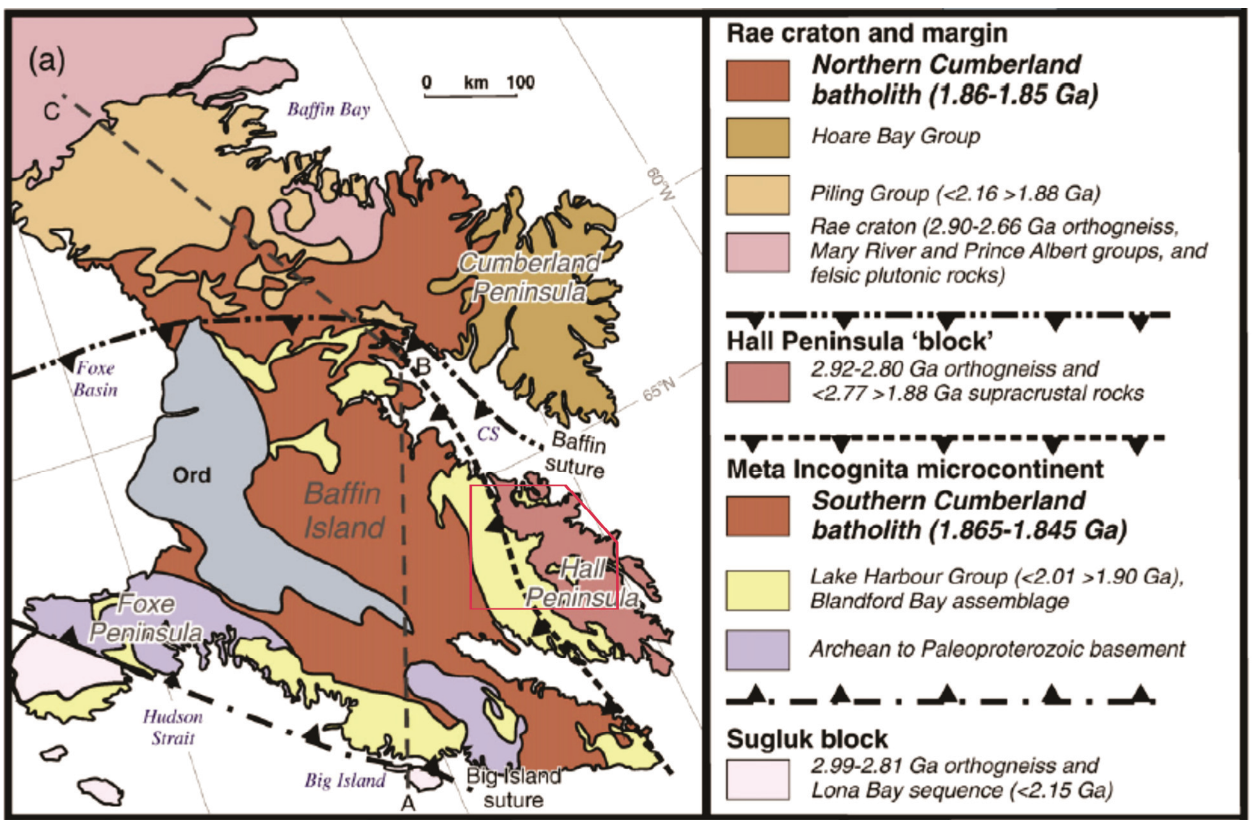


Figure 2: A summary of the simplified geology of southern Baffin Island showing tectonostratigraphic assemblages, such as the Hall Peninsula Block located in the study area. As shown, Hall Peninsula is underlain by Hall Peninsula block (orthogneiss and supracrustal rocks) and Lake Harbour Group assemblages (*modified from* St-Onge et al., 2008 and Whalen 2010).

Hall Peninsula is thought to be underlain by three units: an eastern Archean Gneiss belt (part of the Archean North Atlantic Craton), a central metasedimentary domain which is correlated to the Paleoproterozoic Lake Harbour Group rocks on Meta Incognita Peninsula, and a western Cumberland Batholith (Whalen 2010). Several kimberlite bodies have recently been discovered in the study area and have been the focus of intense diamond exploration since 2005 (Pell 2011; Pell et al**. 2012).** More than 60 kimberlites have been discovered between 2008 and 2011 in the study area, as well as notable base and precious metal till anomalies which may be prospective for magmatic Ni-Cu-PGE metamorphosed SEDEX, and VMS Pb-Zn and Pb-Zn-Cu, and lode gold (Pell 2011). The kimberlite province stretches in a north-south direction for approximately 70 kilometers and in an east-west direction for approximately 40 kilometers (Pell et al. 2012). All of the kimberlites discovered are hosted in rocks belonging to the Hall Peninsula Block (Pell et al. 2012)

5. Surficial Materials

Till throughout Baffin Island is generally thin with the exception of locally thicker deposits in the central region. Small pro-glacial and subaqueous outwash and deltaic sediment bodies also occur attesting of the existence of short-lived proglacial rivers and lakes in the study area (Miller 1985). Based on exploration drill holes, the till in the central plateau area reaches up to 15 m in thickness (Pell 2011). It is thinner in areas proximal to the coasts, where bedrock is discontinuously covered with a thin till veneer about 1-2 m thick. In valley floors and other areas of relatively lower elevation, till is also thicker (Pell 2011). According to Andrews (1989), the till on Baffin Island consists of two types: sandy till with abundant Precambrian clasts (shield type), and a silt-clay matrix-dominated till with abundant Palaeozoic carbonate clasts. The till encountered during field work is from the first “shield” type with a strong local signature characterized by abundant clasts of orthogneisses or Paleoproterozoic metasedimentary rocks found in the study area. Locally, the till can have a strong kimberlitic composition including green matrix, kimberlite and limestone cobbles.

6. Previous Studies

Limited research has been done on the Quaternary geology of Hall Peninsula. Hall Peninsula has been included in regional studies of the Laurentide Ice Sheet (Dyke et al. 2002) and the Quaternary Geology of the north eastern Canadian Shield (Andrews 1989; Miller et al. 2002; Miller et al. 2005; De Angelis 2007; De Angelis and Klemen 2007; Briner, et al. 2009). Few studies have focused on Hall Peninsula itself, but have a primary focus on the record of deglaciation and associated late Foxe and Cockburn Substage moraine systems (Miller 1980; Miller 1985). A 1:500 000 scale predictive surficial geology map was released following a remote predictive mapping (RPM) study based on LANDSAT and digital elevation models (DEM) (Harris et al. 2012).

Baffin Island is dominated by a landscape reflecting varying thermal regimes as shown through bedrock erosion (Andrews 1989). The ice sheet velocity and profile were highly controlled by the substrate and thermal regime (Miller et al. 2000). During the Last Glacial Maximum (LGM) (approximately 21 ka ago), the Laurentide Ice Sheet (LIS) overwhelmed southern Baffin Island, including Hall Peninsula and its offshore islands (Dyke et al. 2002). During early deglaciation, the Hall Ice Divide is thought to have run parallel to the axis of the peninsula and to have flowed away from the divide to the northeast and southwest (Hall et al. 2003).

The oldest moraine on the Peninsula is the Hall Moraine (Miller, 1980; Miller, 1985) (Figure 3). About 50 km to the northwest of the Hall Moraine is the inner Frobisher Bay Moraine, which trends northeast/south-west across the high part of the Peninsula. The Hall Moraine was dated with 3 paired valves of *Mya truncata* that averaged 10, 760 ± 70 ^{14}C yrs BP marking the deglaciation from a terminal moraine complex in Warwick Sound (Miller 1980) and thus marks a stillstand of the margin of the Laurentide Ice Sheet during the overall deglaciation of the area on Hall Peninsula and Frobisher Bay (Miller 1985). At Gold Cove (20 km up-bay) *Mya truncata* yielded ages of 10,100 ± 100 ^{14}C yrs BP (GSC-2725), which is considered to date the deglaciation of the cove (Miller, 1980). Other ages for the deglaciation of the cove included the apparent ^{14}C age of 12,150 ± 140 yr (QC-543), which was later re-dated because the initial age was significantly older than GSC-2725; the new analysis yielded an age of 10,200 ± 210 yr B.P. (GSC-2778) which is statistically indistinguishable from the first one (Miller, 1980). A *M. truncata* shell with the age of 9,725 ± 120 yr (QC-450) was also found in marine limit deposits which shows a transition to marine environment after the deglaciation of Gold Cove (Miller 1980).

Further west, two major moraine systems younger than the Hall Moraine (Figure 3) have been mapped and dated at about 8,600 ^{14}C yrs BP, equivalent to the Cockburn Substage (Miller 1985). The Frobisher Bay Moraine System (Figure 3) was traced from inner Frobisher Bay and up to the northwest where the trace eventually is lost (Miller 1985). Drumlinized till suggests that ice flowed parallel to the axis of the peninsula from the northwest to the southeast (Miller 1985).

Miller (1985) also mapped the Chidliak Moraine which runs south-southeast along the east coast of Hall Peninsula to Chidliak Bay (Miller 1985). The ice that deposited this moraine flowed northeast from the plateau of the peninsula and funnelled through the fjords and bays that line the perimeter (Miller 1985). Shell of *Hiatella arctica* found on the moraine were dated at 8,660 ± 160 ^{14}C yrs BP (GSC-2466), which correlates to the Frobisher Bay Moraine System. East of Chidliak Bay, the drumlins have a northeast trend, which contrasts with the southeast trending features in the centre of the peninsula (Miller 1985).

Previous mapping of a local moraine inland of Popham Bay (Figure 3) suggests that it required ice-flowing from the east to west (Miller 1985). The local moraine was deposited by the Hall Peninsula ice cap, located in the study area. *Hiatella arctica* shells gathered from ice-proximal raised marine deltas yielded an age of 8,890 ±100 ^{14}C yrs (GSC-2586) (Miller 1985). This age correlates the local ice advance to the inner continental moraine system in Chidliak Bay and Frobisher Bay (Miller 1985).

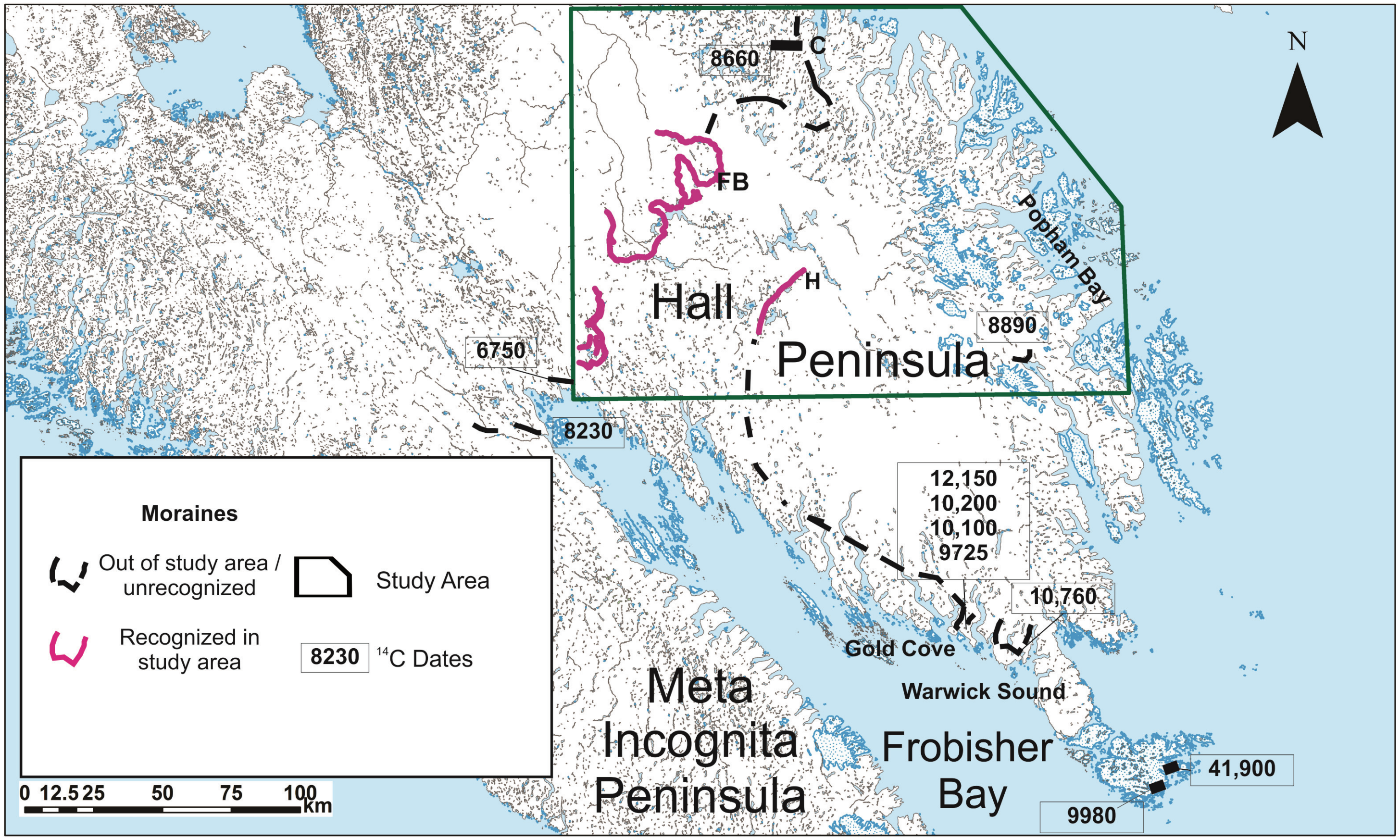


Figure 3: Major moraine systems of Southern Baffin Island and their respective radiocarbon ages (Figure *modified from* Miller 1980). The dashed lines indicate places where the moraines are inferred, and the dotted line is where it is extrapolated. The geomorphology map done in this project is within the trapezoid and includes the Hall Moraine (H) and the Frobisher Bay Moraine (FB). The Chidliak Moraine (C), mapped later by Miller (1985), runs parallel to the east coast and is dated at 8890 and 8660 ^{14}C yrs BP, but was not observed during this study. Figure *modified from* Miller (1980).

Proglacial features of Hall Peninsula include lacustrine shorelines, deltas and overflow channels from the former proglacial lake systems (Miller 1985). The two main series of the lakes identified are associated with the Hall Moraine (older) and the Frobisher Bay Moraine system (younger) (Miller 1985). There are also well developed ice-contact/proximal deltas where the lakes were against the edge of the moraines (Miller 1985). The older lakes are at 630 m asl and drained south (Miller 1985). The younger lakes also lie 630 m asl and are traced to the Frobisher Bay Moraine along the western margin but, to the northeast, the margin is lost amongst the edge of the largest lake (Miller 1985). Miller (1985) postulated that the only way this large lake could have existed was to be dammed by a thin residual ice cap lying between Cumberland Sound and the large lake. There is no evidence in terms of modern moraine deposits, which would support the existence of such an ice body (Miller 1985). However, this ice cap was most likely thin and perhaps cold-based. Cosmogenic dating of bedrock surfaces and boulders from within the inferred ice cap area could test this late ice cover hypothesis.

7. Methods

This study focused on subglacial landforms in order to map and provide information about ice flow dynamics. The mapping of surficial materials (e.g. regolith, till, glaciofluvial and lacustrine deposits) is out of the scope of this report. Remote sensing is frequently used for mapping regional scale glacial features (Clark et al. 2000; De Angelis and Kleman 2007; Kleman and Glasser 2007; Clark et al. 2009; Stokes et al. 2009; Kleman et al. 2010; Trommelen and Ross 2012; Spagnolo et al. 2011; Smith and Knight 2011). Satellite images and air photographs are often used to develop understanding of an area's glacial history, even when little or no previous mapping has been done (Kujansuu 1990). Satellite images can be visually interpreted to highlight specific features of the landscape such as groups of streamlined hills or moraines (Boulton and Clark 1990). Glacial features can thus be reliably mapped by visual interpretation, though it is essential to go through quality checks, such as overlaying geological maps to differentiate glacial features from bedrock features (Clark et al. 2009).

Subglacial landforms often occur in clusters or "fields" that form under certain conditions and different times. These clusters provide insight on glacial dynamics, erosion, transport and deposition. Fields of parallel streamlined ridges thought to have formed by basal ice-flow are referred to as flowsets (Kleman et al. 1997). It has become clear that because of variable degrees of erosion and preservation, the glacial landscape forms a complex patchwork of glacial landforms and sediments resulting from different non-coeval ice-flow events (Stea and Finck 2001; Clarhäll and Jansson 2003; Ross et al. 2009; Stokes et al. 2009; Trommelen et al. 2012). Some of these "patches", referred to as glacial terrain zones or GTZ (cf. Trommelen et al. 2012), may overlap showing complex crosscutting patterns or may be defined by sharp boundaries separating groups of landforms with contrasting orientation or characteristics (e.g. Ross et al. 2009).

For remote sensing, the study took advantage of LANDSAT 7 with Landsat Enhanced Thematic Mapper Plus (ETM+) satellite imagery, publicly available digital elevation models, airborne magnetics, and topographic maps (Table 1). Georeferenced and ortho-rectified air photographs were not used in this study. Satellite images were used to map the study area for meso-and mega-scale subglacial features. A mosaic of available satellite images was created and visualized at a 1:100,000 scale and again at a 1:30,000 scale in order to capture landforms of different sizes. Streamlined ridges (till and bedrock-cored drumlins, mega-flutes, and large *roches moutonnées*) were mapped together as glacial features. There were no distinctions made between different types of streamlined ridges.

Table 1: Presented is a summary of the datasets that were used for remote sensing mapping.

Data Source	Spatial Resolution (horizontal)	Technical Properties	Projection	Source
Satellite imagery (ETM+)	15 meters	Panchromatic Band 8	NAD 83, UTM Zone 19	http://www.geobase.ca
DEM	3 arc seconds	1:250,000 NTS tiles	NAD 83, UTM Zone 19	http://www.geobase.ca
Airborne magnetic geophysical survey images	4 meters		NAD 83, UTM Zone 19	Unpublished; Peregrine Diamonds Limited

A crucial component to understanding the Quaternary history of an area is mapping glacial erosional features. The reconstruction of ice-flow history is done by measuring glacial striations (Parent et al. 1995; McMartin and Henderson 2004; McMartin and Paulen 2009; Plouffe et al. 2011). As summarized by Parent et al. (1995) the ice-flow direction can be established by two sets of criteria: (1) small-scale features such as nailhead striae, crescentic gouges, and rat-tail ridges and (2) medium sized features such as whaleback forms, and meter-scale *roches moutonnées* (too small to be visible on the LANDSAT images). It is common to have multiple features at one site. When there are two or more ice-flow directions observed, cross-cutting and stoss-and-lee relationships are studied to determine the relative age (Parent et al. 1995; McMartin and Paulen 2009). This is achieved by studying the relative positions of the indicators on the outcrop-scale according to the following criteria: a) ice-flow indicators found just on the top parts of an outcrop are usually considered the youngest for that site; b) ice-flow indicators found in depression or lower positions on the same outcrop are typically relatively older (McMartin and Paulen 2009). For example, lower polished surfaces in a down-ice position relative to the ice-flow direction as recorded on top of the outcrop are referred to as "protected surfaces" and the striations on them interpreted as relict or preserved striations from an older ice-flow phase. Also, sometimes deeper grooves or crescentic gouges are crosscut by younger striae superimposed on an angle on top of these features thus giving a clear relative age relationship (Parent et al. 1995; McMartin and Paulen 2009). Quaternary field mapping of striations and other erosional features were used to reconstruct the ice-flow history of the area and to ground-truth the features mapped using remote sensing.

Helicopter-supported fieldwork was based out of camps operated by Peregrine Diamonds Limited during the summers of 2010 and 2011. The data gathered from the field were primarily small-scale ice-flow indicators such as striae, grooves, chattermarks, sculpted outcrops, and in some cases small-medium sized *roches moutonnées* and drumlins. The goal of the 2010 field season was to understand the regional ice-flow in the area. To distinguish the regional flows from the local flows, directional indicators were studied at the tops of bedrock hills as opposed to within valleys. At lower elevations, striation records are often more complex than records of higher elevations, reflecting local topographic influence of ice-flow that developed during late stage deglaciation. The 2011 field season granted more time to investigate these local flows in high priority areas. The field data is stored in a Microsoft Access database and includes station information (station ID and coordinates), paleo-flow data when observed, sample information and photo identification. The ice-flow indicator measurements collected in the field were also visualized in ArcGIS® (ESRI). The coordinate system used for all of the GIS files is NAD 83, UTM Zone 19.

8. Results

8.1 Remote Sensing Results

A total of 1293 streamlined hills, one major moraine system, one local moraine, and a series of U-shaped valleys were mapped using remote sensing techniques (Figure 4; Appendix A). There are discrete landscapes within the study area recognized on the LANDSAT images which include areas near the coast with relatively high density of lakes (Andrews 1989), ponds, fjord interfluves and streamlined hills, a central area which is relatively featureless and blanketed in till and regolith, and the area dominated by the local ice cap.

Four main orientations of ice-flow were found through analysis of the LANDSAT images. Each flow trajectory was confidently established in the field through analysis of the stoss-lee relations of streamlined hills. These flows can be summarized from relatively oldest to youngest as follows: (1) ice-flow to the northeast in fjord interfluve areas; (2) to the north and northwest in relation to the northern fjords; (3) to the east along the eastern coast (Figure 4); and, (4) southeast central to the study area. A southwest flow, which is not strongly represented in the remote sensing results, may be concurrent with the northeast flow (1) flowing on the opposite side of the Hall Ice Divide (Marsella et al. 2000). Field work will be needed in this area to establish the extent of the southwest flow. The southeast flow (5) is found with few striations and the orientation of the late stage moraines. However, most large southeast trending landform features recognized in the satellite imagery are parallel to major bedrock structures visible on the airborne magnetic map and are thus interpreted as bedrock-controlled ridges.

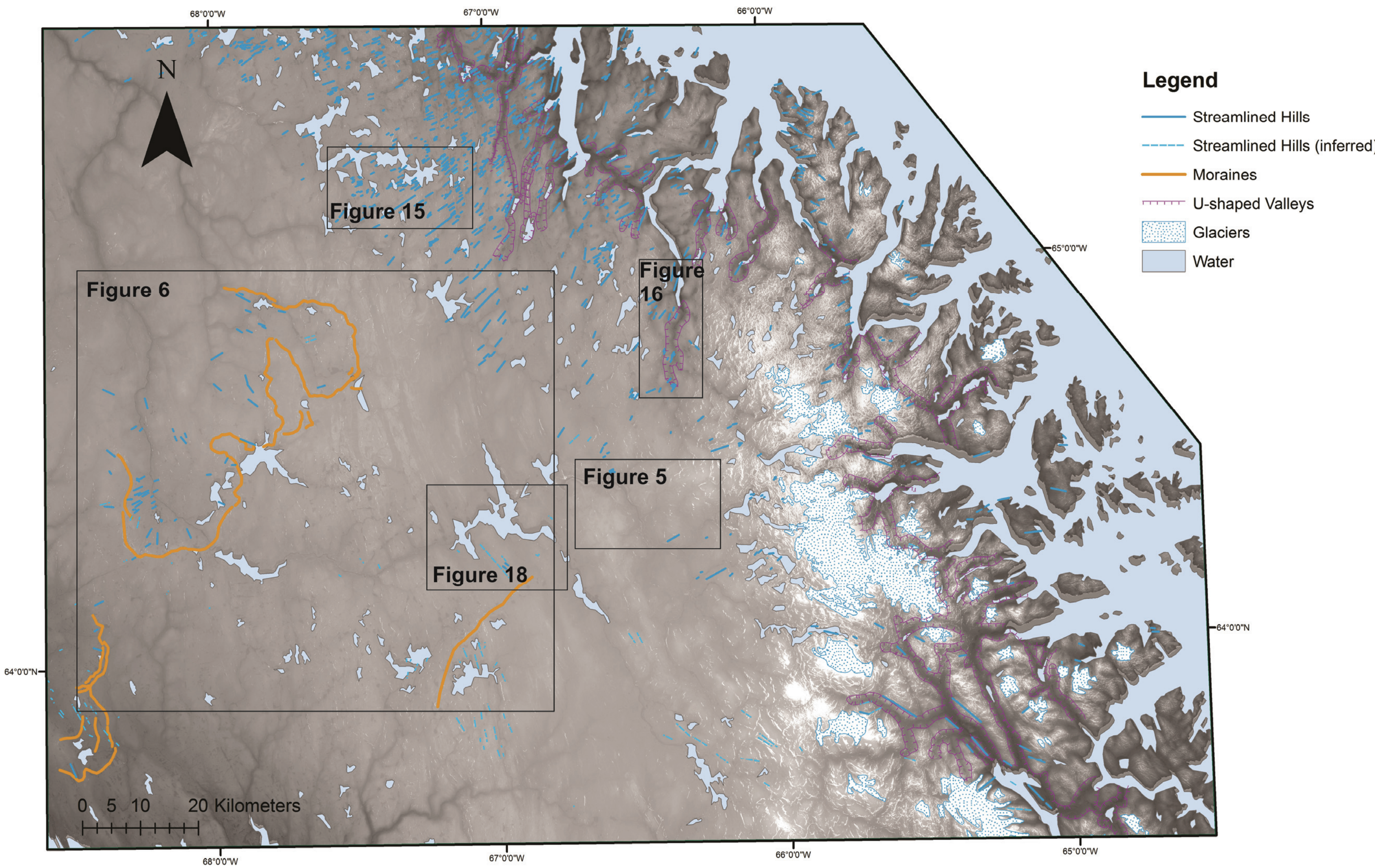


Figure 4: Remote sensing results with moraines, streamlined hills, and u-shaped valleys.

The degree of modification of these northwest/southeast ridges by the southeast-trending ice-flow phase is currently unknown. In the central area, there is rolling topography blanketed with thicker till but no obvious ice-flow indicators at the meso-scale (Figure 5).

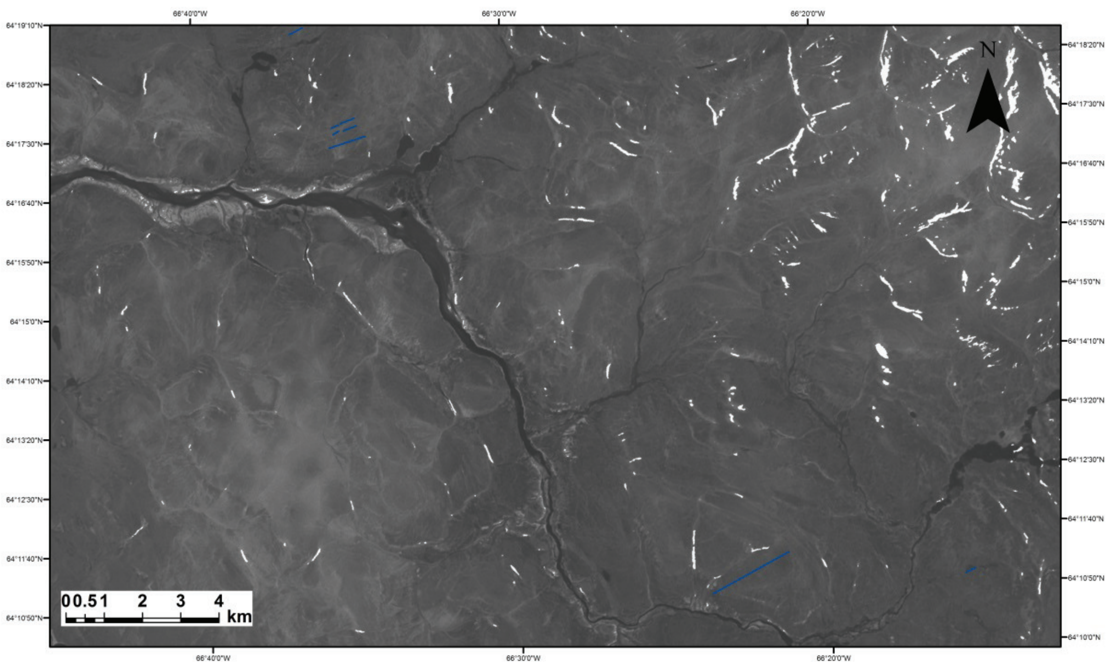


Figure 5: Rolling topography covered in till with few streamlined ridges and fewer lakes.

Other potential glacial streamlined hills were mapped as dashed lines. These uncertain features are either outside the fieldwork area and were thus not ground checked or simply too unclear in origin to be mapped under streamlined hills of more certain glacial origin. The dashed lines can be grouped as follow: (1) Streamlined hills generally in a southern direction, found within the lobate Frobisher Bay Moraine perpendicular to each of the lobes; (2) Southeast-trending hills following the fjords in the southeast of the study area and (3) Southeast-trending hills in the centre of the study area. Group 1 and 3 are likely glacial as they are within the lobes of the end moraines. The third group agree with those previously mapped in the central region of the study area (Miller 1985), though it is shown with magnetic data that the bedrock features are striking southeast/northwest. Ice may have been thin enough for basal flow to be controlled by the southeast bedrock features during the ice advances that deposited the moraines.

Two major moraine systems and two local moraines were previously mapped within the study area (Miller 1980; Miller 1985). Components of the Frobisher Bay Moraine system (Figure 6a-b) were recognized as well as the local Hall Moraine with analysis of the LANDSAT images. The ridges of these moraines are prominent features on the studied images and show that ice flowed approximately from the northwest to the southeast. Parts of the Frobisher Bay Moraine that were not mapped on the LANDSAT include the dashed line segments The Chidliak Moraine that follows the coast and the local moraine showing west flowing ice across from Popham Bay reported by Miller (1985) were not recognized on the LANDSAT images.

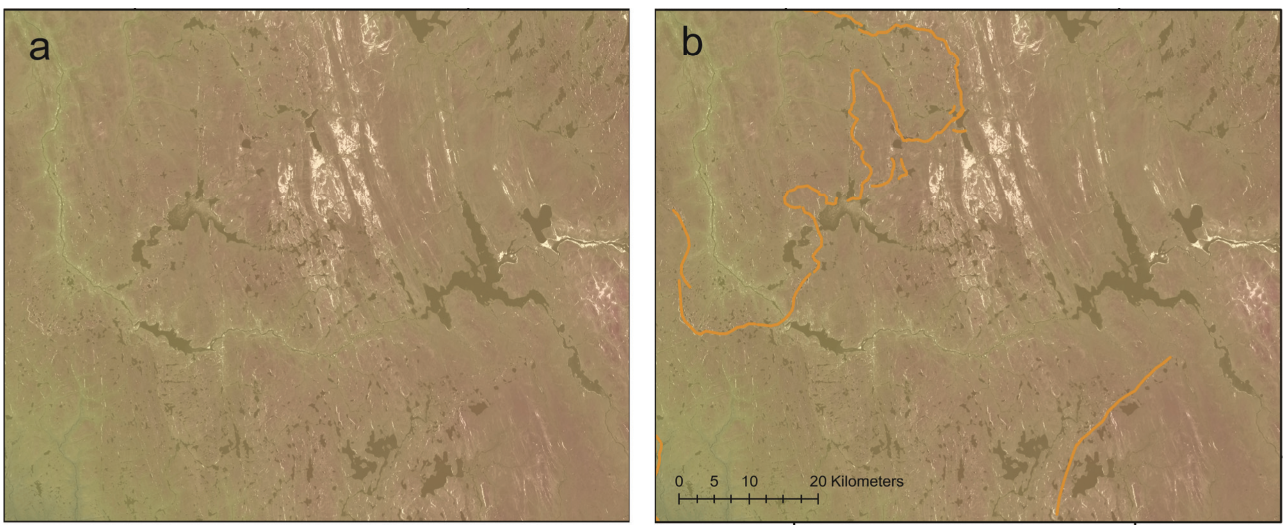


Figure 6: A major segment of the Frobisher Bay Moraine system and Hall Moraine (Blake 1966; Miller 1980). a) The ridge is mapped from the LANDSAT image enhanced with DEM; (b) the same image with the mapped outline of the Frobisher Bay Moraine (lobate feature in the northwest) and the Hall Moraine (the more linear feature in the southeast corner). The areas that appear as white tone are areas of regolith lacking evidence of glacial erosion.

With publically available DEM, U-shaped valleys were mapped throughout the study area (Figure 7). It is interpreted that many of the valleys extend far inland beyond modern fjords and these troughs contributed to funnelling ice and further eroding the troughs through positive feedbacks.

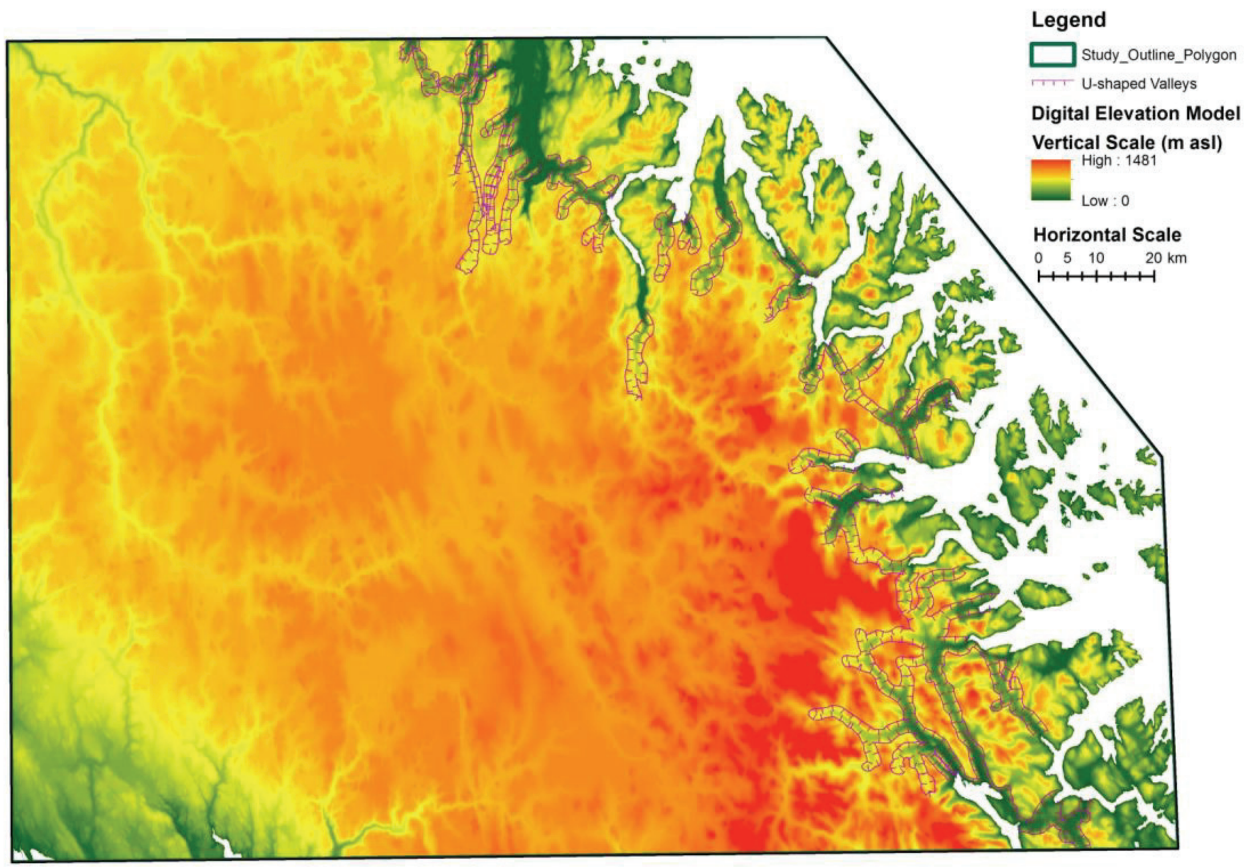


Figure 7: U-shaped valleys in purple mapped on a DEM base. The U-shaped valleys start far inland and eventually lead towards the fjords. Cool colours correspond to low elevations (dark green is sea level) and hot colours correspond to high elevation (1095 m asl).

8.2 Fieldwork Results

Fieldwork focused on meso- and micro-scale ice-flow indicators. Observations were made at 413 stations (Figure 8), with a totalling 456 paleo-flow indicators during the summers of 2010 and 2011 from base camps operated by Peregrine Diamonds Limited (Appendix A; Appendix B).

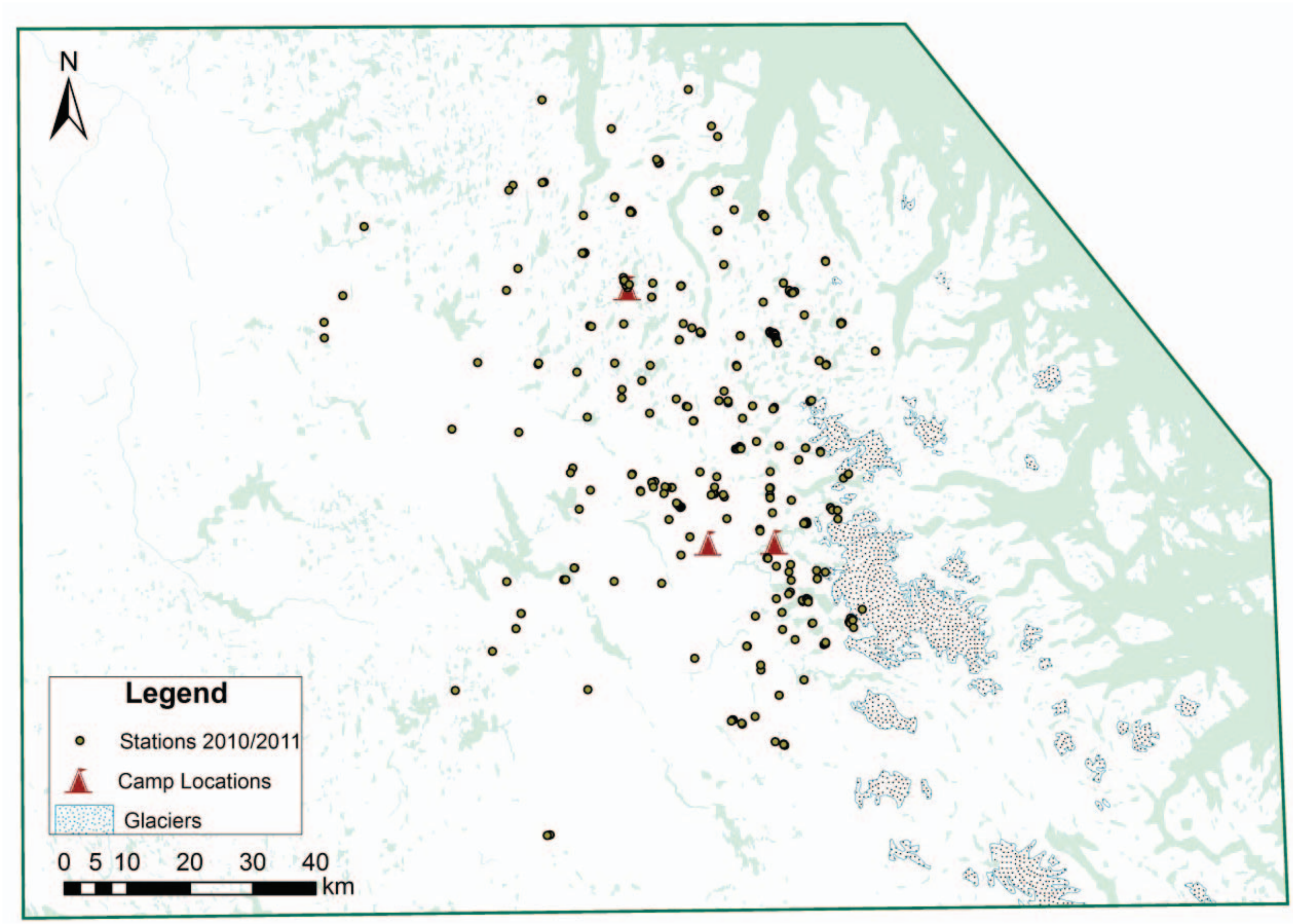


Figure 8: Shown are key locations for 2010 and 2011 fieldwork. Black circles show station locations for 2010 and 2011, red triangles show Peregrine Diamond's three base camps, and the yellow polygon denotes Ptarmigan Fjord.

Of the 456 paleo-flow indicators measured, 400 are striations, 48 are chatter marks, and 15 are *roches moutonnées*. A map showing 113 of the 456 features was made to highlight the main azimuths found (Figure 9).

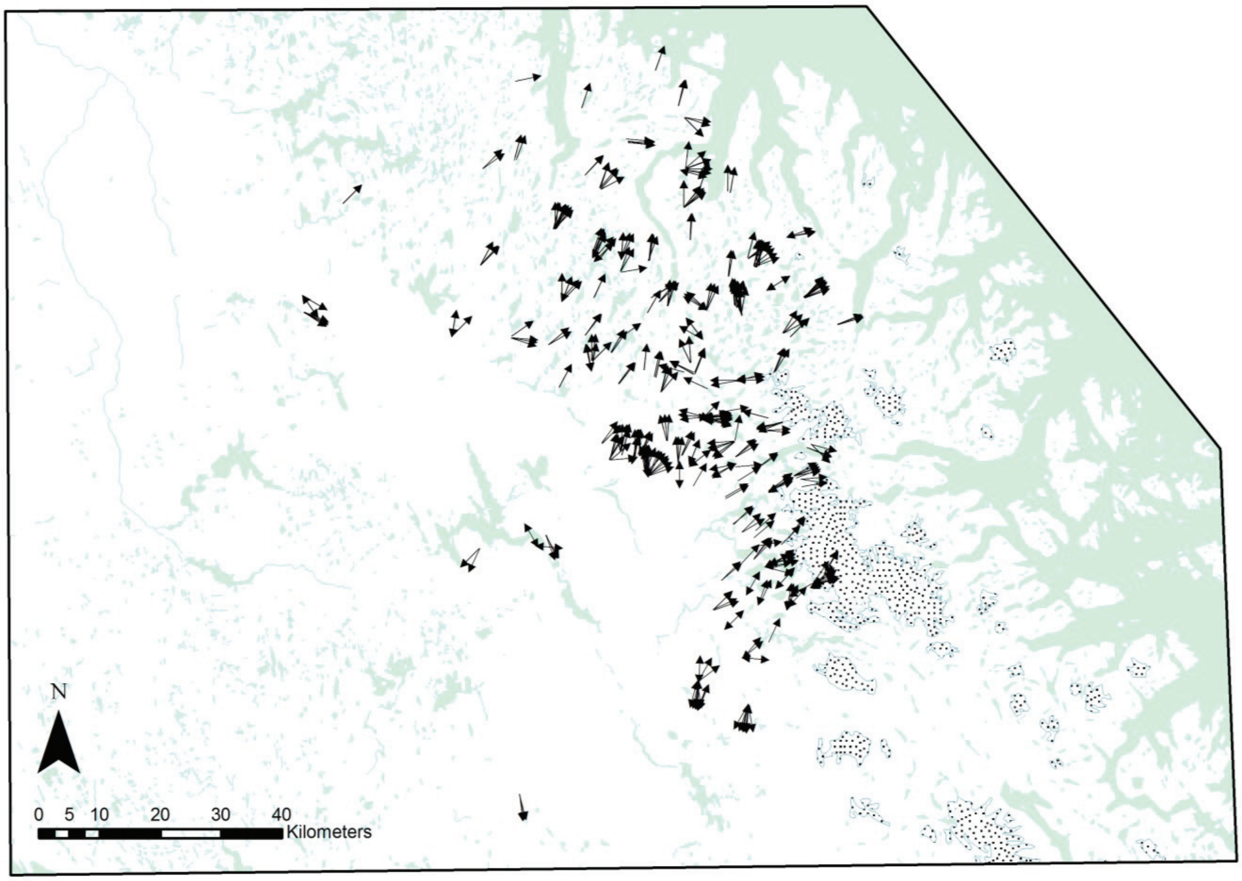


Figure 9: The results of the paleo-flow features measured in the field. The local ice cap is shown in stippled blue.

Streamlined bedrock forms were numerous throughout the field study area. Field observations of these landforms were useful to verify the preliminary geomorphological map based on remote sensing. However, measurement of the general orientation of these landforms in the field was done only if there were no smaller scale features found or if there was an evident age relationship with the striation record preserved on them. Out of the 456 paleo-flow indicators, it was possible to get the sense of direction of 375. There are 14 sites where a clear relative age relationship could be established.

Striations make up the bulk of the paleo-flow indicator data (Figure 10). Grooves, a slightly larger erosional feature, were grouped into the data as striations. Grooves found throughout the study area were grouped together with striations as a paleo-flow feature. Striations and grooves are bidirectional, and directional indicators were sometimes needed to confirm ice-flow direction when an obvious stoss-lee relationship was not present. Directional indicators included chatter marks and crescentic gouges (Figure 11), which were grouped together under chatter marks. Striations are sometimes found parallel to foliation; special care was thus given to ensure high confidence in the measurement.

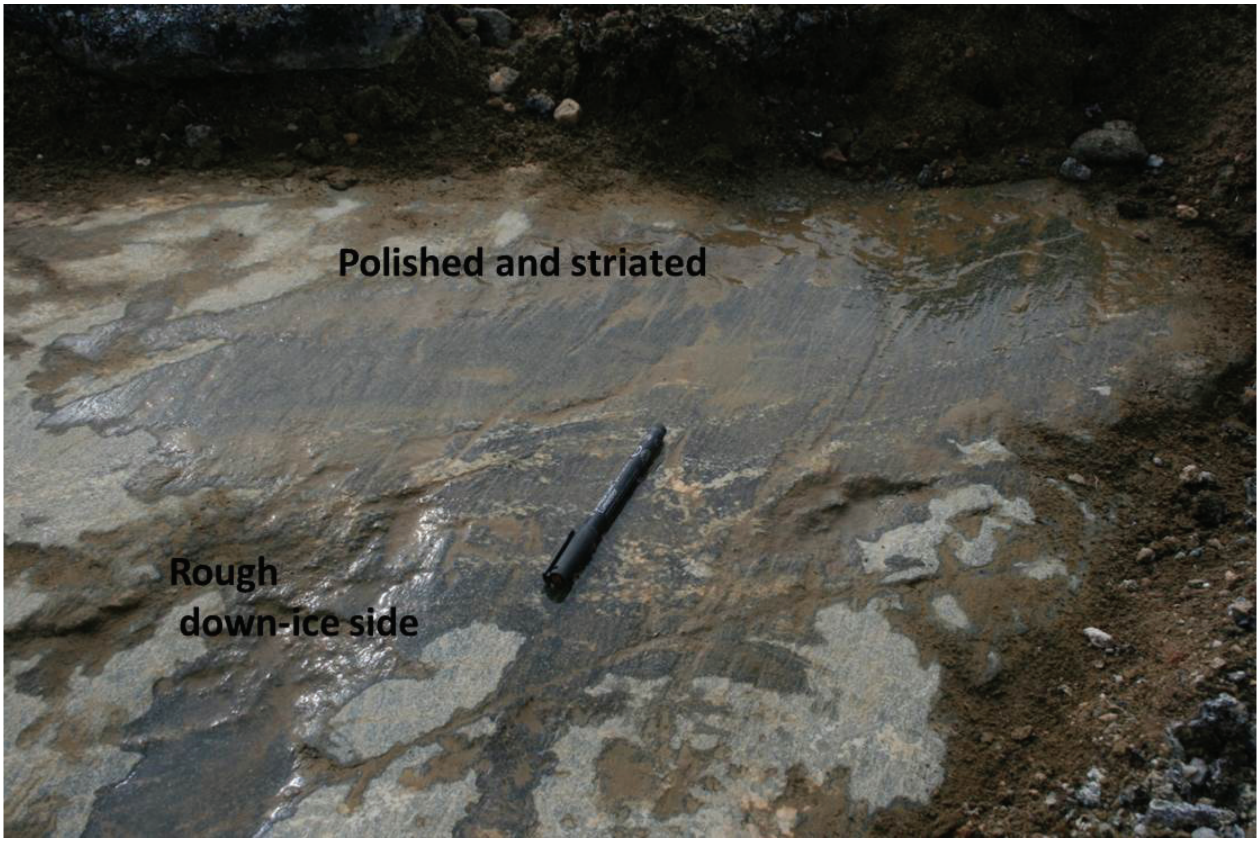


Figure 10: Striation measurements showing stoss-lee relationship indicating direction of flow.

Figure 11: An example of a well striated outcrop showing multiple crescentic gouges indicating the direction (as indicated by the compass). The direction for this station was approximately 183°**,** showing the southern flow. Note the rough (not polished) surface down-ice (upper left) relative to the abraded/polished surface (lower right).

The field observations agree with the landform-scale patterns based on remote sensing. However, more ice-flow directions were recognized in the field such as the flows with a western direction found in valleys that recorded movement from the Hall Ice Cap, and the northwest valley flows directed into Ptarmigan Fjord.

8.3 Relative age relationships

The relative chronology (Figure 12) of the flow-sets was established from field observations, some of which are supported by remote sensing data. Tops of ridges were primarily focused on to identify regional flowsets as opposed to local topographically controlled flowsets, though high priority areas with lower elevations were also studied. The ice-flow directions result from a series of glacial events that are thought to span from the LGM to deglaciation, and final retreat to the icecap.

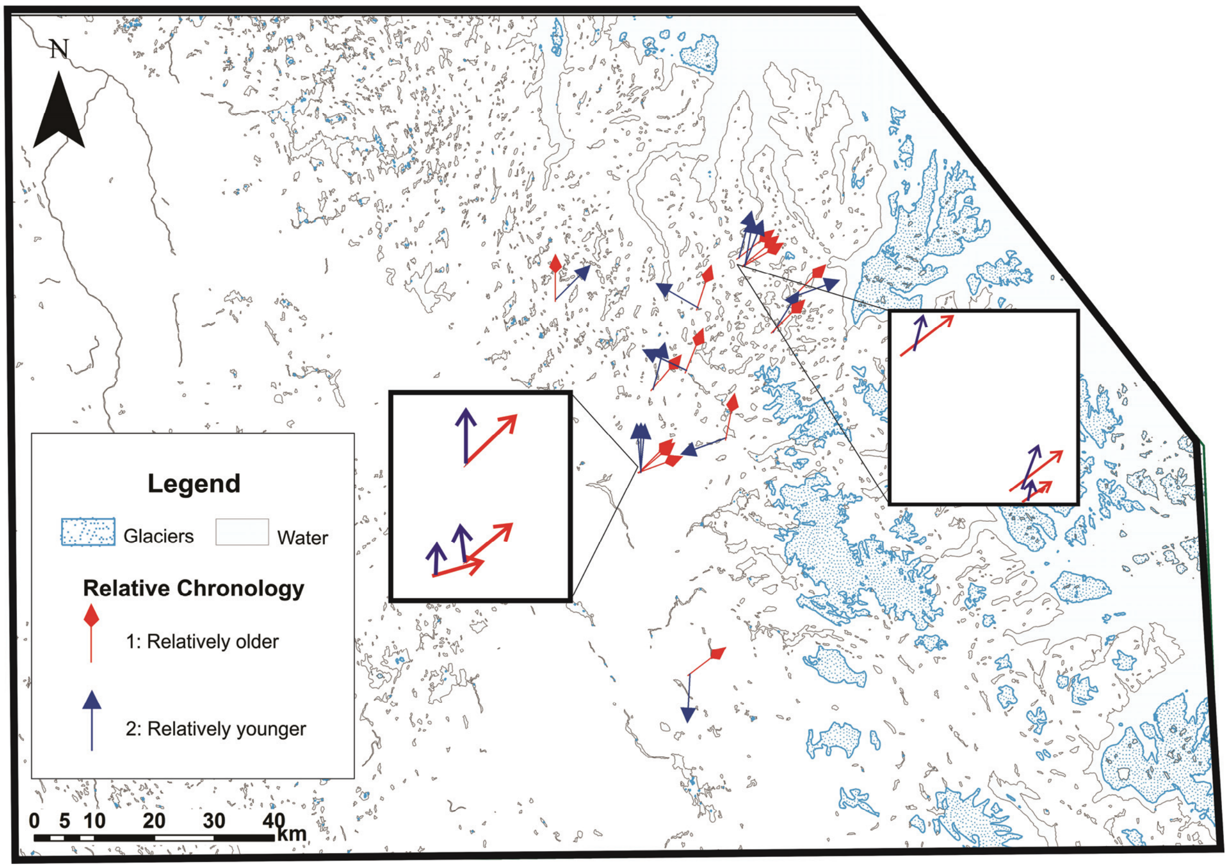


Figure 12: Relative chronology relationships documented in the field. A total of 14 relationships were found, with the majority of them documenting an earlier northeast flow overprinted by various other flows.

Through cross-cutting relationships observed in the field, it is possible to put these ice flow events in chronological order. Compared to other paleo-flow features, relatively few age relationships were found in the field. There were 14 sites where relative age relationships were determined, with each of these sites having either a single pair or multiple features showing chronology (Appendix C). The age relationships were studied by observing their relative positions on the outcrop scale, which vary in nature.

The oldest flow is shown by northeast features (Figure 13). The majority of the south paleo-flow features, found in the south portion of the study area, are likely to be concurrent and opposite of the northeast flow and separated by the Hall Ice Divide that existed in the area (Marsella et al. 2000). The northeast flows are shown to be relatively older than the north and northwest flows in 11 of the 14 locations studied in the field. The other three sites where a relative age relationship was observed showed different results. One location showed a relatively older northern flow and younger northeast flow, contrary to what was observed at the bulk majority of the field sites. Another site showed an older north flow, and a relatively younger southwest flow. There was also a single site where there was an older north flow and a relatively younger southwest flow. Many of the relationships studied consisted of younger striae superimposed on or proximal to older northeast features such as chatter marks (Figure 13).

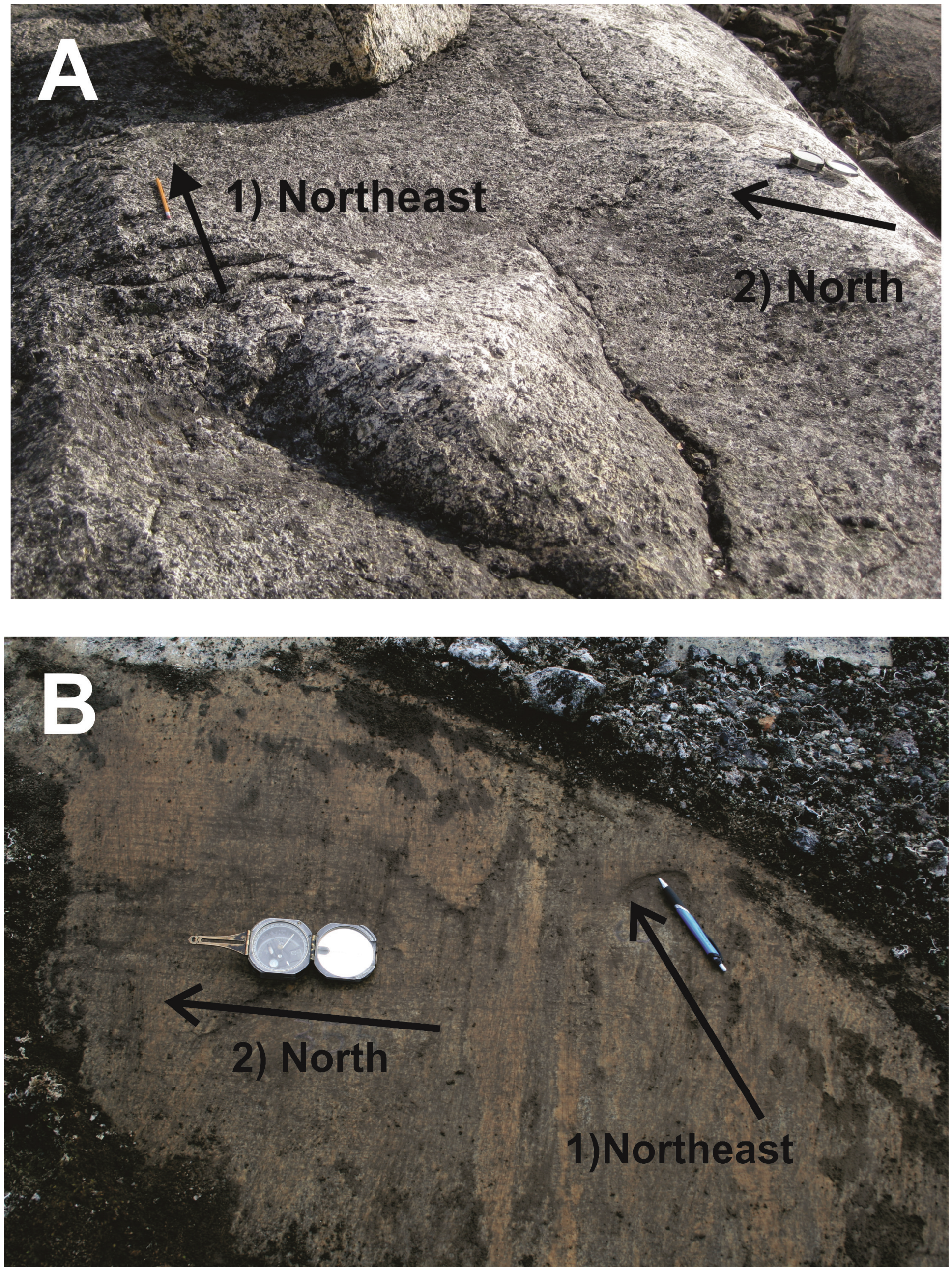


Figure 13 A and B: Two examples of the younger (2) striae on abraded surface on top of the outcrop and older crescentic gouges (1). A northward flow direction was determined for the young striations which are ubiquitous at the site on several adjacent outcrops. The rare crescentic gouges found on few rough surfaces are associated to an older northeast flow. These features have a better preservation potential then striations and polished surfaces. They indicate an ice-flow direction parallel to the shape of many individual outcrops suggesting they were primarily moulded by the older flow.

9. Interpretation of Ice-flow History

Seven main glacial landform and striation directions were identified and grouped into four phases (Figure 14).

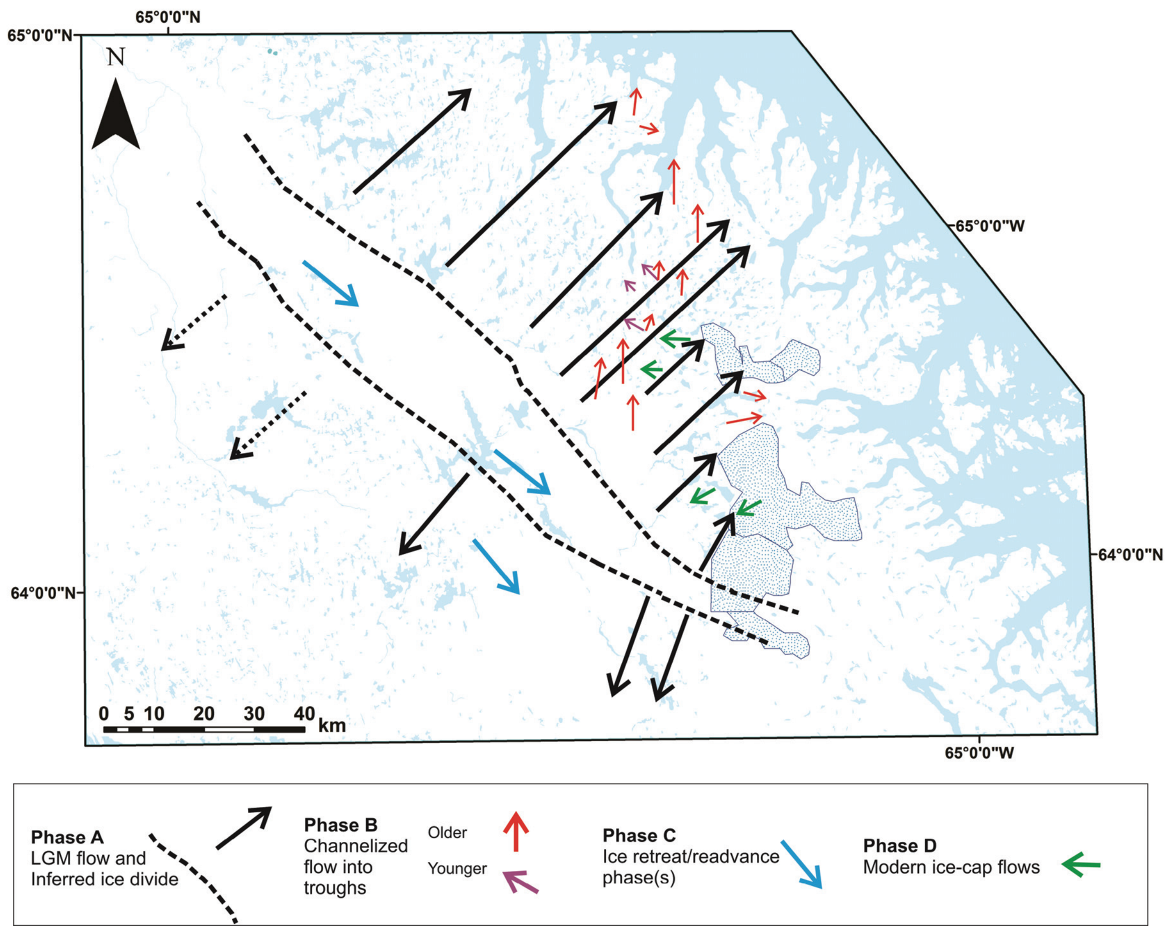


Figure 14: Shown is an ice-flow synthesis, in proposed phases A-D. Through field evidence, it is found that phase A is relatively older than phase B and phase D. Phase C, which the moraines are a part of, have been dated

With the relative age indicators in mind, these phases were chronologically ordered. The results of the field and remote sensing based mapping can be summarized and related as such:

a. Regional Flows (Phase A):

   I. Fjord interfluve areas proximal to the coast (between approximately 500 and 850 m asl): Northeast (varies from 20°-70°; average is 43.5°)

   II. Southern regions: South (directions between 180°-210°)

b. Fjord influenced areas (between 0 m and 650 m asl) (Phase B):
   I. North (approximately 342°-20°) for northern fjord heads,
      - Relatively older fjord influenced flow
   II. Northwest (approximately 300°) east side of Ptarmigan Fjord (Figure 2.13)
      - Relatively younger fjord influenced flow
      - perhaps northeast to the west side of the Ptarmigan Fjord
   III. And east to southeast (72°-112°; 135°) for eastern fjords.
c. Central region (Phase C): Southeast (135°-160°)
d. Hall Ice Cap (Phase D): West (240°-285°) in valleys

The earliest event is the northeast flow interpreted as a regional ice-flow phase (Phase A-I). There is a high degree of parallelism in the orientation of streamlined hills and field-based indicators associated to the northeast flow phase. This suggests that the landscape most likely developed at a time when the ice was relatively thick over that area with ice flow direction being mainly controlled by the ice surface slope. The northeast flows are found throughout the study area, often crosscut by younger flows. The extensive landscape with the strong northeast-trending ice-flow imprint is thus assigned to the LGM. Most of the northeast striations are correlated to this phase, as well as streamlined hills mapped using remote sensing techniques (**Figure 15**). The observations show that the northeast flow was widespread across northern Hall Peninsula. Even proximal to the icecap, northeast flows were found at higher elevations (Figure 15c). Twenty-four southward to south-south-westward ice-flow features are observed in the southern part of the study area (Phase A-II) (Figure 11). These indicators are interpreted to be coeval to the northeast features during the LGM reflecting ice-flow on the southern side of a local ice divide.

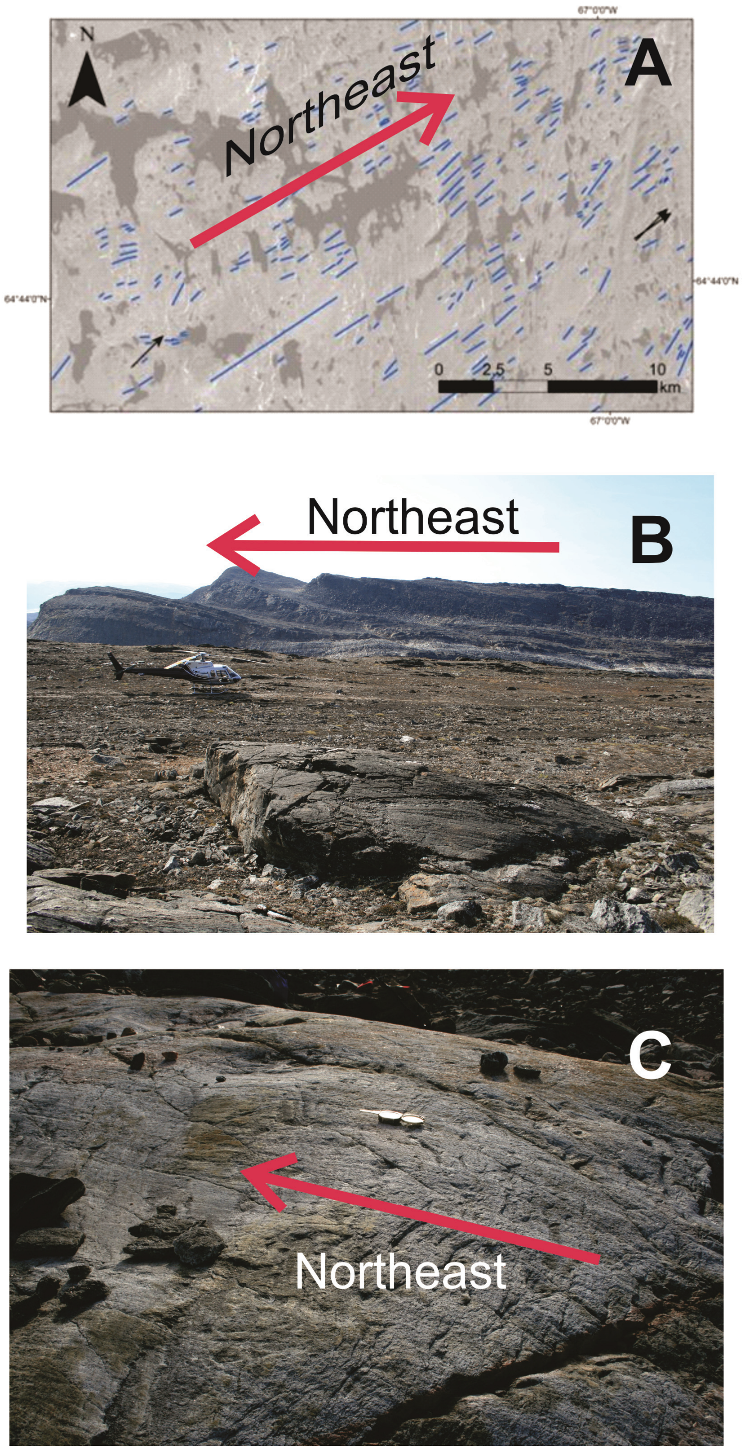


Figure 15: (A) Area proximal to the coast showing north-easterly directed streamlined hills (blue lines) and striae (black arrows) and (B) Roche moutonnée in the fjord interfluves showing a strong northeast flow near Ptarmigan Fjord and (C) chatter marks and striae showing a northeast flow proximal to the icecap.

During deglaciation, ice-flow became focused into topographical troughs (Phase B). Ice-flow directions associated to that phase are more complex and include multiple directions reflecting convergent ice-flow towards discrete troughs (now forming fjords) (Figure 16).

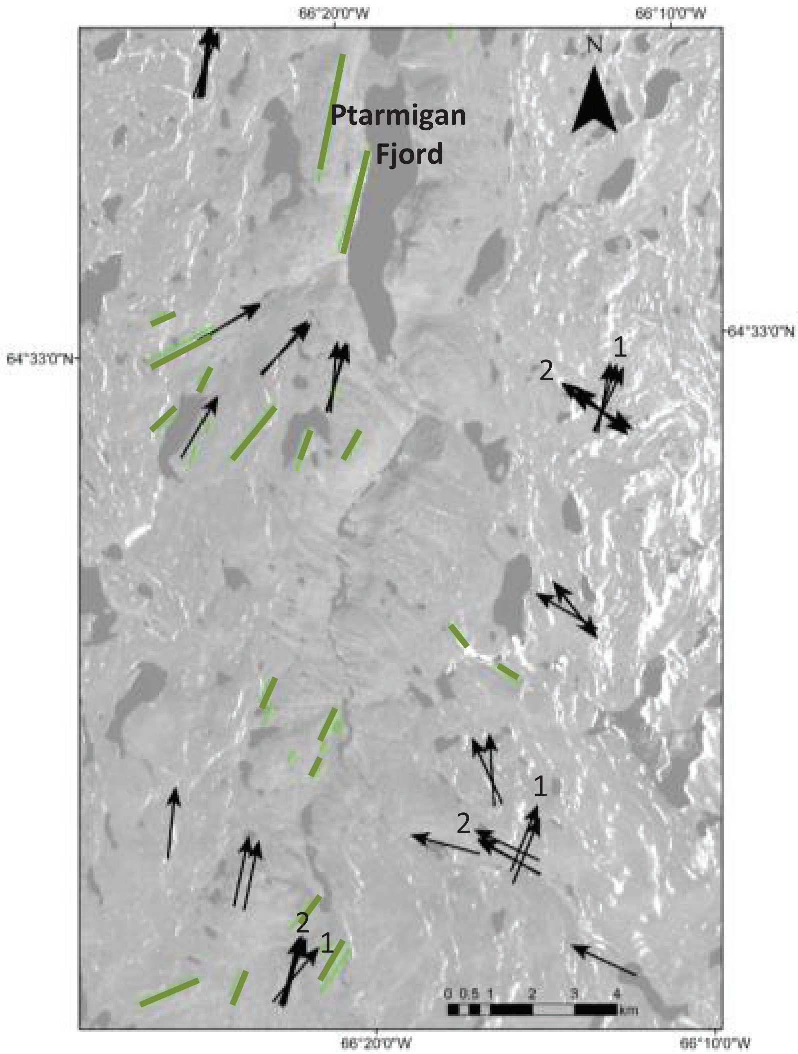
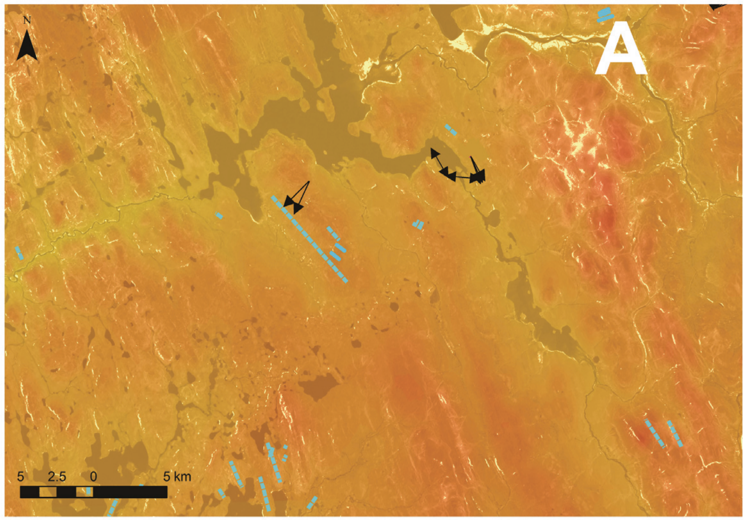


Figure 16: Channelized flow as demonstrated by striations (black arrows) and landforms (green lines) showing a span of directions going into the U-shaped valley created by ice draining into Chidliak Bay through Ptarmigan Fjord.

As deglaciation progressed, ice-flow is thought to have been increasingly topographically controlled. Three sets of striae fall under the earlier deglaciation phase (north, northwest, and east). Some of the northeast flows in the valleys close to the fjords may also be deglacial. The northwest flows probably came later as the ice, which is now represented by the local icecap, separated from the LIS. The north flows were found to be older than the northwest flows at two locations. North and east are the best representative directions of that Phase B. Influence of subglacial bed topography on ice flow dynamics increases as ice gets thinner. Erosional forms found in the field demonstrate the effect of the troughs on the ice, as shown by large *roches moutonnées* and drumlins showing north flow, meso-scale northern drumlins, and grooves directed north into the modern fjords (Figure 17 a-c).

Figure 17: Erosional forms demonstrating fjord's topographic effects: a) Large-scale *roches moutonnées*; b) Well-formed grooves; b) Meso-scale drumlins

Southeast striae and possible streamlined hills, amongst the youngest of the flow events, are found in the western portion of the study area (Figure 18 a-b). The southeast flows have been documented previously (Blake 1966; Miller 1980; Miller 1985). The mapped streamlined hills in the area are parallel to bedrock structures seen with geophysical (magnetic) data, and it is unclear whether glaciers have sculpted them. The deposition of Hall Moraine, the moraine mapped in the southeast of the study area occurred during this deglacial phase (Phase C). The portion of the lobate Frobisher Bay Moraine in the study area is the last local evidence of the Laurentide Ice Sheet.



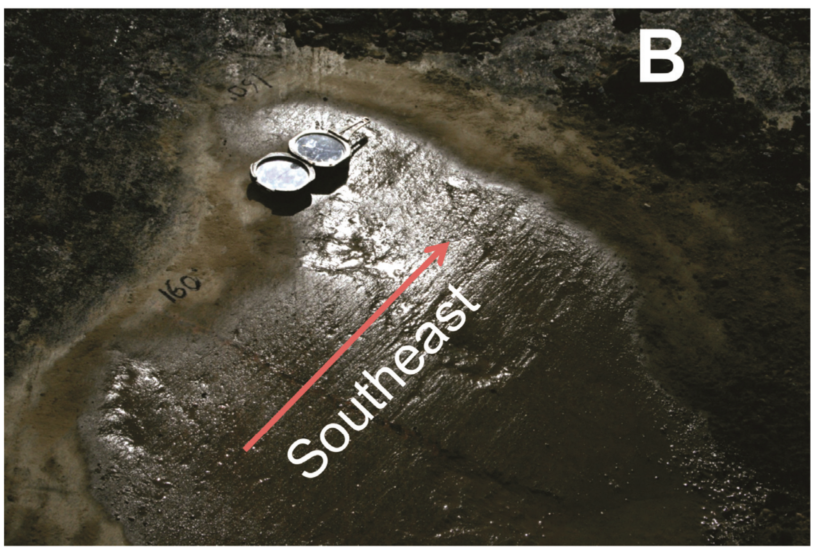


Figure 18: Southeast flowing a) streamlined hills and b) striations in the vicinity of the southeast trending bedrock ridges (marked as blue lines on the map). There is a clear southeast ice-flow phase (perpendicular to local moraines). However, the bedrock ridges in A appear to be parallel to prominent bedrock structures as visible on airborne geophysical data as well as in the field. The degree of glacial remoulding of these ridges is unknown, though the bedrock structures are most likely enhanced by glacial abrasion.

The youngest west flows were found in the valleys near the local ice cap, which record movement from the local ice cap (Figure 19) (Phase D). West trending paleo-flow features are found in the eastern side of the study area (proximal to the icecap).

Figure 19: Late western flows shown with a) striations and b) directional indicators revealing the rounded, up-ice surface and down-ice plucked surface (stoss and lee forms).

For the most part, the higher elevation ridges proximal to the ice cap show the inherited northeastern flow where in the valleys the older flow is overprinted by younger topographically controlled flows (Figure 20). There are large scale *roches moutonnées* and micro-scale striations found in valleys proximal to the ice cap (Phase D).

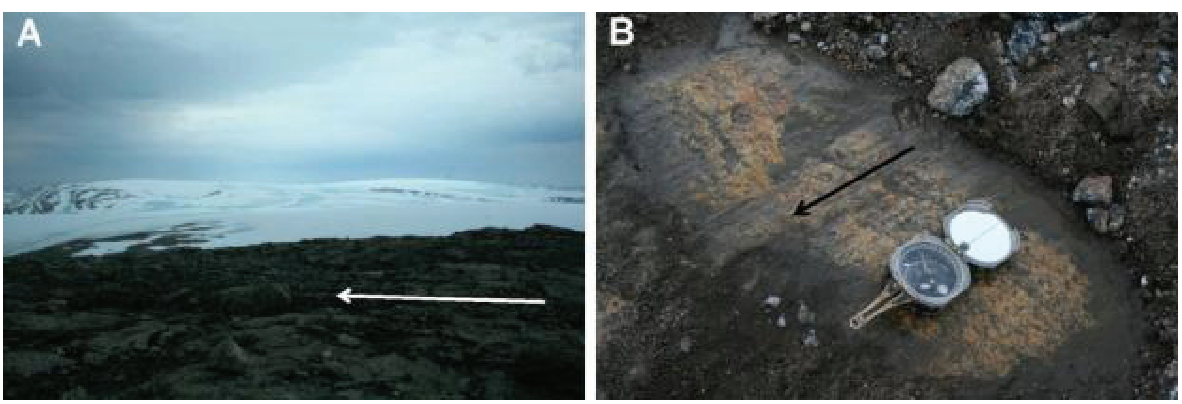


Figure 20: a) Northeastern flow (towards the center of the ice cap) associated to the LIS on top of ridges established by b) stoss-lee relationship showing a smooth abraded up-ice surface, and rough down-ice surface.

10. Conclusion

With the use of remote sensing and targeted field mapping, a subglacial geomorphological map of Hall Peninsula, Baffin Island, has been completed. Mapping consisted of large, kilometre scale subglacial landforms and sub-kilometre, meso-scale landforms as well as outcrop-scale glacial striae and other paleo-ice-flow indicators throughout the study area. A total of 1293 streamlined hills, one major moraine system, one local moraine, and a series of U-shaped valleys were mapped using remote sensing techniques. A total of 456 paleo-flow indicators were measured in the field (400 striations, 48 chatter marks, and 15 *roches moutonnées*). Such mapping is essential for mineral exploration purposes on Hall Peninsula, Baffin Island, and drift prospecting in northern Canada. It is evident that the glacial history could not have been reconciled from remote sensing alone. Field work was necessary to study discrete flows, as well as directional indicators.

The ice-flow system evolution greatly affects the glacial landscape and sediments, as is shown in southern Baffin Island, and the data reveals a complex glacial landscape mosaic reflecting varying subglacial conditions and ice-flow histories, including four ice-flow phases.

11. Acknowledgments

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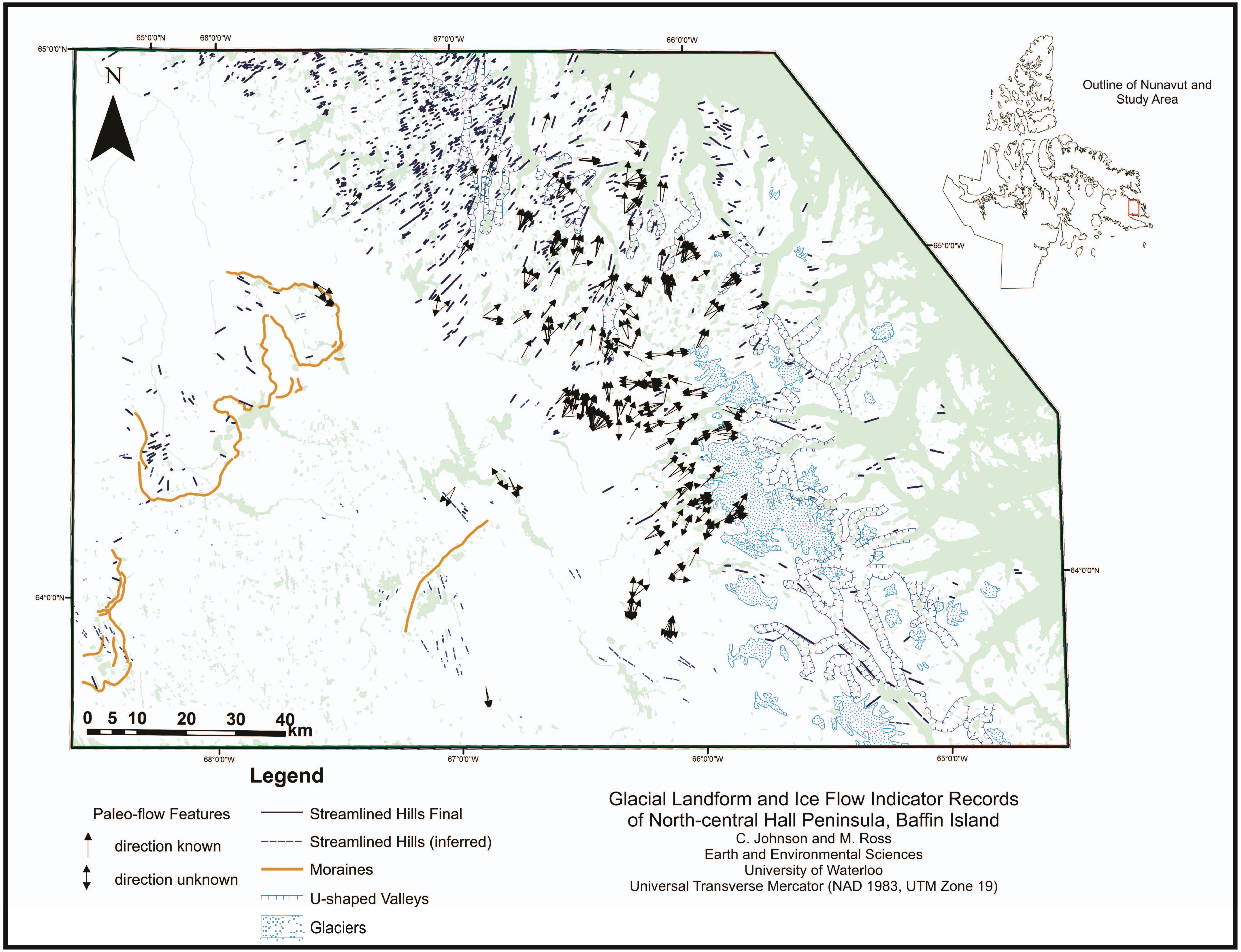
Appendix A: Glacial Landform and Ice Flow Indicator Map



Appendix B: Paleo Ice-flow Data

Station ID	Date	Easting	Northing	Paleoflow Features	Paleoflow Sense	Azimuth
10TIAC001	04/08/2010	619504	7154764	striations	known	55
10TIAC002	04/08/2010	609916	7161045	striations	known	42
10TIAC003	04/08/2010	625480	7148200	striations	known	12
10TIAC003	04/08/2010	625243	7148301	striations	known	12
10TIAC004	04/08/2010	633105	7141454	striations	unknown	45
10TIAC005	04/08/2010	633286	7141491	striations	unknown	80
10TIAC006	04/08/2010	633354	7141461	striations	unknown	72
10TIAC007	04/08/2010	633420	7141461	striations	unknown	90
10TIAC008	04/08/2010	633669	7141719	striations	unknown	81
10TIAC009	04/08/2010	633688	7141738	striations	unknown	105
10TIAC010	04/08/2010	633746	7141872	striations	unknown	80
10TIAC011	04/08/2010	633880	7141700	striations	unknown	80
10TIAC012	04/08/2010	633944	7141716	striations	unknown	85
10TIAC013	04/08/2010	633957	7141527	striations	unknown	105
10TIAC013	04/08/2010	633957	7141527	striations	unknown	91
10TIAC013	04/08/2010	633957	7141527	striations	unknown	86
10TIAC014	05/08/2010	626404.61	7145949.69	striations	known	22
10TIAC015	05/08/2010	626472.63	7145962.21	striations	known	14
10TIAC016	05/08/2010	626414.85	7145915.42	striations	known	14
10TIAC017	05/08/2010	626392.75	7145925.11	roches moutonnées	known	40
10TIAC018	05/08/2010	626391.07	7145921.24	striations	known	14
10TIAC019	05/08/2010	626391.72	7145923.17	striations	known	14
10TIAC020	05/08/2010	616671.61	7137485.54	striations	known	36
10TIAC021	05/08/2010	616597.1	7137361.91	chatter marks	known	45
10TIAC022	05/08/2010	617935.96	7134849.46	striations	known	30
10TIAC023	05/08/2010	617936.47	7134849.92	chatter marks	known	85
10TIAC024	05/08/2010	617952.63	7134774.48	striations	known	32

10TIAC025	05/08/2010	617983.68	7134709.53	chatter marks	known	20
10TIAC025	05/08/2010	617983.68	7134709.53	chatter marks	known	14
10TIAC025	05/08/2010	617983.68	7134709.53	chatter marks	known	50
10TIAC027	05/08/2010	636417.81	7142674.05	chatter marks | striations	known	80
10TIAC028	06/08/2010	643805.06	7117203.96	striations	known	105
10TIAC029	06/08/2010	643796.42	7117229.57	striations	unknown	80
10TIAC030	06/08/2010	643740.82	7117399.82	striations	unknown	62
10TIAC031	06/08/2010	643742.56	7117409.39	striations	unknown	62
10TIAC032	06/08/2010	644413.26	7117686.68	striations	unknown	65
10TIAC033	06/08/2010	644407.9	7117639.68	striations	unknown	75
10TIAC034	06/08/2010	644692.21	7117512.58	striations	known	55
10TIAC035	06/08/2010	644558.58	7117437.94	striations	known	65
10TIAC036	06/08/2010	644649.72	7117098.29	striations	known	74
10TIAC037	06/08/2010	651453.83	7114592.98	striations	known	240
10TIAC038	06/08/2010	651415.17	7114523.79	striations	known	35
10TIAC039	06/08/2010	651202.78	7113966.58	striations	unknown	62
10TIAC040	06/08/2010	651181.33	7113961.29	striations	unknown	55
10TIAC041	06/08/2010	651238.03	7113855.03	striations	unknown	68
10TIAC042	06/08/2010	651372.12	7113713.15	striations	unknown	65
10TIAC045	07/08/2010	607487.37	7122535.85	striations	known	160
10TIAC046	07/08/2010	607427.68	7122547.93	striations	known	155
10TIAC047	07/08/2010	607395.25	7122535.99	striations	known	150
10TIAC050	08/08/2010	641606.14	7121942.31	roches moutonnées	known	50
10TIAC051	08/08/2010	641953.17	7120608.33	chatter marks	known	80
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10TIAC053	08/08/2010	641807.67	7118698.21	striations	known	40
10TIAC054	08/08/2010	641561.17	7118382.52	sriations	known	45
10TIAC055	08/08/2010	641548.81	7118397.35	striations	known	35

10TIAC057	08/08/2010	640595.91	7112757.75	striations	unknown	30
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10TIAC060	08/08/2010	644013.18	7104743.51	striations	known	25
10TIAC061	08/08/2010	640757.97	7094428.64	striations	unknown	192
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10TIAC064	08/08/2010	640926.61	7094307.94	striations	unknown	190
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10TIAC068	08/08/2010	634150.89	7097736.43	chatter marks	known	202
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10TIAC070	08/08/2010	632733.16	7098356.14	striations	known	192
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10TIAC075	08/08/2010	634919.58	7110106.69	striations	known	45
10TIAC076	08/08/2010	634897.45	7110096.91	striations	known	65
10TIAC077	08/08/2010	634894.61	7110095	striations	known	47
10TIAC078	08/08/2010	638105.57	7124190.73	striations	known	52
10TIAC080	09/08/2010	629591.71	7134371.44	striations	unknown	180
10TIAC082	09/08/2010	638651.23	7135258.34	striations	known	47
10TIAC083	09/08/2010	638655.75	7135253.52	striations	known	60
10TIAC084	09/08/2010	638541.19	7135250.14	striations	known	52
10TIAC085	10/08/2010	640707.03	7167890.24	striation	known	52
10TIAC086	10/08/2010	640708.07	7167881.24	chatter marks	known	52
10TIAC087	10/08/2010	640708.78	7167927.92	chatter marks	known	15
10TIAC088	10/08/2010	640710.62	7167864.62	striations	known	55
10TIAC089	10/08/2010	640727.17	7167872.2	striations	known	62

10TIAC090	10/08/2010	640728.05	7167868.78	striations	known	52
10TIAC091	10/08/2010	641675.97	7166551.64	striations	known	60
10TIAC091	10/08/2010	641675.97	7166551.64	roches moutonnées	known	10
10TIAC092	10/08/2010	641683.86	7166549.1	chatter marks	known	70
10TIAC093	10/08/2010	641691.95	7166570.69	striations	known	15
				roches moutonnée		
10TIAC094	10/08/2010	641651	7166718.98	striations	known	50
10TIAC094	10/08/2010	641651	7166718.98	striations	known	22
10TIAC095	10/08/2010	638525.5	7160093.26	striations	known	0
10TIAC096	10/08/2010	638558.06	7160161.92	striations	known	355
				chatter marks		
10TIAC097	10/08/2010	638625.12	7159913.03	striations	known	355
10TIAC098	10/08/2010	638927.69	7159716.28	chatter marks	known	355
10TIAC099	10/08/2010	638916.86	7159704.29	striations	known	10
10TIAC100	10/08/2010	639023.9	7159790.19	striations	known	10
10TIAC101	10/08/2010	639152.84	7159889.82	striations	known	10
10TIAC102	10/08/2010	639205.52	7159925.71	striations	known	350
10TIAC103	10/08/2010	639416.8	7159732.3	striations	known	355
10TIAC104	10/08/2010	639417.42	7159629.67	striations	known	342
10TIAC105	10/08/2010	639429.94	7159228.76	striations	known	355
10TIAC106	10/08/2010	639433.03	7159187.62	striations	known	348
10TIAC107	10/08/2010	639484.6	7159144.24	striations	known	345
10TIAC108	10/08/2010	639539.33	7158862.53	striations	known	355
10TIAC109	10/08/2010	639563.63	7158801.95	striations	known	10
10TIAC110	10/08/2010	639674.69	7158531.65	striations	known	355
10TIAC111	10/08/2010	639796.3	7158336.49	striations	known	355
10TIAC112	10/08/2010	639265.09	7148119.05	striations	unknown	85
10TIAC113	10/08/2010	639235.32	7147960.59	striations	unknown	90
10TIAC114	10/08/2010	639085.59	7147824.89	striations	unknown	75

10TIAC115	10/08/2010	639078.62	7147819	striations	known	260
10TIAC116	10/08/2010	639081.89	7147826.73	chatter marks	known	270
10TIAC117	11/08/2010	644433.84	7129570.26	striations	unknown	58
10TIAC118	11/08/2010	644360.61	7129547.85	striations	unknown	58
10TIAC119	11/08/2010	644346.67	7129747.72	striations	unknown	62
10TIAC120	11/08/2010	644404.16	7129870.94	striations	known	52
10TIAC121	11/08/2010	644230.49	7129785.9	chatter marks	known	62
10TIAC122	11/08/2010	644230.47	7129765.49	striations	known	60
10TIAC123	11/08/2010	644220.85	7129734.68	chatter marks	known	60
10TIAC124	11/08/2010	644161.22	7129843.48	chatter marks	known	55
10TIAC125	11/08/2010	643977.29	7129634.23	striations	known	68
10TIAC126	11/08/2010	648207.7	7132183.56	striations	known	60
10TIAC127	11/08/2010	648239.15	7132148.58	chatter marks	known	80
10TIAC128	11/08/2010	648241.08	7132150.01	striations	known	70
				chhatter marks|		
10TIAC129	11/08/2010	648239.16	7132111.2	striations	known	70
10TIAC130	11/08/2010	648236.9	7132102.72	striations	known	65
10TIAC131	11/08/2010	648483.62	7131778.05	striations	known	70
10TIAC132	11/08/2010	649291.42	7131695.06	striations	known	85
10TIAC133	11/08/2010	649336.14	7131710.62	striations	known	100
10TIAC134	11/08/2010	641972.86	7133307.41	striations	known	56
10TIAC135	11/08/2010	641997.36	7133302.4	striations	known	52
10TIAC136	11/08/2010	650271.01	7136850.21	striations	known	112
10TIAC137	11/08/2010	650274.62	7136849.72	striations	known	110
10TIAC138	11/08/2010	650985.38	7137430.9	striations	known	105
10TIAC139	11/08/2010	651089.93	7137524.54	striations	known	135
10TIAC140	11/08/2010	643159	7139724.77	striations	known	87
10TIAC141	11/08/2010	643151.97	7139714.73	striations	known	95
10TIAC142	11/08/2010	644255.46	7141653.45	striations	known	285
10TIAC143	11/08/2010	644237.56	7141635.31	striations	known	285
10TIAC145	11/08/2010	638958.86	7131325.75	chatter marks	known	58

10TIAC147	12/08/2010	636951.61	7128693.66	striations	known	60
10TIAC148	12/08/2010	637016	7128411.11	striations	known	60
10TIAC149	12/08/2010	624308.17	7132152.15	striations	unknown	350
10TIAC150	12/08/2010	624302.81	7132168.33	striations	known	0
10TIAC150	12/08/2010	624302.81	7132168.33	striations	known	5
10TIAC151	12/08/2010	624302.75	7132166.43	chatter marks	known	70
10TIAC152	12/08/2010	624335.57	7132181.37	striations	known	355
10TIAC152	12/08/2010	624335.57	7132181.37	chatter marks	known	50
10TIAC153	12/08/2010	624418.72	7132231.36	chatter marks	known	355
10TIAC154	12/08/2010	624445.13	7132246.93	chatter marks	known	355
10TIAC155	12/08/2010	624451.04	7132243.26	chatter marks	known	44
10TIAC156	12/08/2010	624454.68	7132244.19	chatter marks	known	30
10TIAC156	12/08/2010	624454.68	7132244.19	chatter marks	known	25
10TIAC156	12/08/2010	624454.68	7132244.19	chatter marks	known	60
10TIAC157	12/08/2010	624336.93	7132292.74	chatter marks	known	45
10TIAC157	12/08/2010	624336.93	7132292.74	chatter marks	known	22
10TIAC157	12/08/2010	624336.93	7132292.74	striations	known	0
10TIAC158	12/08/2010	624159.62	7132340.57	striations	known	355
10TIAC159	12/08/2010	624034.33	7132545.12	striations	known	350
10TIAC160	12/08/2010	623840.15	7132715.22	striations	known	22
10TIAC160	12/08/2010	623840.15	7132715.22	striations	known	3
10TIAC161	12/08/2010	623858.95	7132741.63	striations	known	350
10TIAC161	12/08/2010	623858.95	7132741.63	striations	known	355
10TIAC161	12/08/2010	623858.95	7132741.63	striations	known	8
10TIAC162	12/08/2010	623865.16	7132739.98	striations	known	45
10TIAC163	12/08/2010	623721.24	7132853.54	striations	known	8
10TIAC164	12/08/2010	622910.48	7135335.85	striations	known	0
10TIAC165	12/08/2010	622889.04	7135355.07	striations	known	22
10TIAC166	12/08/2010	622881.11	7135325.98	striations	known	30
10TIAC167	12/08/2010	622946.53	7135361.28	chatter marks	known	2
10TIAC168	12/08/2010	622970.54	7135338.03	striations	known	22

10TIAC169	12/08/2010	622170.26	7135318.81	striations	known	5
10TIAC170	12/08/2010	622132.89	7135314.09	striations	known	0
10TIAC170	12/08/2010	622132.89	7135314.09	striations	known	0
10TIAC171	12/08/2010	622004.32	7135301.39	striations	known	13
10TIAC172	12/08/2010	621875.55	7135464.72	striations	known	10
10TIAC173	12/08/2010	620244.71	7136295.78	striations	known	12
10TIAC174	12/08/2010	619788.39	7136158.71	striations	known	12
10TIAC174	12/08/2010	619788.39	7136158.71	striations	known	4
10TIAC174	12/08/2010	619788.39	7136158.71	striations	known	350
10TIAC174	12/08/2010	619788.39	7136158.71	striations	known	14
10TIAC175	12/08/2010	619803.39	7136112.89	chatter marks	known	350
10TIAC176	12/08/2010	619991.36	7135422.87	striations	known	15
10TIAC177	13/08/2010	625562.89	7198686.57	striations	known	20
10TIAC178	13/08/2010	629262.42	7192837.54	striations	known	16
10TIAC178	13/08/2010	629262.42	7192837.54	striations	known	13
10TIAC179	13/08/2010	630237.98	7191181.35	roches moutonnées | striations	known	108
10TIAC179	13/08/2010	630237.98	7191181.35	roches moutonnées |striations	known	100
10TIAC179	13/08/2010	630237.98	7191181.35	striations	known	135
10TIAC180	13/08/2010	620915.87	7187275.51	striations	known	100
10TIAC181	13/08/2010	620991.38	7187030.56	striations	known	96
10TIAC182	13/08/2010	620865.33	7186946.85	striations	known	87
10TIAC183	13/08/2010	620761.54	7187098.86	striations	known	92
10TIAC184	13/08/2010	620532.05	7187560.97	striations	known	95
10TIAC185	13/08/2010	624360.89	7167369.06	striations	known	20
10TIAC186	13/08/2010	624392.8	7167408.42	striations	known	7
10TIAC186	13/08/2010	624392.8	7167408.42	striations	known	10
10TIAC187	13/08/2010	624453.8	7167409.8	striations	known	7

10TIAC188	13/08/2010	624472.76	7167450.97	striations	known	5
10TIAC189	13/08/2010	624420.89	7167430.09	striations	known	6
11TIAC002	21/07/2011	615647.46	7167564.93	striations	unknown	45
11TIAC003	21/07/2011	615588.4	7168077.63	striations	known	22
11TIAC003	21/07/2011	615588.4	7168077.63	striations	known	42
11TIAC004	21/07/2011	615389.44	7168594.66	striations	known	22
11TIAC005	21/07/2011	615287.57	7168714.04	striations	known	22
11TIAC006	22/07/2011	615231.21	7168744.61	striations | roches moutonnées	known	20
11TIAC007	22/07/2011	615345.87	7168198.7	striations	unknown	28
11TIAC008	22/07/2011	630150.93	7176212.53	striations	known	50
11TIAC009	22/07/2011	630173.46	7176273.37	chatter marks	known	38
11TIAC009	22/07/2011	630173.46	7176273.37	chatter marks	known	40
11TIAC009	22/07/2011	630173.46	7176273.37	chatter marks	known	55
11TIAC010	22/07/2011	630197.23	7176268.63	chatter marks	known	0
11TIAC011	22/07/2011	630251.19	7176257.94	striations	known	45
11TIAC013	22/07/2011	629881.48	7182411.84	striations	known	98
11TIAC013	22/07/2011	629881.48	7182411.84	striations	unknown	105
11TIAC014	22/07/2011	630271.35	7182499.15	striations	known	98
11TIAC015	22/07/2011	630369.5	7182645.28	striations	known	7
11TIAC016	22/07/2011	630362.29	7182672.3	striations	known	50
11TIAC016	22/07/2011	630362.29	7182672.3	striations	known	70
11TIAC017	22/07/2011	630402.49	7182648.38	striations	known	90
11TIAC018	22/07/2011	630448.38	7182669.14	striations	known	70
11TIAC019	22/07/2011	632885.77	7179524.88	striations	known	20
11TIAC020	22/07/2011	637425.96	7178816.82	chatter marks	known	0
11TIAC021	22/07/2011	637747.79	7178532.45	striations	known	10
11TIAC022	22/07/2011	641971.62	7166291.9	striations	known	20
11TIAC023	22/07/2011	642044.24	7166339.94	striations	known	21
11TIAC024	22/07/2011	642528.92	7166557.22	striations	known	0

11TIAC024	22/07/2011	642528.92	7166557.22	striations	known	5
11TIAC025	22/07/2011	642216.68	7166324.21	striations	known	0
11TIAC027	22/07/2011	644055.69	7162796.06	striations	unknown	58
11TIAC028	23/07/2011	609057.09	7172691.09	striations	known	28
11TIAC029	23/07/2011	609083.71	7172721.61	striations	known	35
11TIAC030	23/07/2011	609089.36	7172710.66	striations	known	5
11TIAC031	23/07/2011	609082.38	7172696.65	striations	known	22
11TIAC032	23/07/2011	609082.13	7172699.06	striations	known	22
11TIAC033	23/07/2011	609032.55	7172669.2	striations	known	0
11TIAC033	23/07/2011	609032.55	7172669.2	striations	known	22
11TIAC035	23/07/2011	608845.22	7172602.6	striations	known	23
11TIAC035	23/07/2011	608845.22	7172602.6	striations	known	25
11TIAC036	23/07/2011	608728.56	7172670.34	striations	known	30
11TIAC036	23/07/2011	608728.56	7172670.34	striations	known	45
11TIAC036	23/07/2011	608728.56	7172670.34	striations	known	45
11TIAC037	23/07/2011	608747.24	7172673.62	striations	known	14
11TIAC038	23/07/2011	608709.49	7172655.72	striations	known	32
11TIAC038	23/07/2011	608709.49	7172655.72	striations	known	37
11TIAC039	23/07/2011	608696.17	7172656.17	striations	known	30
11TIAC042	24/07/2011	647372.4	7171412.27	striations	unknown	70
11TIAC042	24/07/2011	647372.4	7171412.27	striations	known	78
11TIAC042	24/07/2011	647372.4	7171412.27	striations	known	80
11TIAC044	24/07/2011	649832.29	7161522.69	striations	known	55
11TIAC045	24/07/2011	649816.41	7161511.86	striations	known	58
11TIAC046	24/07/2011	649831.2	7161590.34	striations	known	52
11TIAC046	24/07/2011	649831.2	7161590.34	striations	known	60
11TIAC048	24/07/2011	649883.34	7161375.28	chatter marks	known	45
11TIAC048	24/07/2011	649883.34	7161375.28	chatter marks	known	70
11TIAC049	24/07/2011	644916.54	7149039.94	striations	known	22
11TIAC049	24/07/2011	644916.54	7149039.94	striations	known	25
11TIAC050	24/07/2011	645216.58	7149205.95	striations	known	32

11TIAC052	24/07/2011	647553.31	7154899.62	striations	known	45
11TIAC053	24/07/2011	647551.98	7154935.46	striations	known	45
11TIAC055	24/07/2011	655360.17	7157043.44	striations	known	68
11TIAC055	24/07/2011	655360.17	7157043.44	striations	known	72
11TIAC055	24/07/2011	655360.17	7157043.44	striations	known	74
11TIAC056	24/07/2011	637484.08	7164841.43	striations	known	6
11TIAC056	24/07/2011	637484.08	7164841.43	striations	known	10
11TIAC061	26/07/2011	650037.59	7161522.96	striations	known	42
11TIAC061	26/07/2011	650037.59	7161522.96	striations	known	54
11TIAC062	26/07/2011	650049.39	7161530.43	striations	known	42
11TIAC063	26/07/2011	650069.82	7161483.07	striations	known	55
11TIAC064	26/07/2011	650069.79	7161483.63	striations	known	65
11TIAC065	26/07/2011	649922.01	7161430.39	striations	known	45
				chatter marks |		
11TIAC065	26/07/2011	649922.01	7161430.39	striations	known	70
11TIAC065	26/07/2011	649922.01	7161430.39	chatter marks	known	70
11TIAC067	26/07/2011	646433.12	7155523.17	striations	known	32
11TIAC067	26/07/2011	646433.12	7155523.17	striations	known	45
11TIAC067	26/07/2011	646433.12	7155523.17	striations	known	45
11TIAC067	26/07/2011	646433.12	7155523.17	striations	known	62
11TIAC067	26/07/2011	646433.12	7155523.17	striations	known	62
11TIAC068	26/07/2011	633873.34	7159469.88	striations	known	25
11TIAC069	26/07/2011	633843.55	7159492	striations	known	18
11TIAC069	26/07/2011	633843.55	7159492	striations	unknown	120
11TIAC069	26/07/2011	633843.55	7159492	chatter marks	unknown	312
11TIAC070	27/07/2011	633846.96	7159476.34	striations	known	10
11TIAC070	27/07/2011	633846.96	7159476.34	striations	known	305
11TIAC071	27/07/2011	633218.33	7154783.01	striations	unknown	322
11TIAC071	27/07/2011	633218.33	7154783.01	striations	unknown	322
11TIAC072	27/07/2011	633306.76	7154585.11	striations	known	300
11TIAC074	27/07/2011	631941.44	7148804.5	striations	known	22

11TIAC074	27/07/2011	631941.44	7148804.5	striations	known	298
11TIAC074	27/07/2011	631941.44	7148804.5	striations	known	300
11TIAC075	27/07/2011	631896.62	7149105.65	striations	known	22
11TIAC075	27/07/2011	631896.62	7149105.65	striations	known	295
11TIAC076	27/07/2011	631272.6	7150683.84	striations	known	335
11TIAC076	27/07/2011	631272.6	7150683.84	striations	known	356
11TIAC077	27/07/2011	630454.2	7149172	striations	known	285
11TIAC079	28/07/2011	573959.37	7176847.44	striations	known	45
11TIAC079	28/07/2011	573959.37	7176847.44	roches moutonnées	known	45
11TIAC081	28/07/2011	567589.89	7161651.62	roches moutonnées	known	120
11TIAC081	28/07/2011	567589.89	7161651.62	striations	unknown	145
11TIAC082	28/07/2011	567666.51	7159135.11	striations	known	112
11TIAC082	28/07/2011	567666.51	7159135.11	striations	known	115
11TIAC082	28/07/2011	567666.51	7159135.11	striations	known	118
11TIAC082	28/07/2011	567666.51	7159135.11	striations	known	123
11TIAC084	28/07/2011	633808.00	7141838.09	striations	unknown	85
11TIAC084	28/07/2011	633808.00	7141838.09	striations	unknown	105
11TIAC084	28/07/2011	633808.00	7141838.09	striations	unknown	264
11TIAC084	28/07/2011	633808.00	7141838.09	striations	known	275
11TIAC084	28/07/2011	633808.00	7141838.09	striations	known	285
11TIAC086	29/07/2011	627475.73	7159963.49	striations	known	5
11TIAC086	29/07/2011	627475.73	7159963.49	striations	known	15
11TIAC086	29/07/2011	627475.73	7159963.49	striations	known	18
11TIAC087	29/07/2011	646600.79	7141101.38	striations	known	248
11TIAC087	29/07/2011	646600.79	7141101.38	striations	known	255
11TIAC088	29/07/2011	646612.62	7140941.62	striations	known	255
11TIAC088	29/07/2011	646612.62	7140941.62	striations	known	260
11TIAC089	29/07/2011	649395.88	7130349.44	striations	known	80
11TIAC096	01/08/2011	632586.77	7098362.51	chatter marks	known	30

11TIAC096	01/08/2011	632586.77	7098362.51	roches moutonnées	known	53
11TIAC096	01/08/2011	632586.77	7098362.51	striations	unknown	183
11TIAC096	01/08/2011	632586.77	7098362.51	striations	unknown	183
11TIAC096	01/08/2011	632586.77	7098362.51	striations	known	184
11TIAC096	01/08/2011	632586.77	7098362.51	chatter marks	known	188
11TIAC097	01/08/2011	647146.89	7110366.85	striations	unknown	25
11TIAC099	01/08/2011	647182.47	7110354.59	striations	unknown	10
11TIAC100	01/08/2011	647187.11	7110351.09	striations	unknown	14
11TIAC103	01/08/2011	601664.57	7154951.66	roches moutonnées	known	95
11TIAC103	01/08/2011	601664.57	7154951.66	striations	known	100
11TIAC103	01/08/2011	601664.57	7154951.66	striations	known	108
11TIAC104	01/08/2011	601761.93	7155120.7	striations	known	55
11TIAC105	01/08/2011	592063.67	7155235.18	striations	unknown	10
11TIAC105	01/08/2011	592063.67	7155235.18	striations	known	45
11TIAC106	01/08/2011	607835.57	7153716.41	striations	known	50
11TIAC106	01/08/2011	607835.57	7153716.41	striations	known	60
11TIAC108	02/08/2011	603132.64	7080001.32	striations	known	165
11TIAC108	02/08/2011	603132.64	7080001.32	striations	known	170
11TIAC108	02/08/2011	603132.64	7080001.32	striations	known	173
11TIAC112	02/08/2011	596656.7	7120363.38	striations	known	25
11TIAC112	02/08/2011	596656.7	7120363.38	striations	known	45
11TIAC112	02/08/2011	596656.7	7120363.38	striations	known	225
11TIAC113	02/08/2011	606052.63	7120659.01	striations	unknown	95
11TIAC114	02/08/2011	621683.63	7134410.06	striations	unknown	12
11TIAC114	02/08/2011	621683.63	7134410.06	striations	known	15
11TIAC113	02/08/2011	606052.63	7120659.01	striations	unknown	330
11TIAC117	03/08/2011	631226.23	7170829.62	striations	known	2
11TIAC117	03/08/2011	631226.23	7170829.62	striations	known	4
11TIAC121	03/08/2011	646105.88	7120790.37	striations	known	45

11TIAC121	03/08/2011	646105.88	7120790.37	striations	known	45
11TIAC124	03/08/2011	638239.89	7124056.38	striations	known	45
11TIAC129	05/08/2011	637104.34	7107092.84	striations	unknown	45
11TIAC132	05/08/2011	645370.32	7113794.51	striations	known	42
11TIAC133	05/08/2011	645369.56	7113795.21	striations	unknown	43
11TIAC136	05/08/2011	647412.3	7110698.23	striations	unknown	42
11TIAC137	05/08/2011	651778.46	7114360.59	striations	unknown	45
11TIAC137	05/08/2011	651778.46	7114360.59	striations	unknown	50
11TIAC137	05/08/2011	651778.46	7114360.59	striations	unknown	55
11TIAC138	05/08/2011	651731.23	7114237.93	striations	unknown	70
11TIAC138	05/08/2011	651731.23	7114237.93	striations	unknown	75
11TIAC139	05/08/2011	653270.7	7115954.86	striations	known	30
11TIAC139	05/08/2011	653270.7	7115954.86	striations	known	30
11TIAC139	05/08/2011	653270.7	7115954.86	striations	known	32
11TIAC139	05/08/2011	653270.7	7115954.86	striations	known	32
11TIAC140	05/08/2011	647406.86	7121877.15	striations	known	35
11TIAC140	05/08/2011	647406.86	7121877.15	striations	known	35
11TIAC140	05/08/2011	647406.86	7121877.15	striations	known	40
11TIAC141	08/08/2011	639575.79	7117654.61	striations	known	43
11TIAC142	08/08/2011	636261.68	7114876.05	striations	known	45
11TIAC142	08/08/2011	636261.68	7114876.05	striations	known	50
11TIAC144	08/08/2011	640042.16	7102275.08	striations	unknown	50
11TIAC145	08/08/2011	640042.25	7102276.76	striations	known	40
11TIAC145	08/08/2011	640042.25	7102276.76	striations	unknown	95
11TIAC146	11/08/2011	619924.39	7167892.67	striations	unknown	4
11TIAC146	11/08/2011	619924.39	7167892.67	striations	known	20
11TIAC146	11/08/2011	619924.39	7167892.67	striations	known	26
				roches moutonnées |		
11TIAC147	11/08/2011	619762.8	7165659.03	striations	known	20
11TIAC147	11/08/2011	619762.8	7165659.03	striations	known	30

11TIAC148	11/08/2011	619728.95	7165636.31	striations	known	80
11TIAC149	11/08/2011	615291.42	7161381.33	striations	known	25
11TIAC149	11/08/2011	615291.42	7161381.33	striations	known	25
11TIAC151	11/08/2011	613852.63	7155147.78	striations	known	35
11TIAC151	11/08/2011	613852.63	7155147.78	striations	known	38
11TIAC152	11/08/2011	614995.35	7149604.35	striations	known	10
11TIAC152	11/08/2011	614995.35	7149604.35	striations	unknown	348
11TIAC152	11/08/2011	614995.35	7149604.35	striations	unknown	350
11TIAC153	11/08/2011	609517.2	7146553.81	striations	known	28
11TIAC154	11/08/2011	619443.75	7147182.28	striations	known	36
11TIAC154	11/08/2011	619443.75	7147182.28	striations	known	38
11TIAC155	12/08/2011	626127.81	7160728.73	striations	known	40
11TIAC155	12/08/2011	626127.81	7160728.73	striations	known	45
11TIAC156	12/08/2011	624753.62	7161412.57	striations	known	58
11TIAC156	12/08/2011	624753.62	7161412.57	striations	known	60
11TIAC157	12/08/2011	624167.08	7158825.02	striations	known	30
11TIAC158	12/08/2011	618191.1	7152345.21	striations	known	30
11TIAC158	12/08/2011	618191.1	7152345.21	striations	known	35
11TIAC159	12/08/2011	615026.04	7150972.95	striations	known	0
11TIAC159	12/08/2011	615026.04	7150972.95	striations	known	7
11TIAC159	12/08/2011	615026.04	7150972.95	striations	known	45
11TIAC159	12/08/2011	615026.04	7150972.95	striations	known	45
11TIAC160	12/08/2011	623644.18	7149430.5	striations	known	6
11TIAC161	12/08/2011	634189.37	7146378.13	striations	known	295
11TIAC162	12/08/2011	638597.59	7137845.59	striations	known	230
11TIAC162	12/08/2011	638597.59	7137845.59	striations	known	235
11TIAC162	12/08/2011	638597.59	7137845.59	striations	known	250
11TIAC162	12/08/2011	638597.59	7137845.59	striations	known	255
11TIAC162	12/08/2011	638597.59	7137845.59	striations	known	265
11TIAC162	12/08/2011	638597.59	7137845.59	striations	known	11
11TIAC163	12/08/2011	638551.66	7134100.65	striations	unknown	238

11TIAC163	12/08/2011	638551.66	7134100.65	striations	unknown	243
11TIAC163	12/08/2011	638551.66	7134100.65	striations	unknown	258
11TIAC164	13/08/2011	627454.85	7137799.44	striations	known	4
11TIAC164	13/08/2011	627454.85	7137799.44	striations	known	345
11TIAC164	13/08/2011	627454.85	7137799.44	chatter marks	known	345
11TIAC164	13/08/2011	627454.85	7137799.44	striations	known	354
11TIAC165	13/08/2011	629222.75	7134170.37	striations	known	0
11TIAC165	13/08/2011	629222.75	7134170.37	striations	known	9
11TIAC165	13/08/2011	629222.75	7134170.37	striations	known	355
11TIAC166	13/08/2011	638597.5	7133696.58	striations	known	85
11TIAC171	14/08/2011	640757.61	7094440.34	striations	known	170
11TIAC171	14/08/2011	640757.61	7094440.34	striations	known	185
11TIAC171	14/08/2011	640757.61	7094440.34	striations	known	190
11TIAC171	14/08/2011	640757.61	7094440.34	striations	known	200
11TIAC171	14/08/2011	640757.61	7094440.34	striations	known	200
11TIAC171	14/08/2011	640757.61	7094440.34	striations	known	210
11TIAC172	14/08/2011	632421.61	7098189.08	striations	unknown	170
11TIAC172	14/08/2011	632421.61	7098189.08	striations	unknown	195
11TIAC173	14/08/2011	639605.06	7122795.86	striations	known	45
11TIAC173	14/08/2011	639605.06	7122795.86	striations	known	59
11TIAC174	14/08/2011	641848.85	7123101.24	striations	known	49
11TIAC176	12/07/2011	616372.24	7179419.85	striations	known	18
11TIAC176	12/07/2011	616372.24	7179419.85	roches moutonnées	known	40
11TIAC176	12/07/2011	616372.24	7179419.85	striations	known	20
11TIAC176	12/07/2011	616372.24	7179419.85	striations	known	18
11TIAC177	15/07/2011	616370.56	7179147.99	roches moutonnées	known	62
11TIAC177	15/07/2011	616370.56	7179147.99	roches moutonnées	known	42
11TIAC178	18/07/2011	610157	7160977	striations	unknown	22

11TIAC178	18/07/2011	610157	7160977	chatter marks	known	0
11TIAC178	18/07/2011	610157	7160977	striations	known	45
11TIAC178	18/07/2011	610157	7160977	chatter marks	known	0
11TIAC179	18/07/2011	596624	7166694	striations	known	45
11TIAC179	18/07/2011	596624	7166694	striations	known	42
11TIAC179	18/07/2011	596624	7166694	striations	known	28
11TIAC180	18/07/2011	597047	7182653	striations	known	55
11TIAC180	18/07/2011	597047	7182653	striations	known	45
11TIAC181	18/07/2011	613832	7181504	striations	known	42
11TIAC181	18/07/2011	613832	7181504	striations	known	44
11TIAC182	20/07/2011	616192	7167667	striations	known	38
11TIAC183	20/07/2011	602289	7197015	striations	known	78
11TIAC184	20/07/2011	602653	7183960	striations	known	20
11TIAC185	20/07/2011	602309	7183847	striations	known	15
11TIAC186	20/07/2011	613305	7192444	striations	known	18
11TIAC187	20/07/2011	629753	7135407	striations	known	28
11TIAC188	20/07/2011	629753	7135407	striations	known	23
11TIAC189	20/07/2011	631322	7133864	striations	unknown	52
11TIAC190	20/07/2011	631132	7134232	striations	unknown	22
11TIAC191	20/07/2011	631700	7130372	striations	known	30

Appendix C: Relative Age Relationships

Station ID	Paleoflow Features	Paleoflow Sense	Azimuth	Relative Age	Nature of Relationship
10TIAC017	roches moutonnées	known	40	1	Superimposed Striae
	striations	known	14	2	
10TIAC085	striation	known	52	1	
	chatter marks	known	52	1	
	chatter marks	known	15	2	
10TIAC094	striations	known	15	2	Superimposed Striae
	roches moutonnées | striations	known	50	1	
	striations	known	1	2	
10TIAC150	striations	known	0	2	Superimposed Striae
	striations	known	5	2	
	chatter marks	known	70	1	
10TIAC152	striations	known	355	2	Protected surface | Superimposed striae
	chatter marks	known	50	1	
10TIAC157	chatter marks	known	45	1	Superimposed striae
	chatter marks	known	22	1	
	striations	known	0	2	
11TIAC065	striations	known	45	1	Unpolished chatter marks
	chatter marks | striations	known	70	2	
	chatter marks	known	70	2	
11TIAC067	striations	known	32	2	Positions on outcrop
	striations	known	45	1	
	striations	known	45	1	
11TIAC069	striations	known	18	1	Superimposed striae

	striations	unknown	120	2	
	chatter marks	unknown	312	2	
11TIAC074	striations	known	22	1	Superimposed striae
	striations	known	298	2	
	striations	known	300	2	
11TIAC075	striations	known	22	1	Superimposed striae
	striations	known	295	2	
11TIAC096	chatter marks	known	30	1	Superimposed striae
	roches moutonnées	known	53	1	
	striations	unknown	183	2	
	striations	unknown	183	2	
	striations	known	184	2	
	chatter marks	known	188	2	
11TIAC178	chatter marks	known	0	1	Superimposed striae
	striations	known	45	2	
	chatter marks	known	0	1	
11TIAC162	striations	known	230	2	Protected surface
	striations	known	235	2	
	striations	known	250	2	
	striations	known	255	2	
	striations	known	265	2	
	striations	known	11	1	