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The Glacial Geomorphology of the North-West sector of the Laurentide Ice Sheet

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Abstract

This paper presents a new map of the glacial geomorphology of $\sim$ 800,000 km^2 of north-west Canada. The mapped area includes parts of Northwest Territories and Nunavut which were covered by the Laurentide Ice Sheet during the Late Wisconsinan glaciation. It has been hypothesized that ice streaming occurred here during this time and the area has also been identified as a potential drainage pathway of glacial Lake Agassiz. Mapping was carried out remotely using a range of spaceborne imagery with varying spatial resolutions, including Landsat ETM+, ASTER and SRTM. Aerial photography was also used in areas where cloud obscured the Landsat imagery. The map records 94,780 individual landforms including moraines, eskers, large meltwater channels and lineations. Highly elongate bedforms with convergent flow traces and abrupt lateral margins are abundant throughout the mapped area and most likely represent former zones of streaming flow. Numerous eskers can be traced for tens of kilometres and are found both parallel and sub-parallel to abundant lineations. Moraine ridges are also identified which mark Late Wisconsinan ice margin positions and a series of smaller ridges are also identified within areas of hummocky topography. The map is intended to form the basis of a regional ice sheet reconstruction from the Last Glacial Maximum through to deglaciation, which we suggest is likely to involve marked changes in the spatial and temporal activity of ice streams.

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1. Introduction

The Laurentide Ice Sheet (LIS) covered much of Canada and extended south to 36°N in the Southern Great Lakes Region (Mickelson and Colgan, 2003). At its maximum extent, it was connected to the Cordilleran Ice Sheet across the Rocky Mountains to the west and to the Innuitian Ice Sheet in the Canadian High Arctic (Fulton, 1989). Its geometry was complex and featured a number of dynamic sub-systems, including ice streams, which have the ability to rapidly drain large volumes of ice and thus dominate ice sheet mass balance and their response to climate change (Stokes and Clark, 2001; Bennett, 2003; Pritchard et al., 2009). An understanding of ice stream activity which can be incorporated into ice sheet reconstructions and modelling is therefore vital (e.g. Stokes and Tarasov, 2010). Present day ice streams can be identified, and their short-term activity monitored, by measuring the surface velocity of ice sheets. However, in order to understand their long-term behaviour (including location, timing, geometry and mechanisms of flow), reconstructions of their activity in palaeo-ice sheets are necessary by examining the geomorphological and sedimentological record.

The activity and differing dynamics of both marine and land-terminating ice streams is well documented across the LIS (Patterson, 1997; Stokes and Clark, 2004; Jansson, 2005; De Angelis and Kleman, 2008; 2007; Evans et al., 2008; Ross et al., 2009; Stokes et al., 2009; O'Cofaigh et al., 2010). In the north-western sector of the LIS, Beget (1987) suggested a low profile ice surface and streaming flow, based on drift limits along the western Cordillera. Streaming has also been depicted in the north-west LIS by Kleman and Glasser (2007) and Winsborrow et al. (2004), although little detailed analysis is presented. Prest et al. (1968) provide a continental map at a scale of 1:5,000,000 that indicates a complex bedform arrangement in the north-west sector. However, the map does not identify areas of cross-cutting bedforms which are vital for the development of accurate palaeo-ice sheet reconstructions (cf. Kleman and Borgstrom, 1996). More recently, Shaw et al. (2010) have identified ice flowlines within this sector of the LIS, but a map which identifies individual bedforms, and therefore provides the basis for a definitive regional ice sheet reconstruction, is yet to be constructed.

2. Study Area

The mapped area spans the border between NWT and Nunavut, Canada (Figure 1). The region largely consists of low lying plains which are occupied by a series of major river systems and two large lakes; Great Bear Lake and Great Slave Lake. Away from the Yukon Mountains, summits attain a relatively subdued maximum altitude of $\sim$ 480-500 m. Physiographically, the study area spans four key areas: the Western Cordillera, Interior Plains, Precambrian Shield and Arctic Coastal Plain (Vincent, 1989). The largest of these geological areas is the metamorphosed Precambrian Canadian Shield which encircles Hudson Bay in the east and has minimal sediment cover. In contrast, to the west, the majority of the study area occupies the Interior Plains. This region is dominated by thick, soft-sediment marine and fluvial sequences, deposited by rivers and shallow inland seas (Vincent, 1989). The westernmost portion of the study area occupies the Canadian Cordillera; an area of mountainous terrain consisting of the deformed margin of the North American Craton (Vincent, 1989). In the north, the Arctic Coastal Plain is a lowland area of continuous permafrost which stretches along the coast of northern Canada from Meighen Island in the east to Alaska in the west (Murton, 1996; Côté and Burn, 2002).

The last continental glaciation of western NWT was during the Late Wisconsinan, when ice reached its maximum extent $\sim$ 21 cal. ka BP (Dyke et al., 2003). This was the only continental ice to reach as far west as the Rocky Mountains during the Quaternary (Duk-Rodkin and Lemmen, 2000). However, since the Late Pliocene, north-west Canada has been affected by several montane and continental glaciations (Dallimore and Matthews, 1997; Barendregt and Duk-Rodkin, 2004; England et al., 2009). The ice margin chronology from Dyke et al. (2003) indicates a relatively stable offshore ice margin until $\sim$ 16.2 cal. ka BP. Rapid eastward retreat of the ice margin then followed until the area became ice free around 11.5 cal. ka BP (Dyke et al., 2003).

3. Methods: Map Production

Satellite remote sensing is advantageous as it allows for rapid and systematic coverage of large areas at a variety of scales which could not be achieved using aerial photography or by ground survey. Satellite imagery can also be manipulated to enhance the visualisation of geomorphology and consequently, a greater number of landforms can be identified (Clark, 1997).

A combination of spaceborne and airborne imagery (Landsat ETM+, ASTER and SRTM) was use to map the glacial geomorphology. Freely available Landsat Enhanced Thematic Mapper (ETM+) images were obtained from the Global Landcover Facility (GLCF) (http://glcf.umiacs.umd.edu/index.shtml) and imported into Erdas Imagine 9.3 for manipulation. Landsat ETM+ scenes were downloaded to cover the study area, and then projected into Universal Transverse Mercator (UTM) zone 10 North (Figure 2). Band combinations were adjusted in order to optimise the visualisation of the geomorphology. In order to avoid bias in the mapping process, landforms were identified at a range of scales and using a variety of band combinations. False colour imagery with a band combination of 7, 5, 2 (R, G, B) was found to be the most beneficial for mapping.

Figure 1. The location of the mapped area NWT and Nunavut, Canada (highlighted by the red line). All locations noted in this paper are labelled on this figure. The black numbered boxes indicate the location of each of the Figures within the study area.

Landsat ETM+ bands 1-5 and 7 provide a spatial resolution of 30 m on false colour imagery while the panchromatic band 8 provided a higher spatial resolution of 15 m.

Aerial photography was used in areas where cloud obscured the Landsat ETM+ imagery. The photography was sourced from the National Air Photograph Library of Canada in Ottawa and from Google Earth. Photos were imported into Erdas Imagine 9.3 and orthorectified to the Landsat ETM+ imagery. Air photos were available at a variety of scales in black and white (hard copies) and colour (from Google Earth). The GTOPO30 Digital Elevation Model (30 arc second grid spacing), obtained from the USGS website, provides the background to the map.

Each landform type was digitised in a separate shapefile (some as lines and some as polygons) and upon completion of mapping, vector layers were then exported (.eps files) into Adobe Illustrator CS4 to compile the map. The map is intended for printing and visualisation at A0 size.

4. Identification and Classification of Glacial Geomorphology

A total of 94,780 landforms were mapped and seven landform types were identified: major moraine ridges, hummocky topography, ribbed moraine, eskers, lineations, large meltwater channels and lake strandlines. These landforms provide information about ice flow orientation, meltwater/lake drainage and ice margin geometry. They represent the fundamental building blocks of the glacial inversion method which uses the spatial arrangement of glacial bedforms to distinguish their formative conditions (Kleman and Borgstrom, 1996; Kleman et al., 2009). The map will subsequently inform a regional reconstruction of ice sheet flow patterns and as such, the map focuses on lineations, moraines and other large landforms.

4.1 Lineations

Streamlined lineations are abundant throughout the study area and range from oval-shaped hills (drumlins) to more elongate mega-scale lineations. Mean length/width ratios (elongation) of between 2:1 and 3:1 are suggested by Menzies (1979) to be characteristic of drumlin morphology. In contrast, mega-scale lineations are ridges and furrows which form in subglacial sediment, and can be longitudinally continuous for many tens of kilometres (Clark et al., 2003; King et al., 2009; Stokes et al., 2011). They occupy the

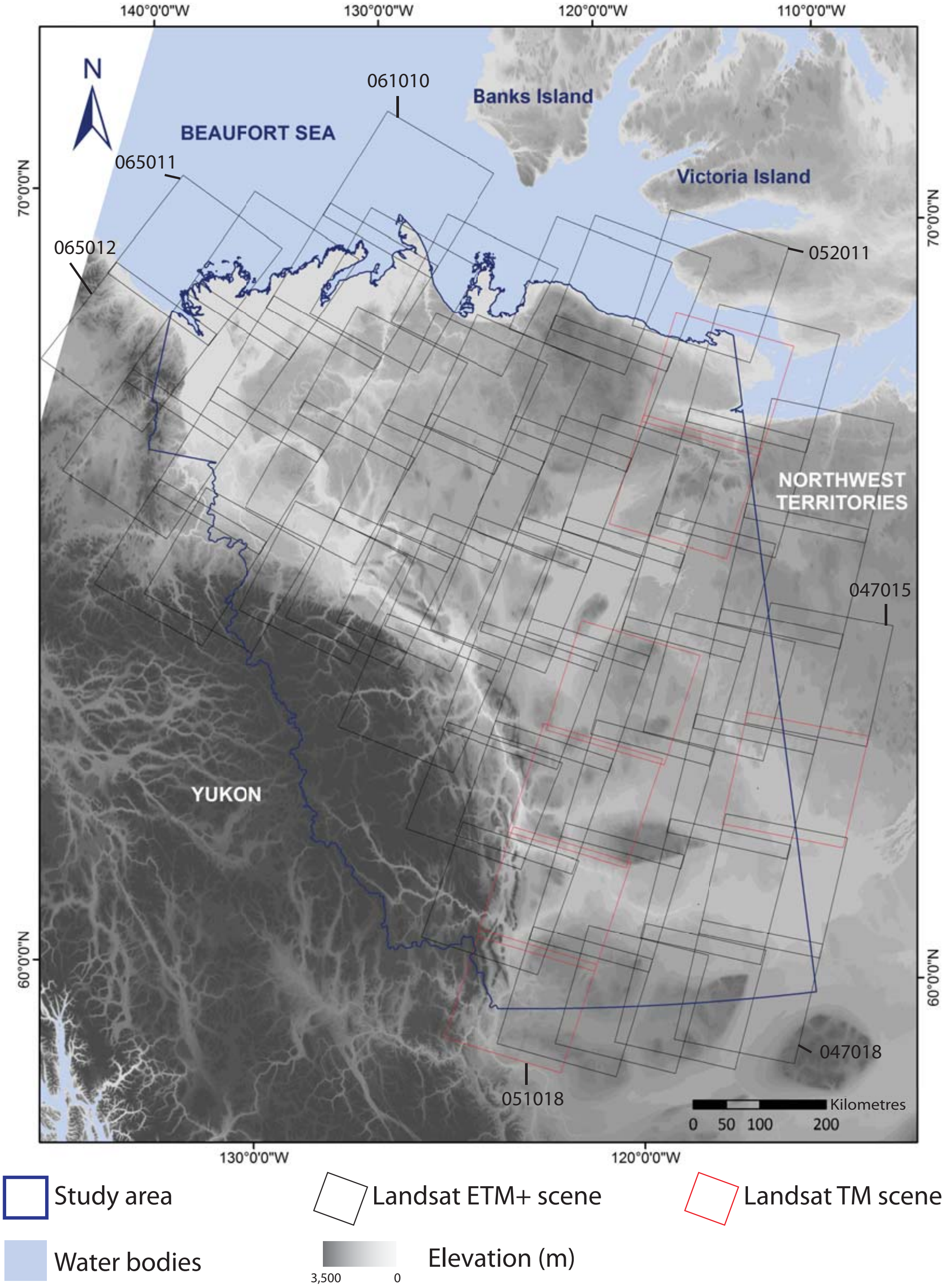


Figure 2. The location of the Landsat ETM+ and Landsat TM scenes (and selected path and row numbers) used to produce the geomorphological map.

opposite end of the lineation landform continuum to drumlins, being much greater in length and elongation (Clark, 1993). Where landforms exhibit moderate elongation it is often challenging to distinguish drumlins from mega-scale lineations and it is conceivable that they form a continuum (Figures 3, 4 and 5). Thus, all streamlined bedforms with long-axes aligned parallel to the direction of ice flow have therefore been grouped together as one class: lineations.

The lineations sometimes exceed 50 km in length, with some reaching ∼ 100 km. The spatial distribution of the 88,536 lineations is not uniform across the study area. Lineations are abundant along the Amundsen Gulf Coast and appear in smaller groups of varying orientations north of Great Bear Lake. The most elongate landforms are identified west of Great Bear Lake roughly following the current path of the Mackenzie River in a broad zone ∼ 100 km wide. Previous work on palaeo-ice sheets (e.g. Stokes and Clark, 2002; Hart, 1999) and observations from the beds of contemporary ice streams indicate that bedform elongation is related to ice velocity (King et al., 2009). Areas of highly attenuated landforms are therefore assumed to delimit areas of fast ice flow within the LIS (Clark, 1993; Hart, 1999; Stokes and Clark, 2002; King et al., 2009).

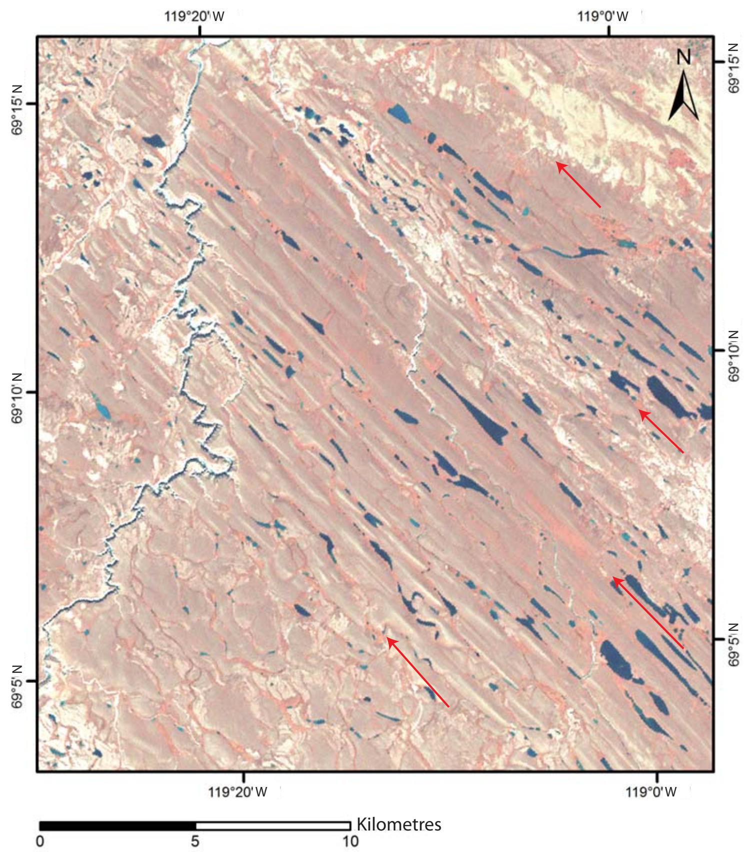
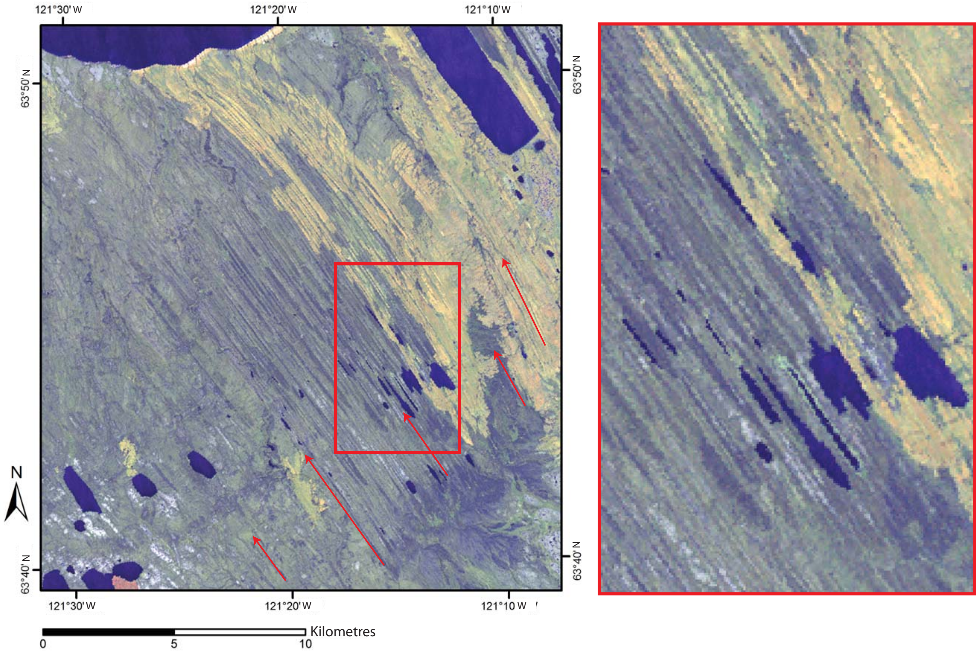
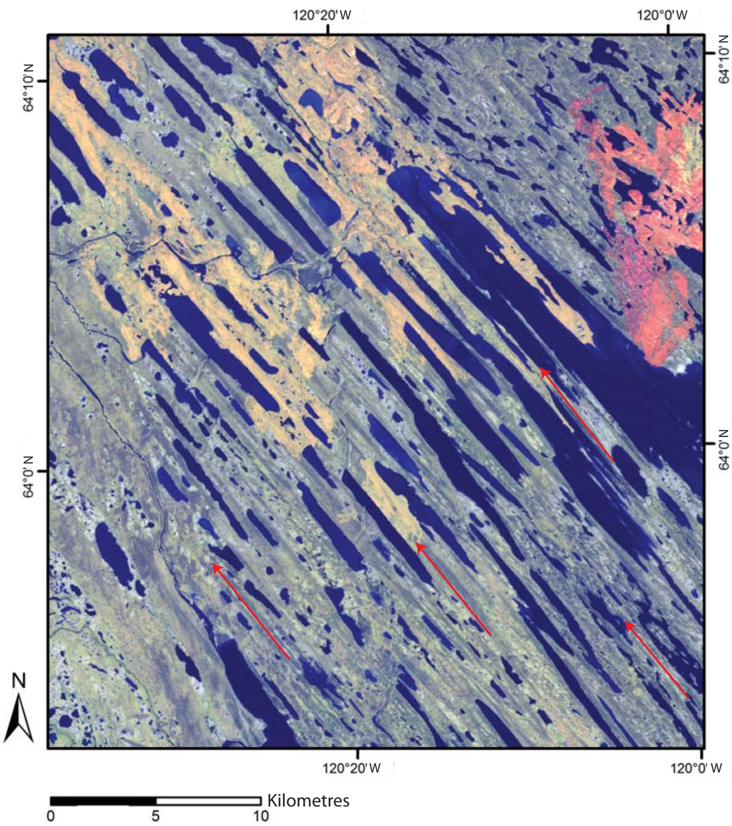


Figure 3. Landsat ETM+ scene (band combinations R, G, B: 4, 3, 2) showing elongate drumlinised landforms up to 4 km long along the Arctic Ocean coast. The red arrows indicate the orientation of the drumlins. Location shown on Figure 1.



(a)



(b)

Figure 4. Two examples of mega-scale lineations found to the west of Great Bear Lake (Landsat ETM+ band combination R, G, B = 6, 5, 2). The changes in colour across the images are due to differences in reflectivity from different land cover. Some mega-scale lineations can be traced for hundreds of kilometres. (a) narrow, highly elongate features which show a high degree of parallel conformity and are very closely spaced. (b) broader elongate bedforms interspersed with lakes. Bedform density is lower than in (a). The red arrows indicate the orientation of the mega-scale lineations and also their parallel conformity. Location shown on Figure 1.

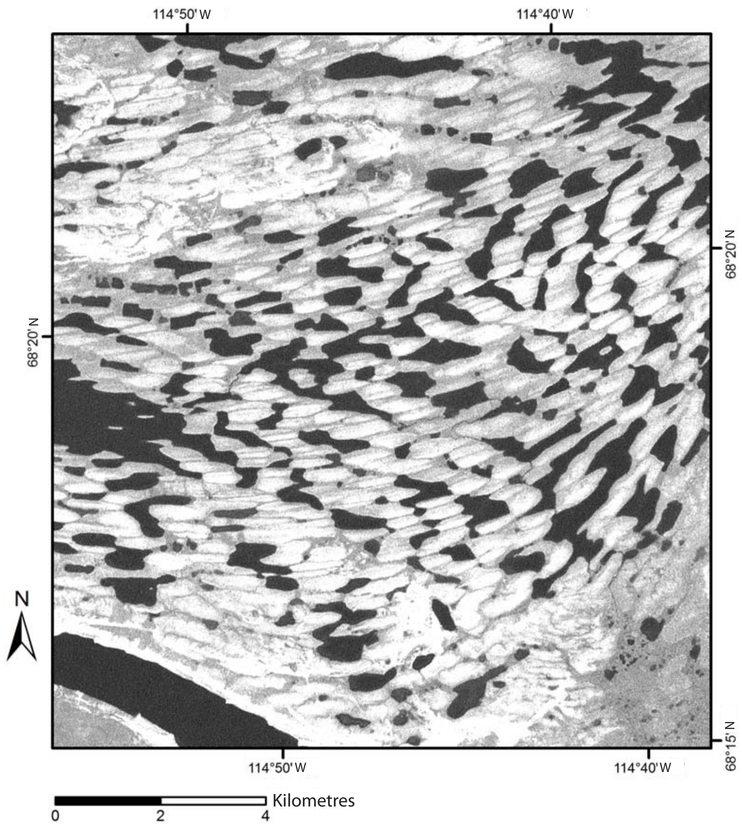


Figure 5. Cross-cutting bedforms along the Amundsen Gulf Coast as visualised on Landsat ETM+, band 8. Successive generations of ice flow are indicated by cross-cutting drumlins (lineations) and, potentially, ribbed moraine. Location shown on Figure 1.

4.2 Major Moraine Ridges

Major moraines occur as curvilinear ridges both parallel and perpendicular to lineations (Figure 6). Although moraine ridges more commonly overprint lineations, ridges with overprinted lineations are also present. The mapped ridges are typically 1-2 km wide and up to few hundred kilometres long with clearly visible crestlines (Figure 6). 734 moraine ridges have been mapped throughout the study area but it is acknowledged that much smaller ridges probably exist that have not been mapped at this scale. Many of these moraines were originally mapped by Prest et al. (1968) on the Glacial Map of Canada and were later mapped by Dyke and Prest (1987). A large group of closely spaced moraine ridges has been mapped along the southern side of the Tuktoyaktuk Peninsula which are known locally as the Eskimo Lakes (Mackay, 1956).

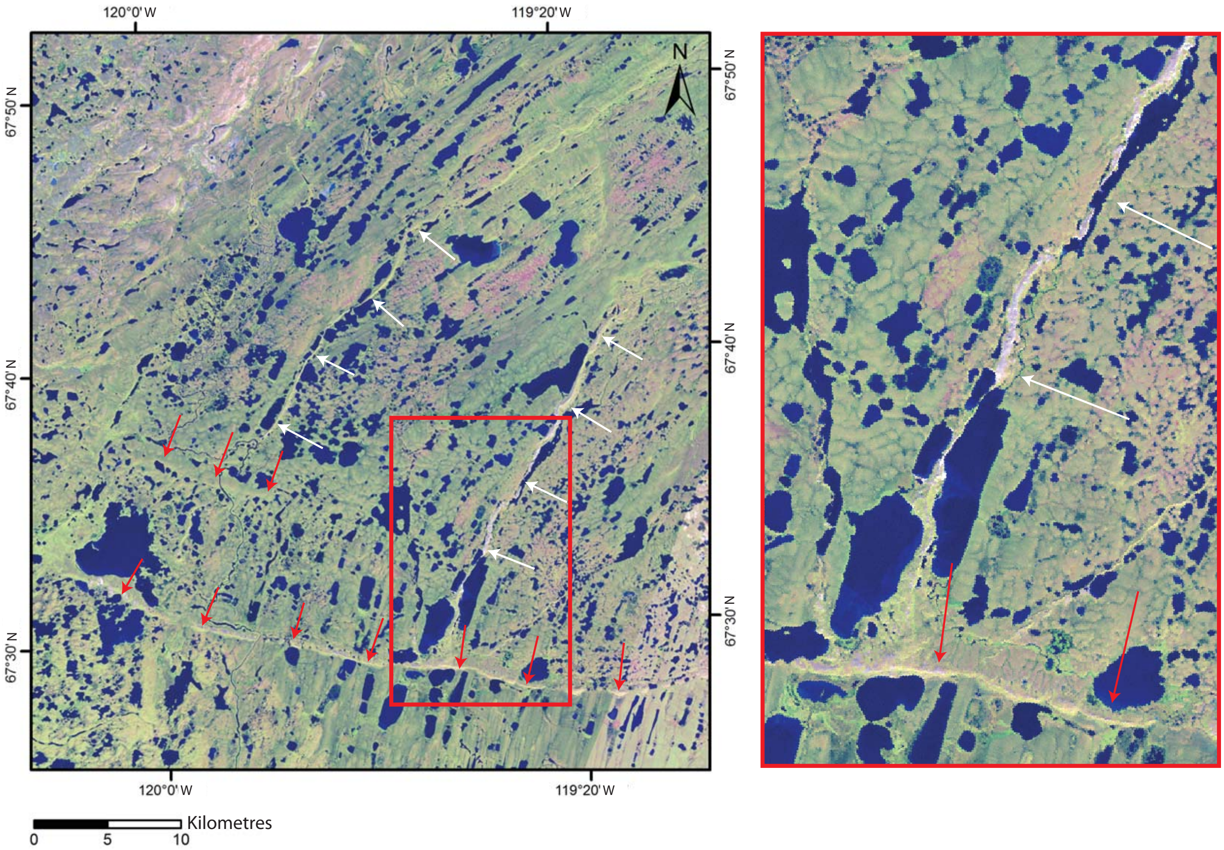


Figure 6. A moraine ridge trending east to west (yellow arrows) across a Landsat ETM+ image (band combination R, G, B = 6, 5, 2). On the western side of the image, a further shorter ridge is also visible to the north of the main ridge. Eskers also run from north to south (red arrows), perpendicular to the moraine ridges, and are surrounded by numerous lineations. The red box provides a closer view of a section of the imagery. Aside from the large esker trending north to south, a smaller esker is also visible at 45° to the main moraine ridge on the zoomed image. Location shown on Figure 1.

4.3 Hummocky Topography

Hummocky topography is extensive throughout the northern part of the study area and is identified as an irregular undulating surface of peaks and, often, ponded depressions. While visualisation of localised areas of hummocky topography reveals a largely chaotic arrangement, coarser scale visualisation often allows for the identification of regional patterns of linear organisation in some locations (cf. Dyke and Savelle, 2000). While some workers argue that hummocky topography is indicative of regional ice stagnation and down-wasting (Andersson, 1998), it is also suggested that it represents a series of complex ridges which formed during the retreat of an active ice margin (see Munro and Shaw, 1997; Eyles et al., 1999; Munro-Stasiuk and Sjogren, 1999; Dyke and Savelle, 2000). Similar ridges have been reported by Storrar and Stokes (2007) on Victoria Island. Of particular note is the Melville Hills moraine complex (Figure 7) which is located to the east of Paulatuk (Figure 1). Hummocky topography is also mapped extensively around the Mackenzie delta and the Tuktoyaktuk Peninsula. In contrast to the Melville Hills area, this hummocky topography exhibits minimal relief and internal ridges are completely indistinguishable.

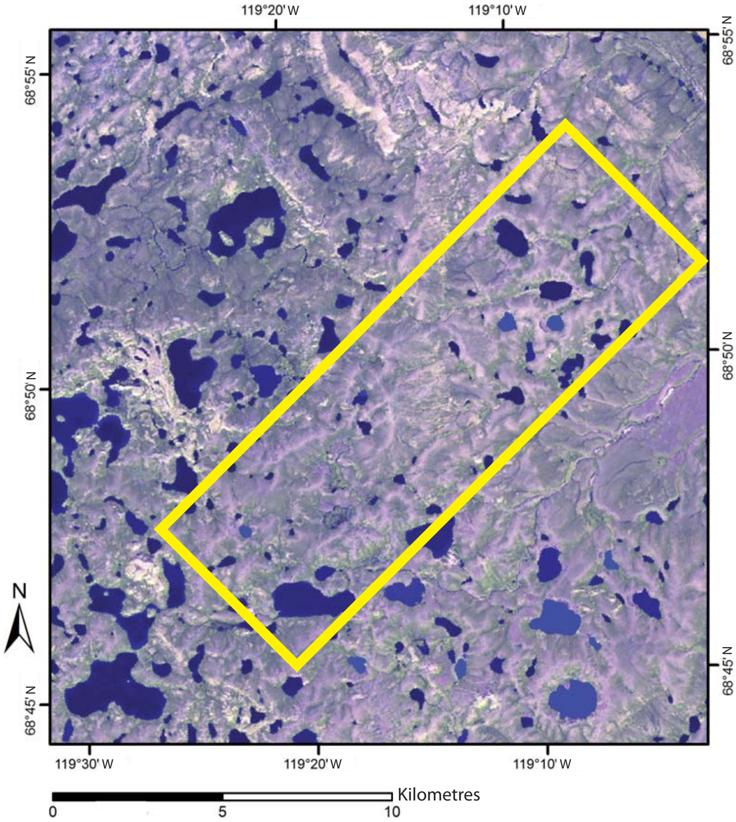


Figure 7. Irregular hummocky topography in the Melville Hills area as visualised on Landsat ETM+ (band combination R, G, B = 6, 5, 2). Some organisation in a north-east to south-west orientation is visible in the centre of the image (highlighted by the yellow outline box). Elsewhere on the image, the arrangement of the moraine appears more chaotic. Location shown on Figure 1.

4.4 Ribbed Moraine

Ribbed moraine (Hättestrand and Kleman, 1999; Dunlop and Clark, 2006; Fisher and Shaw, 1992) appear as a series of morphologically similar, closely spaced ridges aligned transverse to ice flow (Figure 8). They are found in swarms and are most common in the east-west trending trough which extends out of Great Slave Lake towards the Yukon Mountains. The moraines are generally orientated perpendicular to the long axis of the trough (NNE to SSW) in a similar fashion to that noted by Marich et al. (2005) in Newfoundland. Marich et al. (2005) report bedform areas of no larger than 5 km^2 for ribbed moraine which are continuous, evenly spaced and oriented parallel to one another. This is comparable to the ribbed moraine mapped here, where 82% of the bedforms have an area ≤ 5 km^2. Smaller ribbed moraine have also been identified further east by Aylsworth and Shilts (1989) where they cover much larger areas nearer the Keewatin Ice Divide.

A number of formative mechanisms have been invoked for ribbed moraine. Early work suggests formation in a marginal or near-marginal position (Cowan, 1968; Lundqvist, 1989). However, since the 1980s, studies have exclusively proposed a subglacial origin (Hättestrand and Kleman, 1999; Marich et al., 2005; Linden et al., 2008; Möller, 2010). Most recently, Dunlop et al. (2008) propose that ribbed moraine results from a subglacial sediment instability which produces their characteristic regular morphology and wavelength. Although their origin is still debated (e.g. Hättestrand and Kleman, 1999; Dunlop and Clark, 2006), their presence is usually associated with a switch in the basal thermal regime and/or areas of slower-flowing ice (e.g. Fisher and Shaw, 1992; Kleman and Hättestrand, 1999; Stokes et al., 2008).

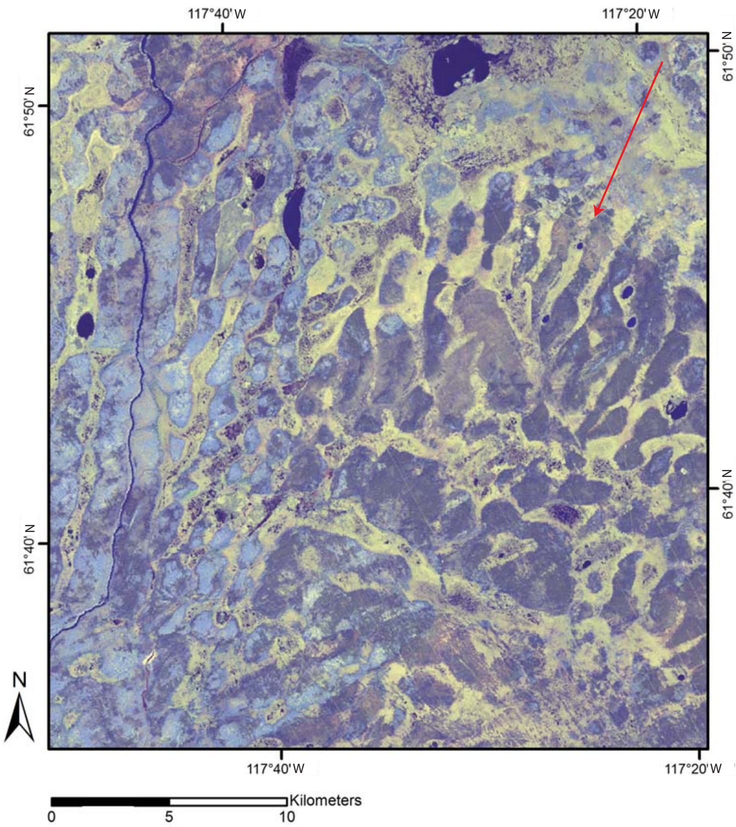


Figure 8. Ribbed moraine (Landsat ETM+ band combination R, G, B = 6, 5, 2) north of Great Slave Lake. This area of bedforms exhibits a regular morphology and spacing. Elsewhere ribbed moraine occur in smaller and more isolated areas. The arrow indicates the mean long axis orientation of the bedforms. The ribbed moraine is coloured grey and is surrounded by lighter coloured material. Location shown on Figure 1.

4.5 Eskers

Eskers are elongate sinuous ridges of glacio-fluvial sand and gravel that represent the infillings of subglacial meltwater channels (Bannerjee and MacDonald, 1975) and a total of 1,320 eskers have been mapped. While some eskers remain isolated and relatively linear throughout their length (Figure 6), others display a more complex morphology. Eskers broadly radiate away from the Canadian Shield in the east which reflects ice flow from the Keewatin dome during the Late Wisconsinan.

Although eskers are found aligned with the surrounding lineations, they are also observed perpendicular to lineations throughout the study area. They exhibit a range of lengths from 100 metres to 15 km with a mean length of 1.8 km. However, esker fragments can be traced for over 100 km (e.g. north-east of Great Bear Lake). There is a surprising lack of eskers in the north-western part of the mapped area and, where present, eskers are often misaligned with the surrounding lineations (short, “deranged" eskers; see Brennand, 2000). This may reflect the complex changes in ice flow orientation and dynamics occurring here during deglaciation but can also be attributed to the surficial geology of the region. In the east, where the Canadian Shield provides a mass of rigid substrate, drainage within channelized flow would be expected (Clark and Walder, 1994; Brennand, 2000). However, where the ice-bed interface is gently sloping and consists of deformable sediment (as is the case in the north-west part of the mapped area), a drainage network consisting of wide, shallow channels or sheet-flow may be expected (Shreve, 1985; Clark and Walder, 1994; Brennand, 2000). The formation of eskers would therefore be limited. Indeed, eskers are found to generally decrease in number from east to west away from the Canadian Shield; a distribution which is also noted by Clark and Walder (1994).

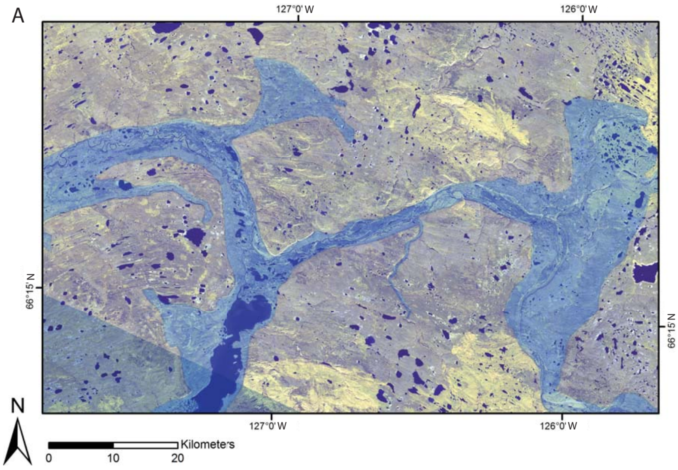
4.6 Large Meltwater Channels

A series of large channels, frequently occupied by mis-fit streams, dominate the landscape in the north-western part of the mapped area (Figure 9a and b). The 46 mapped channels cover an area of 14,300 km^2. The channels are occasionally in excess of 10 km wide and form a fragmented network which cross-cuts the surrounding geomorphology. These channels probably mark the drainage pathway of glacial meltwater both alongside and away from the ice sheet during deglaciation but may also represent a network of subglacial tunnels. Smaller meltwater channels are likely to exist but our mapping was restricted to the larger channels by the resolution of the imagery and the need to create a regional geomorphological map. Major meltwater channels dissect areas of hummocky topography and a number of channels drain towards the present route of the Mackenzie River. Large meltwater channels, similar to those mapped here, have been identified by Mackay and Matthews (1973) near Fort Good Hope (Figure 9). These channels were cut during the early stages of deglaciation by overflow from a nearby ice-dammed lake. Numerous fragmented lake strandlines also exist which may aid in the reconstruction of proglacial lakes that are known to have existed in the region (Craig, 1965; Dyke et al., 2003). We depict the major contiguous strandlines which are greater than 10 km long on the map.

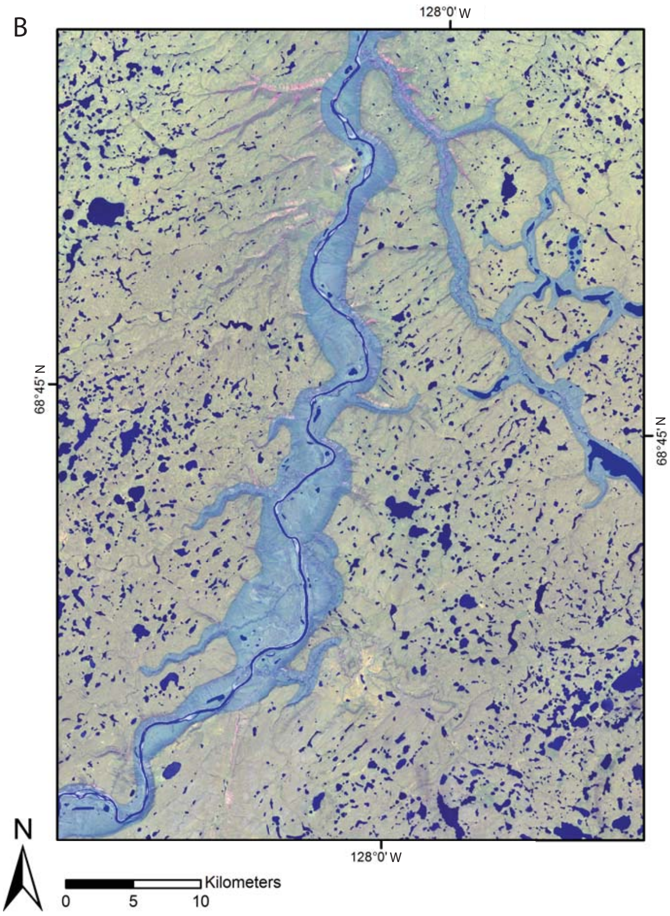
5. Conclusions and Implications

This paper presents a new map of the glacial geomorphology of north-west Canada; an area once covered by part of the LIS. Mapped features include lineations, moraine ridges, hummocky topography, ribbed moraine, eskers, strandlines and large meltwater channels. This large, regional scale map documents the spatial distribution of more than 94,000 landforms. Unlike datasets of a smaller sample size, it has a range of potential applications including investigating regional ice flow patterns, landform morphometry, landform genesis and meltwater and proglacial lake drainage.

Preliminary conclusions indicate that, during deglaciation, dynamic switches in ice flow orientation occurred within this sector of the LIS. These switches are recorded by complex arrangements of eskers, highly attenuated lineations and partially over-printed bedforms, often in combination. The most attenuated bedforms are clustered in a sinuous, but fragmented corridor $\sim$ 90 km wide, trending south-east/north-west along the western edge of Great Bear Lake towards the Arctic Ocean. Convergent and divergent patterns of lineations with abrupt lateral margins have also been identified around Great Bear Lake, along the Amundsen Gulf coast and in the vicinity of the Anderson River. This arrangement of bedforms provides potential evidence for palaeo-ice streaming(cf. Stokes and Clark, 1999). Areas of higher ground generally remain free of lineations, most notably around the Melville Hills and to the north-east of Fort Simpson. It is assumed that these areas were occupied by cold-based ice (Kleman and Glasser, 2007) or, as suggested by Dyke et al. (2003) for the Melville Hills, remained ice free during the Late Wisconsinan.



(a)



(b)

Figure 9. Landsat ETM+ image (band combination R, G, B = 6, 5, 2). a) an abandoned meltwater channel near Fort Good Hope. The western section of this channel was originally identified by Mackay and Matthews (1973). b) a channel along the Anderson River. Location shown on Figure 1.

Software

Landsat ETM+ imagery was manipulated in Erdas Imagine 9.3 and figures were created in ESRI ArcGIS 9.3 and Adobe Illustrator CS4.

Acknowledgements

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