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Glacial geomorphology of the east-central Canadian Arctic

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Abstract:

This article describes palaeoglaciological mapping of the portion of the Canadian Arctic formerly covered by the north-easternmost Laurentide Ice Sheet. The mapped area stretches between the meridians 106°W and 61°W, and the parallels 60°N and 75°N, embracing an area of 3.19 x 10^6 km^2. The work was focused on determining the location of landforms that are required as input for a glaciological inversion model, i.e. glacial lineations, eskers, moraine ridges, ribbed moraine and De Geer moraines; and forms the basis of a reconstruction of the geometry and evolution of palaeo-ice streams in this portion of the Laurentide Ice Sheet. Emerged areas were mapped through the geomorphological interpretation of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite images. Information on striae and other minor indicators of glacial activity were extracted from maps and reports by the Geological Survey of Canada, published articles and, for a few locations, by the author's own observations. Information on landforms located on some submerged areas where extracted from publicly available sonar surveys. All data were digitally processed within a Geographical Information System and stored in a spatially enabled database. The results are presented as a printable map at 1:2,400,000 scale.

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1. Introduction

The ability of human societies to adapt to future climate and environmental changes is intimately tied to our understanding of their past occurrences because these provide the reference frame against which our hypothesis on the long term behaviour of natural systems can be compared. In this regard, the availability of reliable palaeoglaciological reconstructions becomes crucial (Shumskiy, 1955; Koltyakov et al., 1984; Hughes, 1998). The inversion of the geomorphological record provides a means for unravelling the former extent and configuration of palaeo-ice sheets (Dyke and Prest, 1987; Boulton and Clark, 1990; Dyke et al., 2003; Kleman et al., 2006) and maps are the fundamental prerequisite for obtaining such reconstructions.

This text describes palaeoglaciological mapping of a portion of the Canadian Arctic formerly covered by the northern Keewatin and Foxe/Baffin sectors of the Laurentide Ice Sheet (LIS; Fig. 1). The work forms the basis of a palaeoglaciological reconstruction of this portion of the LIS that explicitly incorporates its palaeo-ice streams. The reconstructions and analyses based on the present map are presented elsewhere (De Angelis and Kleman, 2005; 2007).

2. Previous Mapping

The studied region lies entirely within Canadian territory and mainly comprises the Nunavut province, except for a smaller portion on the south-west corner, which is located in the Northwest Territories, and the south-eastern corner, which lies in the Québec Province. Systematic geomorphological and glacial-geological mapping in the region was pioneered by Tyrrell (1897), Taylor (1956), Lee (1959) and Craig and Fyles (1960) in the Keewatin area (central Nunavut); and by Ives and Andrews (1963) and Blake (1966) on Baffin Island. These early studies showed the existence of a complex glacial record and provided evidence for a multi-domed LIS (Lee, 1959; Andrews and Miller, 1979), which became unambiguously evident with the appearance of the comprehensive Glacial Map of Canada (Prest et al., 1968). Later, regional mapping, such as by Aylsworth and Shilts (1989), has been largely focused on enriching the picture provided by the Glacial Map of Canada at varying levels of detail, a task undertaken by the Geological Survey of Canada and published in its extensive report and map series. Detailed glacial-geological surveys also appear in several published articles.

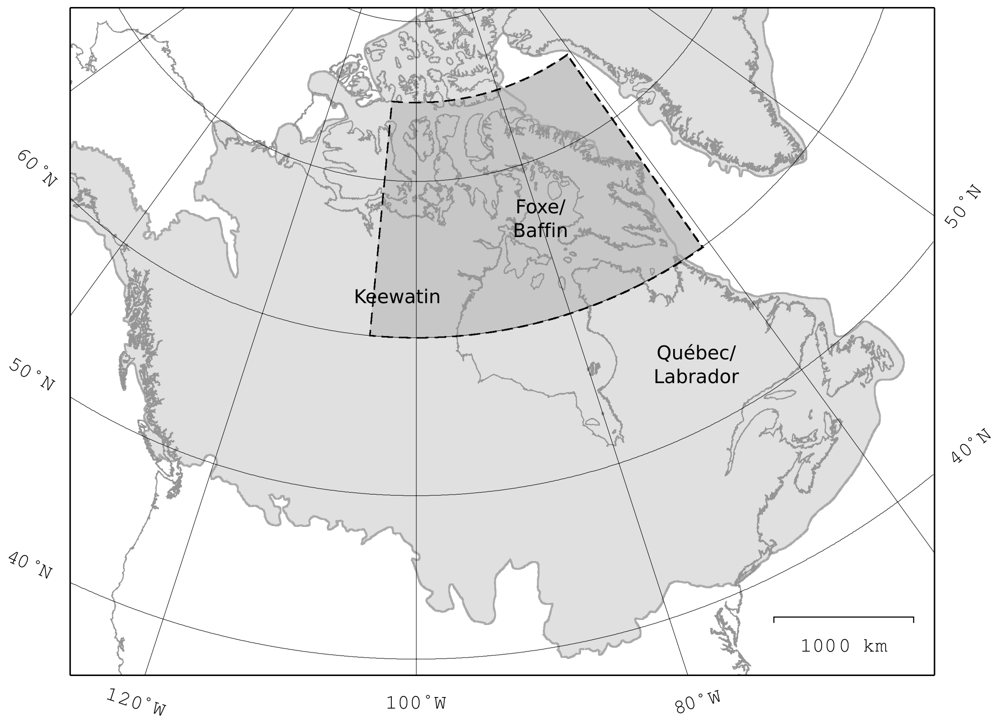

Figure 1 Laurentide Ice Sheet at 18 kyr BP (after Dyke et al., 2003) and location of the region of interest (shaded area). The names correspond to the three main sectors of the Laurentide Ice Sheet.

The present map is inspired by, and partially builds on previous similar work (Table 1) but differs in that it is almost completely based on the interpretation of satellite images and that it is explicitly designed for the purpose of unravelling the location and evolution of palaeo-ice streams. Accordingly, this map incorporates the features required by a glaciological inversion model (Kleman et al., 2006), particularly mega-scale glacial lineations (Clark, 1993). The glaciological inversion model is a scheme that formalizes the use of the landform record to reconstruct ice sheet configurations and provides guidelines to make the process less subjective. The main procedure consists in the recognition of landform assemblages forming coherent glaciological patterns and their subsequent integration into landform “swarms”. Swarms are defined on the basis of spatial continuity and resemblance to a glaciologically plausible pattern, following the least complex possible solution. Landform swarms represent the first level of abstraction in the regional interpretation and serve to reduce the cartographic information into a manageable number of entities.

Subregion	**Reference**
Entire region	Prest et al. (1968); Fulton (1995)
Keewatin	Aylsworth and Shilts (1989); Ozyer and Hicock (2002); Kleman et al. (2002); Stokes and Clark (2003); Mc-Martin and Henderson (2004); Stokes et al. (2006)
Victoria Island	Hodgson (1994), Clark and Stokes (2001)
Somerset Island	Dyke (1983)
Prince of Wales Island	Dyke and Morris (1988); Dyke et al. (1992)
Boothia Peninsula	Dyke (1984)
Melville Peninsula	Dredge (1995), Dredge (2000) and Dredge (2001)
Northern Baffin Island	Dyke and Hooper (2001); Little et al. (2004)
Central Baffin Island	Tippett (1985); Andrews (1989); Clärhill (2002)
Southern Baffin Island	Blake (1966); Miller et al. (1988); Miller and Kaufman (1990); Laymon (1992), Manley (1996); Kleman and Jansson (1996)
Northern Québec & Labrador	Veillete et al. (1999); Clark et al. (2000); Daigneault and Bouchard (2004); Gray (2001)
Hudson Strait	Laymon (1992); Manley (1996)
Hudson Bay	Josenhans and Zevenhuisen (1990)

Table 1: Cartography, reports and articles used for control according to subregions

3. Methods

3.1 Basis and implementation

All mapping procedures were performed digitally within a Geographic Information System (GIS). In order to keep geometrical uniformity with Canadian cartography, the GIS database was based on a Lambert Conformal Conical projection referenced to the North American Datum 1983 (NAD83) with standard parallels located at 49°N and 77°N. The centre of projection is located at 83°W, 68°N. The mapped area stretches between the meridians 106°W and 61°W, and the parallels 60°N and 75°N, embracing a total of 3.19 x 10^6 km^2, from which 1.55 x 10^6 km^2 correspond to emerged land.

3.2 Imagery

Landsat 7 ETM+ imagery was selected because of its excellent spatial coverage and the high resolution ($\sim$ 15 m pixel size) panchromatic band (band 8; 0.52 - 0.90 μm). In addition, one Landsat 5 TM image (path/row 029/010; 28.5 m pixel size) was also used to fill a small gap in Landsat 7 ETM+ imagery over northern Baffin Island. A total of 156 scenes were necessary to cover the region with only minor gaps (Fig. 2). Most images were downloaded from Global Land Cover Facility (GLCF), maintained by the University of Maryland, USA (http://glcfapp.umiacs.umd.edu) and the rest from GeoGratis (http://geogratis.cgdi.gc.ca/), maintained by Natural Resources Canada. Images from GLCF were obtained in GeoTIFF format, projected in the corresponding Universal Transverse Mercator (UTM) zones and referenced to the World Geodetic Datum 1984 (WGS84). Images from GeoGratis are also referred to WGS84 but are provided in raw Landsat format and it was necessary to convert them to GeoTIFF. For both groups, no conversion was applied to change the datum from WGS84 to NAD83 because of the negligible difference between these two coordinate systems over North America (Schwarz, 1989). All images were later reprojected from the original UTM zones to the Lambert Conformal Conical projection.

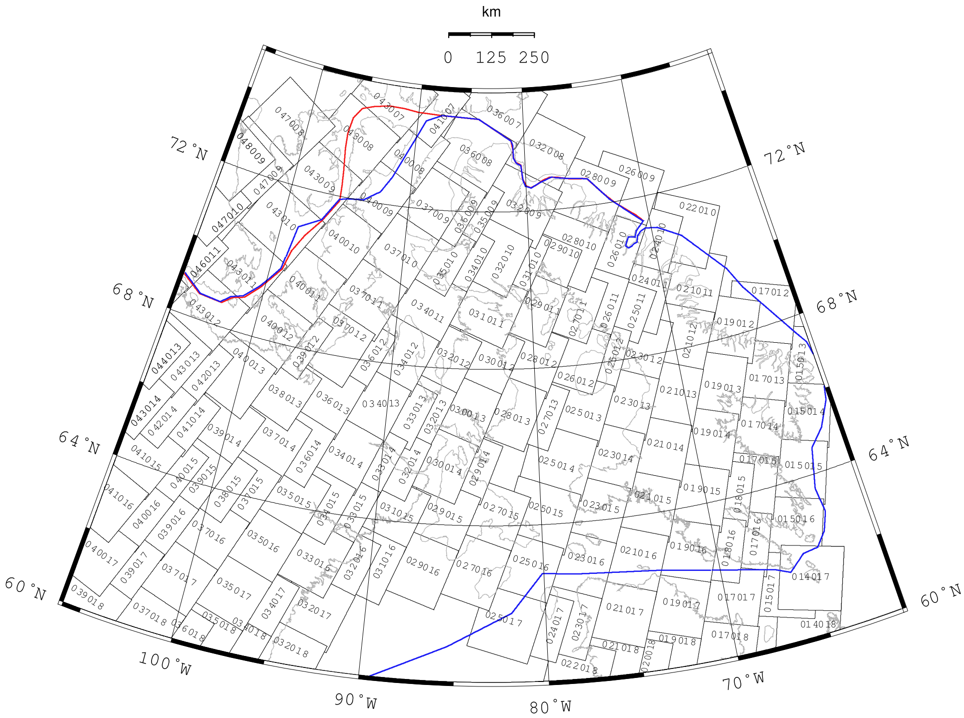

Figure 2 Coverage by satellite images (squares) of the region of interest and tracks of the sonar surveys: Northwest Passage Transit (red) and Hudson Bay Transit & Nastapoka Islands (blue), both performed by the Ocean Mapping Group, University of New Brunswick, Canada (http://www.omg.unb.ca/). Numbers centred in the Landsat scenes indicate path/row pairs.

3.3 Mapping

Landforms were manually digitized into vector layers after visual interpretation (e.g. Clark, 1997). Adjustments in contrast were applied empirically to individual images in order to improve landform detectability. In general, there exists considerable overlap of images across the region, which translated into an advantage in that slightly different views where available by images taken in different years. Accordingly, the potential bias and uncertainties introduced by the solar azimuth and elevation (e.g. Smith and Wise, 2007), low relief or cover type (e.g. Jansson and Glasser, 2005) were substantially diminished. Six groups of landforms were mapped (Table 2): 1) directional landforms without information about sense of ice movement: flutes, mega-scale glacial lineations (Clark, 1993, Fig. 3) and streamlined bedrock; 2) directional landforms with information about sense of ice movement: drumlins (Fig. 4a), crag-and-tails, carbonate till plumes

(Dredge, 2000) and some mega-scale glacial lineations; 3) eskers (Fig. 4b); 4) moraine ridges; 5) ribbed moraine; and 6) De Geer moraine. Relative age determinations made on the basis of cross-cutting relationships were also mapped (Clark, 1993, Fig. 5). These features result from the partial modification of subglacial landforms by a later flow in a different direction and allow the building of a relative chronology of ice flow events. Mapping reported here involves approximately 25,900 features.

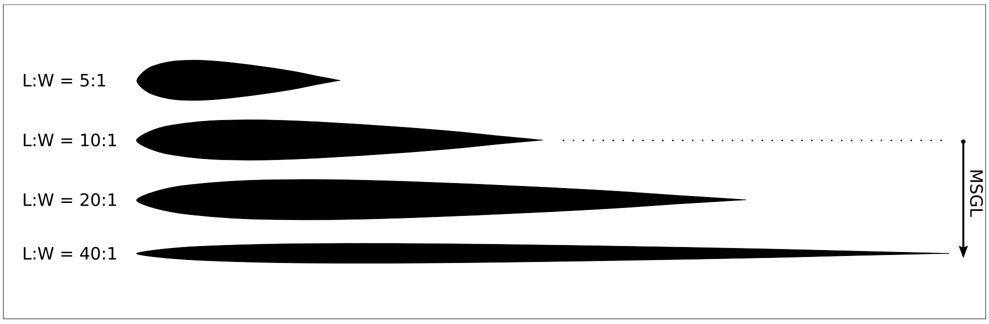

Figure 3 Examples of till lineations of different proportions. Length/width ratios larger than 10:1 are considered to be the result of fast glacier flow (Stokes and Clark, 2002). These largest forms are usually denominated mega scale glacial lineations (MSGL Clark, 1993).

3.4 Ancillary data sources

Map sources: Several published map sources were used to control mapping and fill small gaps in image coverage. The two main sources comprise the Glacial Map of Canada (Prest et al., 1968) and Surficial Materials of Canada (Fulton, 1995). Additional evidence was extracted from published literature and reports by the Geological Survey of Canada (Table 1).

Submerged landforms: Information about landforms in some submerged areas was available from two publicly available sonar surveys: the Northwest Passage Transit and the Hudson Bay Transit & Nastapoka Islands, both by the Ocean Mapping Group, University of New Brunswick, Canada (http://www.omg.unb.ca/). These surveys provide information about the submarine geology and geomorphology of parts of the Hudson Strait, eastern Baffin Island, Lancaster Sound, Peel Sound and Queen Maud Gulf (Fig. 2). For Hudson Bay, some lineation evidence was available from the study of Josenhans and Zevenhuisen (1990).

Landform Group	**Characteristics**
Directional landforms (glacial lineations)	Streamlined glacial landforms with the long-axis aligned with ice flow direction. In most cases (e.g. flutes, drumlins) these comprise landforms composed of till although erosional forms, such as streamlined bedrock and crag-and-tails, were also mapped. The distinction has been made between those landforms where the sense of ice movement can be distinguished due to longitudinal asymmetry (e.g. Fig. 5) and those where that was not possible. As the purpose of the map was to reconstruct palaeo-ice streams, mapping was focused on large lineations (> 5 km long), in particular mega-scale glacial lineations (Clark, 1993), which may attain lengths of several tens of kilometres and large elongation ratios (Fig. 3). For practical reasons, small lineations (< 1 km length) were not mapped.
Eskers	Ridges composed of glaciofluvial material (Fig. 4b), usually aligned with glacial lineations. May form complex systems with tributary eskers and reach lengths of > 100 km.
Moraine ridges	Ridges that are usually arranged transverse to glacial lineations. May attain combined lengths of > 100 km, as in northern Keewatin.
Ribbed moraine	Transverse ridges that occur in groups and may form extensive (e.g. thousands of square kilometres) fields, displaying a wide variety of shapes and arrangements (Dunlop and Clark, 2006).
De Geer moraines	Small transverse ridges that usually occur in areas below the highest marine limit (Lindén and Möller, 2005). Usually display delicately defined arrangements of fairly regularly spaced ridges. May also form large fields.

Table 2: Landform characteristics and identification

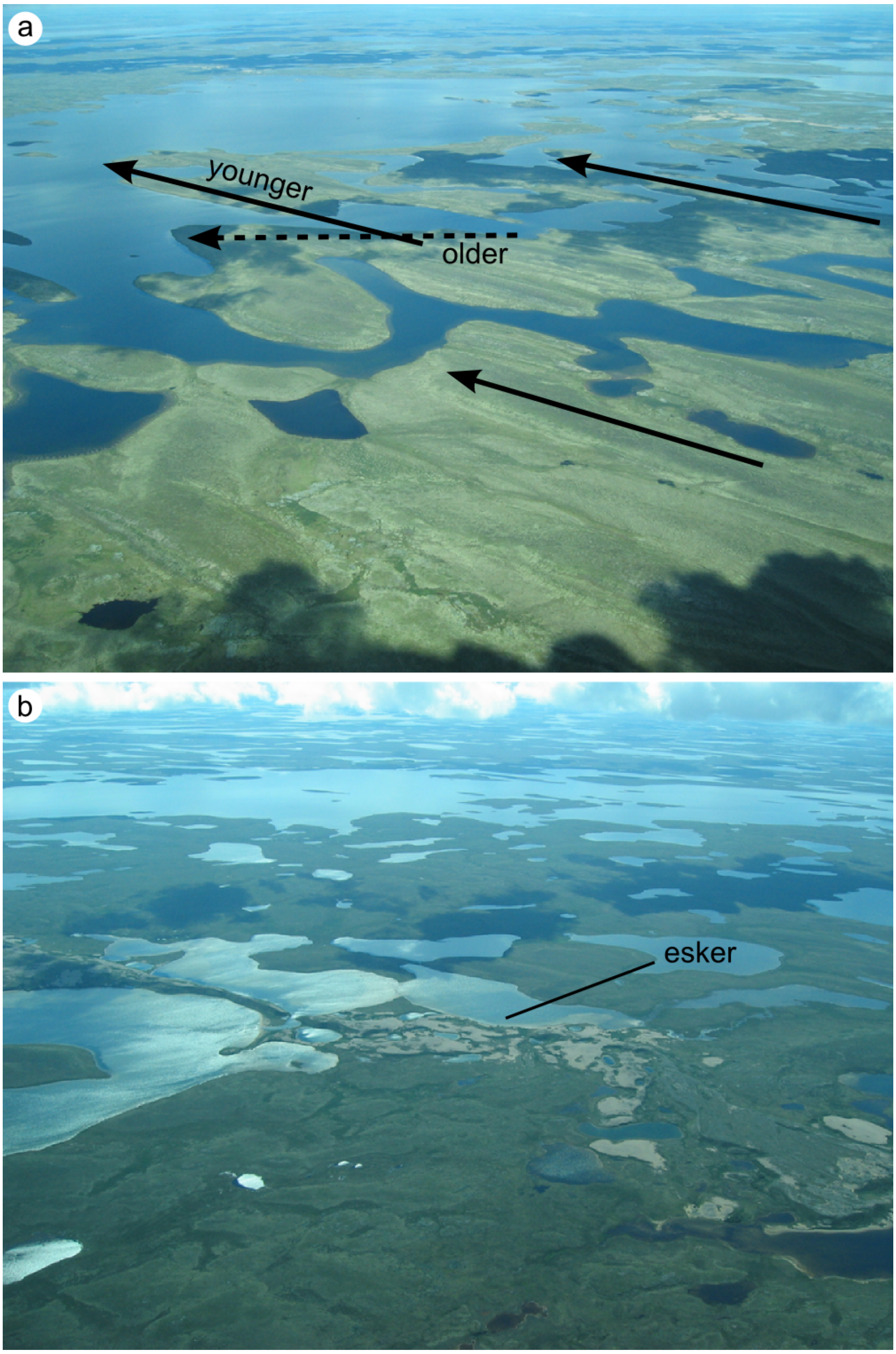

Figure 4 Oblique aerial pictures of areas in north-western Keewatin, showing typical landscapes of the region: a. cross-cutting relationships between glacial lineations of different age. b. deglacial esker. Both pictures taken during a reconnaissance flight conducted on 29 July 2005 (Photos: Hernán De Angelis).

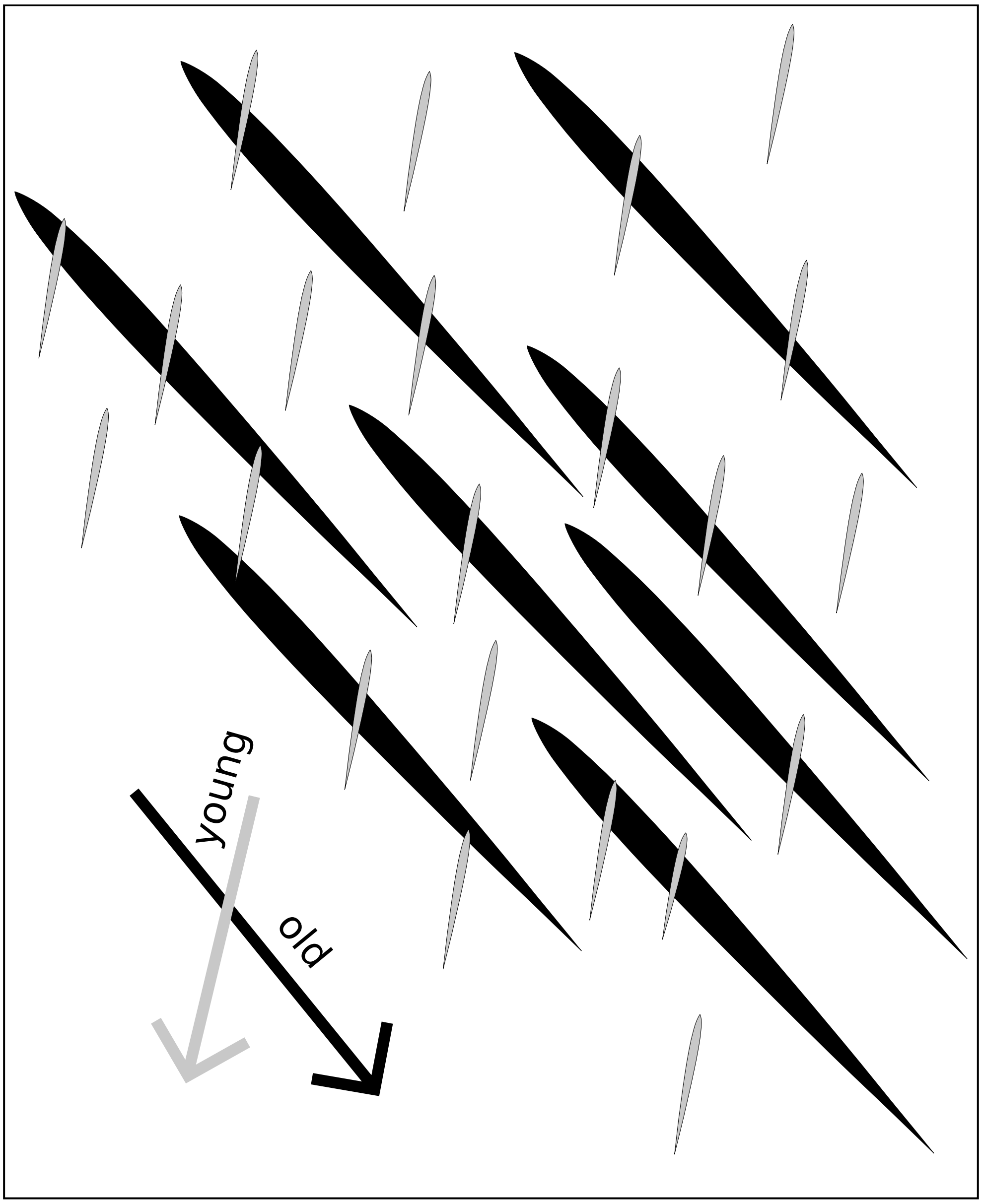

Figure 5 Schematic example of cross-cutting relationships, which are used for relative age determinations of intersecting landform systems.

Low-altitude oblique aerial photography: A validation field campaign was carried out on July 2005. Low altitude oblique aerial pictures from several locations in the westernmost rim of the region of interest were acquired for use in the validation of the mapping, particularly cross-cutting relationships (Fig. 4).

Topography: A digital elevation model (DEM) was used for providing a first order reference for the topographic context. This was compiled using topography from the Global Land 1-Km Base Elevation model (GLOBE, Hastings et al., 1999) and bathymetry from the ETOPO2 model (http://www.ngdc.noaa.gov).

Coastlines: Coastlines were drawn for reference purposes only by using the World Vector Shoreline database included in the Generic Mapping Tools mapping software package (Wessel and Smith, 1998).

3.5 Methodological notes

Due to the size of the region and the heterogeneity of the landform record, careful and consistent mapping techniques were required to minimize the spatial bias in the cartographic representation. Mapping reported here was completed in two successive steps, first at 1:250,000 and later at 1:100,000 scale. This approach was designed to achieve a consistent cartographic homogeneity over areas featuring well preserved landforms of large size (>5 km) and to identify areas requiring closer inspection. In some cases (e.g. Baffin Island and central Boothia Peninsula), mapping was performed at 1:75,000 due to the faintness and small size of the landforms. A principle of representativity was applied, meaning that mapping was accomplished with the objective of achieving a good representation of the landform patterns. All images were analysed several times at smaller scales, i.e. 1:500,000, in order to assess the consistency across the region as well as to eliminate aberrations such as feature duplication due to image overlaps and inadequate spatial representation of landform assemblages. The accuracy of the mapping was tested in two different ways. Where low-altitude oblique aerial photographs were available, ground-truthing was made by comparing the observed landforms and cross-cutting relationships with those mapped on satellite imagery. For the rest of the map, accuracy checks were made by using the mentioned map sources as independent controls.

The positional accuracy of landforms mapped from satellite imagery is considered to be better than 250 m (Landsat 7 Science Data Users Handbook, http://landsathandbook.gsfc.nasa.gov/handbook.html) which corresponds to ∼0.1 mm in the printed map. In the case of submerged landforms, which have been extracted from published sonar surveys, the positional accuracy is estimated to be better than 2,500 m (∼1 mm in the printed map).

4. Map design

Due to the size of the area and the amount of information contained in the map, the layout and symbology were chosen to keep the map as simple and intuitive as possible. In general, the colours are the same as those of the Glacial Map of Canada (GMC), except for the elongated lineations, which are not depicted in the GMC and De Geer moraine areas, which are here depicted as coloured areas instead of patterned areas as in the GMC. Lineations are shown as short segments, with arrowheads where a sense of flow could be determined. Elongated lineations are depicted in red, whereas standard ones are in black. Eskers and moraine ridges are simple lines coloured in blue and brown, respectively. Areas of ribbed and De Geer moraines are shown in yellow and blue, respectively. Cross-cutting relationships are coded as a pair of coloured segments centred in a circle. The idea behind this binary symbol is that it is easier to see and is less prone to confusion than the classical barbed one.

5. Conclusions

A glacial-geomorphological map of the portion of the Canadian Arctic formerly covered by the northern Keewatin and Foxe/Baffin sectors of the LIS has been compiled through the interpretation of high resolution satellite images. This map depicts the spatial distribution of glacial landforms that are required by a glaciological inversion model (Kleman et al., 2006) and constitutes the fundamental database from which the geometry and evolution of palaeo-ice streams in the north-easternmost LIS have been reconstructed (De Angelis and Kleman, 2005; 2007). This map is inspired by, and partially builds on previous similar work such as the Glacial Map of Canada (Prest et al., 1968), but differs in that it is almost completely built upon the interpretation of satellite images. Accordingly, the map does not replace earlier or contemporary work by the Geological Survey of Canada, but provides a complementary view with the additional incorporation of features in submerged areas, the distinction of mega-scale glacial lineations and several previously unmapped cross-cutting relationships. Besides its original purpose, this map is also suitable for the assessment of the output of numerical models at the ice sheet scale (e.g. Napieralski et al., 2007).

Software

Digitizing was accomplished first in ESRI ArcGIS and later in OpenEV. Vector layers were originally stored as ESRI Shapefiles and were afterwards imported into a PostGIS database for processing and analysis. This was performed using PostGIS SQL commands via custom Perl programs and Geographic Resources Analysis Support System (GRASS). Production of the DEM required resampling of the 2 arc-minute ETOPO2 grid into a 30 arc-minute spacing, to match the GLOBE spacing, and the subsequent replacement of the topographic information contained in ETOPO2 by that from GLOBE. The resulting grid was reprojected into a 1 km pixel raster file in Lambert Conformal Conical projection. These procedures were performed using GMT (Wessel and Smith, 1998) and Geospatial Data Abstraction Library (GDAL). Map production was accomplished with GMT and cosmetic details finished with Inkscape.

Data

The author has supplied data (a CSV table) used in the production of the accompanying map. This PDF has a ZIP archive embedded within it (stored as a .ZI file extension) containing the data and can be accessed by right-clicking on the “paperclip” icon at the beginning of this section (you will need to save the file and edit the file extension to .ZIP). Whilst the contents of the ZIP file are the sole responsiblity of the author, the journal has screened them for appropriateness.

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