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Ice streams in the Laurentide Ice Sheet: a new mapping inventory

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Rapidly flowing ice streams dominate the drainage of continental ice sheets and are a key component of their mass balance. Due to their potential impact on sea level, their activity in the Antarctic and Greenland Ice Sheets has undergone detailed scrutiny in recent decades. However, these observations only cover a fraction of their 'life-span' and the subglacial processes that facilitate their rapid flow are very difficult to observe. To circumvent these problems, numerous workers have highlighted the potential of investigating palaeo-ice streams tracks, preserved in the landform and sedimentary record of former ice sheets. As such, it is becoming increasingly important to know where and when palaeo-ice streams operated. In this paper, we present a new map of ice streams in the North American Laurentide Ice Sheet (LIS; including the Innuitian Ice Sheet), which was the largest of the ephemeral Pleistocene ice sheets and where numerous ice streams have been identified. We compile previously published evidence of ice stream activity and complement it with new mapping to generate the most complete and consistent mapping inventory to date. The map depicts close to three times as many ice streams (117 in total) compared to previous inventories, and categorises them according to the evidence they left behind, with some locations more speculative than others. The map considerably refines our understanding of LIS dynamics, but there is a clear requirement for improved dating of ice stream activity.

Keywords: ice stream; Laurentide Ice Sheet; glacial landform record; mega-scale glacial lineations

1. Introduction

Ice flow in the Antarctic and Greenland ice sheets is organised into a spatial pattern of ice streams draining ice from the interior toward the margin and into the ocean (Bentley, 1987; Rignot, Mouginot, & Scheuchl, 2011). The same spatial organisation of flow toward the ice margin has been suggested for the Pleistocene ice sheets of the northern hemisphere (Denton & Hughes, 1981; Hughes, Denton, & Grosswald, 1977; Kleman & Glasser, 2007; Stokes & Clark, 2001) and robust evidence for ice stream activity has been recognised in the glacial landform and sedimentary record (Clark & Stokes, 2003; Dyke & Morris, 1988; Patterson, 1998;

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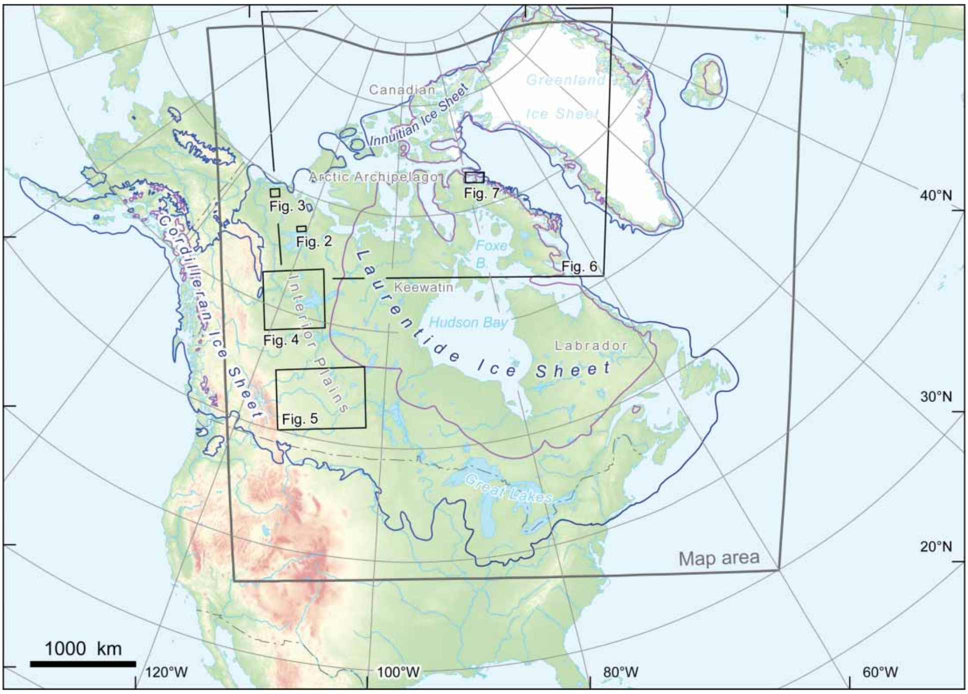

Figure 1. Location map. Outline of the map sheet is indicated in grey and locations of Figures 2–7 are indicated by black rectangles. Ice sheet extent (Dyke, Moore, & Robertson, 2003) is shown for 18 ^{14}C ka (21.4 ka BP) in dark blue and for 9 ^{14}C ka (10.2 ka BP) in purple.

Sharpe, 1988; Stokes & Clark, 2001). The largest ice sheet to grow and disappear was the North American Laurentide Ice Sheet (LIS; Figure 1) for which numerous palaeo-ice streams have been hypothesised (see reviews in Patterson, 1998; Stokes & Clark, 2001; Winsborrow, Clark, & Stokes, 2004). Here, we present a new and updated map of palaeo-ice streams in the LIS (including the Innuitian Ice Sheet), building on earlier syntheses (Patterson, 1998; Winsborrow et al., 2004) and updated to include more recent publications and new mapping at the ice sheet scale.

2. A brief review of previous work

Recognition of the importance of ice streams in the LIS was outlined by Hughes et al. (1977) and Denton and Hughes (1981), who depicted a number of ice streams, based mainly on topographic inferences. Dyke (1984), Dyke and Morris (1988) and Sharpe (1988) were among the first to directly link elements of the glacial landform and sedimentary record with fast ice flow and Dyke and Prest (1987a, 1987b) included ice streams in their seminal publications describing the Late Wisconsinan and Holocene history of the LIS based on topographic and sedimentary evidence. Subsequently, Patterson (1997, 1998) compiled a map of known ice streams, and she argued that the lobate southern margin of the LIS was produced by ice streams. These were referred to as terrestrial (i.e. land-terminating) ice streams, which do not have any modern analogues. Moreover, the development of geomorphological criteria to identify palaeo-ice streams (Kleman & Borgström, 1996; Stokes & Clark, 1999) has led to a major growth in the number of hypothesised ice streams (De Angelis & Kleman, 2005, 2007; Ross, Campbell, Parent, & Adams, 2009; Ross, Lajeunesse, & Kosar, 2011; Shaw et al., 2006; Stokes, Clark, & Storrar, 2009). Winsborrow et al. (2004) also provided an inventory and supporting evidence for each of the hypothesised ice streams within the LIS. More recently, new remote sensing products and digital elevation models have permitted the glacial landform mapping at a regional and ice sheet scale (Atkinson, Utting, & Pawley, 2014; Brown, Stokes, & O'Cofaigh, 2011; De Angelis, 2007a; Shaw, Sharpe, & Harris, 2010; Storrar & Stokes, 2007; Trommelen & Ross, 2010), augmenting the Glacial Map of Canada (Prest, Grant, & Rampton, 1968).

Evidence of Laurentide ice stream dynamics has also been found in the ocean sedimentary record in the form of layers of ice-rafted debris (Heinrich layers; Heinrich, 1988). These have been interpreted to record major collapses of the ice sheet (in which ice streaming appears prominent) with inferred effects on the global climate system (Andrews, 1998; Bond et al., 1992; Heinrich, 1988; Rashid & Piper, 2007; Rashid, Saint-Ange, Barber, Smith, & Devalia, 2012). The growth in the identification of ice streams has been mirrored by attempts to test and refine numerical models of their activity in the LIS (Kaplan, Pfeffer, Sassolas, & Miller, 1999; Marshall & Clarke, 1997; Marshall, Clarke, Dyke, & Fisher, 1996; Pfeffer et al., 1997; Stokes & Tarasov, 2010; Tarasov & Peltier, 2004; Winguth, Mickelson, Colgan, & Laabs, 2004).

3. Methods

We define ice streams as discrete arteries of enhanced ice flow bordered by slower moving ice (after Swithinbank, 1954, rephrased). Initially, we collated published literature hypothesising ice stream activity. Ice streams reported in literature were checked and mapped and, in some cases, their outlines and tracks were re-mapped from recent satellite and digital elevation imagery that might not have been available to the original authors (see below). This also ensured homogeneity of the mapped ice streams. A small number of ice streams inferred from types of evidence other than that visible in remotely sensed and digital elevation data were adopted without major modification. In addition, areas that had not been previously systematically mapped for ice streams have been surveyed using remotely sensed-data to ensure completeness in the mapping. This has resulted in the identification of several newly hypothesised ice streams (cited as new mapping on the main map).

Table 1. Data used for the mapping from the landform record.

Data type	Originator	Area used
Landsat Image Mosaic of Canada	Government of Canada; Natural Resources Canada; Earth Sciences Sector; Canada Centre for Mapping and Earth Observation	All LIS bed except of areas with intensive agriculture
Canadian Digital Elevation Data DEM	Government of Canada; Natural Resources Canada; Earth Sciences Sector; Canada Centre for Mapping and Earth Observation	Interior Plains
National Elevation Dataset DEM	U.S. Geological Survey	Great Lakes region
Great Lakes Bathymetry DEM	National Oceanic and Atmospheric Administration, National Geophysical Data Center	Great Lakes region
International Bathymetric Chart of the Arctic Ocean (IBCAO) DEM	Jakobsson, Cherkis, Woodward, Macnab, and Coakley (2000)	Atlantic seaboard
GEBCO_08 Grid DEM	General Bathymetric Chart of the Oceans (GEBCO)	North of 60° N
ArcticNet swath bathymetry DEM	ArcticNet	Channels of the Canadian Arctic Archipelago

Note: DEM, Digital Elevation Model.

A variety of data were used to distinguish ice stream tracks in the glacial landform record and these are listed in Table 1. The northern portion of the mapped area has been surveyed using a false colour composite Landsat image mosaic (Table 1, Figures 2–4). Satellite imagery was less useful along the southern and southwestern LIS margin due to the dominance of the agricultural land. Instead, medium to high-resolution digital elevation models (DEMs, Table 1, Figure 5) were used to map this area. The International Bathymetric Chart of the Arctic Ocean DEM

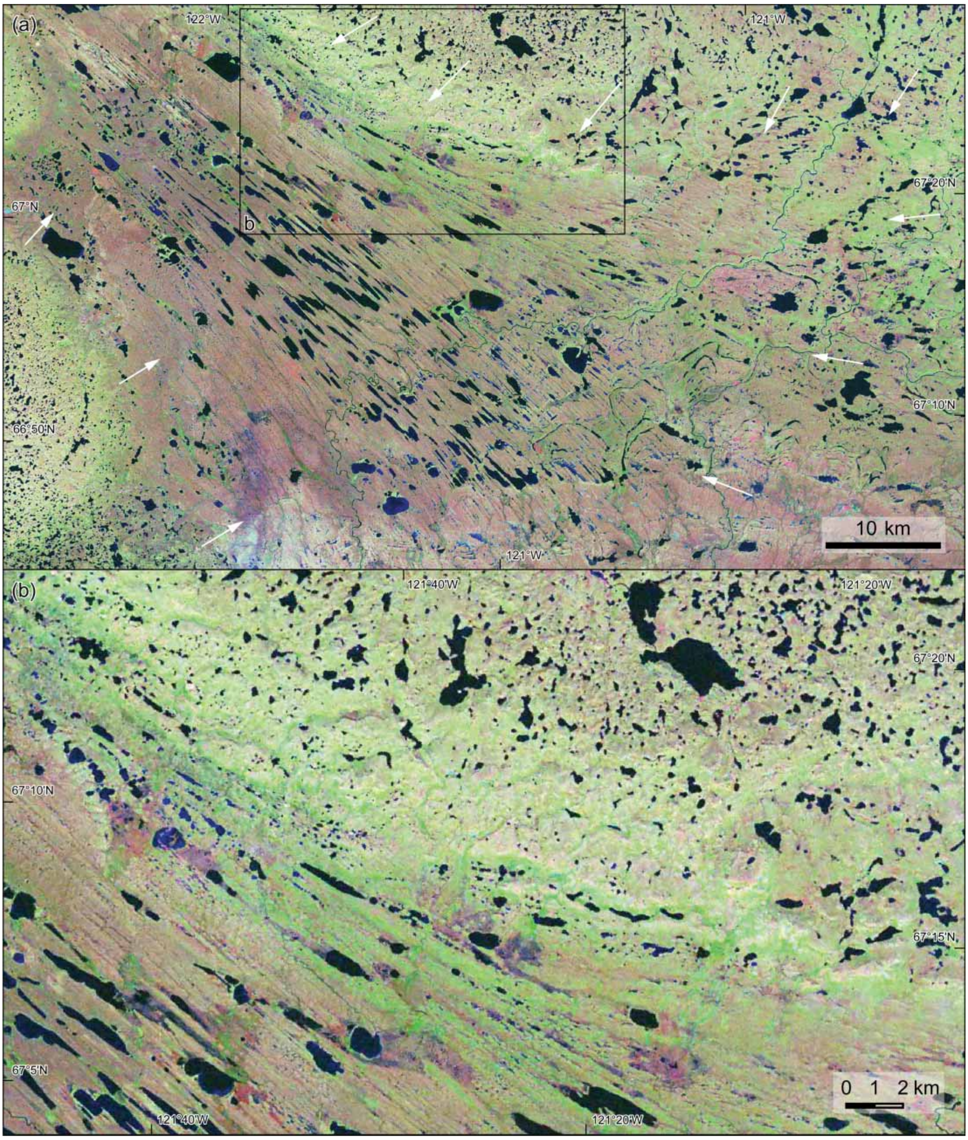

Figure 2. An example of a full bedform imprint from the Haldane Ice Stream (see Figure 1 for location). Panel (a) depicts a large portion of the ice stream track of the Haldane Ice Stream with an onset zone and lateral margins indicated by white arrows. Note the convergent flow pattern and a gradient in bedform attenuation from the ice stream margin toward the centre of the ice stream. (b) Detail of a lateral margin (see panel (a) for location). Lateral shear moraine is identifiable as a lighter-coloured band in the centre of the panel. Ice flow direction is from lower right to upper left in both panels.

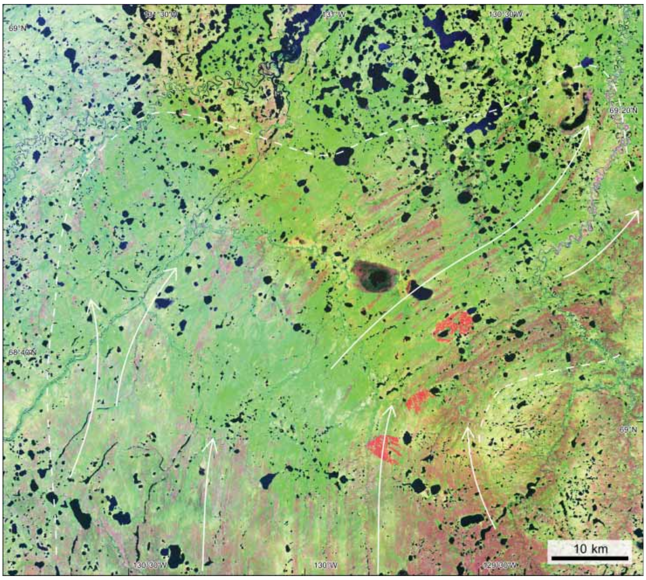

Figure 3. An example of a discontinuous bedform imprint from the downstream portion of the Anderson Ice Stream (see Figure 1 for location). Well-developed streamlining (lower centre) gradually peters out toward the lateral margins and the downstream portion of the Anderson Ice Stream. Bedform directions are indicated by white arrows and approximate limit of a streamlined terrain is indicated by a dashed white line.

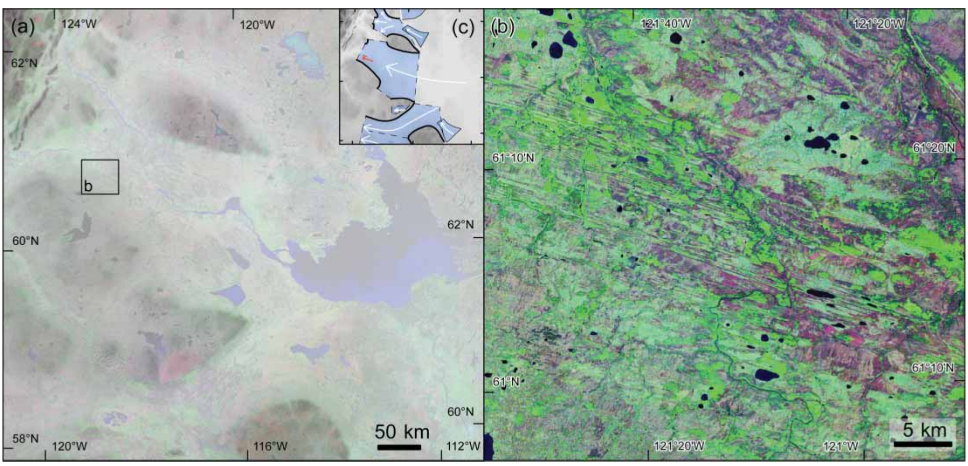

Figure 4. An example of an isolated bedform imprint of the Great Slave Lake Ice Stream. (a) Broad troughs in the north-central portion of the Interior Plains (see Figure 1 for location) seen in a DEM-derived image draped with the Landsat Image Mosaic of Canada. The trough floors are largely devoid of a continuous pattern of glacial lineations. However, isolated patches of extremely well-developed mega-scale glacial lineations occur both on the trough floors – see panel (b), and on the slopes and upper surfaces of the intervening plateaux. Although the glacial troughs define an ice stream configuration in the area (panel c), streamlined terrain on the plateau surfaces (mapped as ice stream fragments) indicates a stage of fast ice flow that was not controlled by topography.

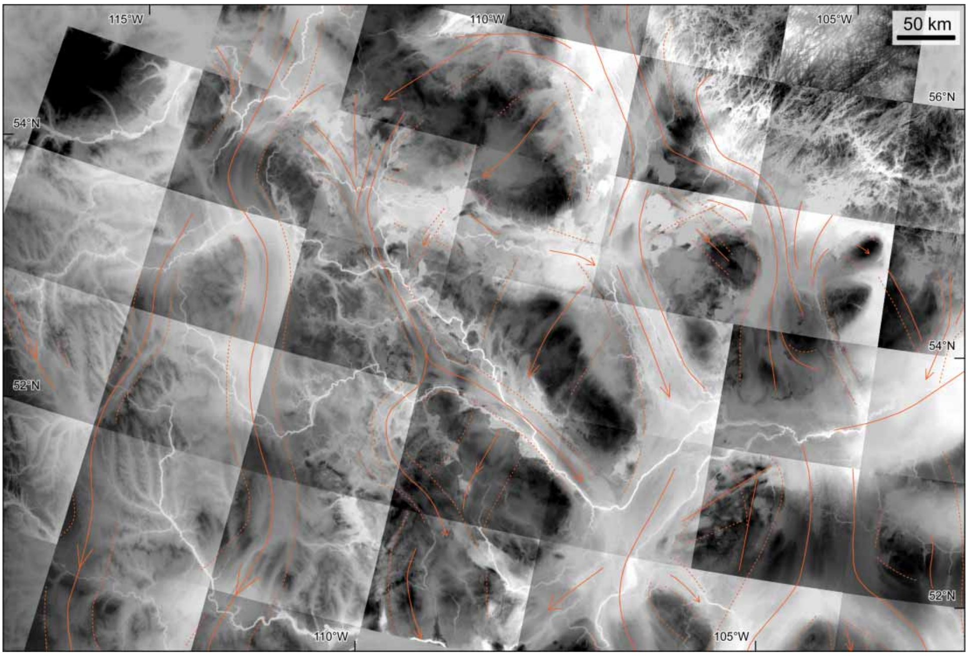

Figure 5. Southern portion of the Interior Plains seen in a mosaic of Canadian Digital Elevation Data tiles (see Figure 1 for location). Displaying hypsography separately for each tile enhances topography in areas with low relief. Networks of ice stream tracks, represented by corridors of smooth topography as well as isolated areas of streamlined terrain can be seen in the data. Lateral margins are drawn by a dotted line (where distinguished) and centre-lines of the ice stream tracks are drawn by full lines.

(Table 1, Figure 6) was used for areas north of the 60th parallel, whereas the continental shelf south of 60° N was mapped from General Bathymetric Chart of the Oceans data (Table 1). High-resolution swath bathymetry has been utilised where available (Table 1, Figure 7).

Ice streams have been mapped based on several types of evidence, which we formally categorise and show on the map. These include the bedform imprint (Figures 2–5 and 7), topographic constraints (Figures 4, 6, and 7) and major sedimentary depo-centres (Figure 6; Batchelor and Dowdeswell, 2013). Other types of evidence include the sedimentary characteristics of subglacial tills or ice rafted debris traced to its sediment sources. Ice streams inferred from their bedform imprint (after (King, Hindmarsh, & Stokes, 2009; Kleman et al., 2006; Stokes, 2002; Stokes & Clark, 1999, 2001, 2002) have been further categorised into three classes: (i) ice streams with a full bedform imprint (Figures 2, 5, and 7), (ii) ice streams with discontinuous bedform imprint (Figures 3 and 5) and, (iii) ice streams with only an isolated bedform imprint (Figure 4). In addition to these an extra class of ice stream fragment has been introduced where isolated evidence of fast ice flow occurs but no inferences can be made about the outline of the zone of fast ice flow (Figures 4 and 5). Ice stream margins, and in some cases ice streams *per se*, have been defined by broad-scale topography, i.e. by the limits (and the existence of) glacial troughs (Figures 4, 6, and 7). Where distinct topography was missing, ice stream margins were either recognised as an edge of the bedform imprint (in some cases constituted by a lateral shear margin moraine; see Figure 2 and (Stokes & Clark, 2002) or drawn as undefined (Figure 3). Multiple types of evidence have been found for some ice streams (Figures 4 and 7) whereas other mapped ice streams are only based on one type of evidence (Figures 2 and 3). The strength of the evidence therefore varies and while some ice streams are documented by a robust record, the existence of others is more speculative.

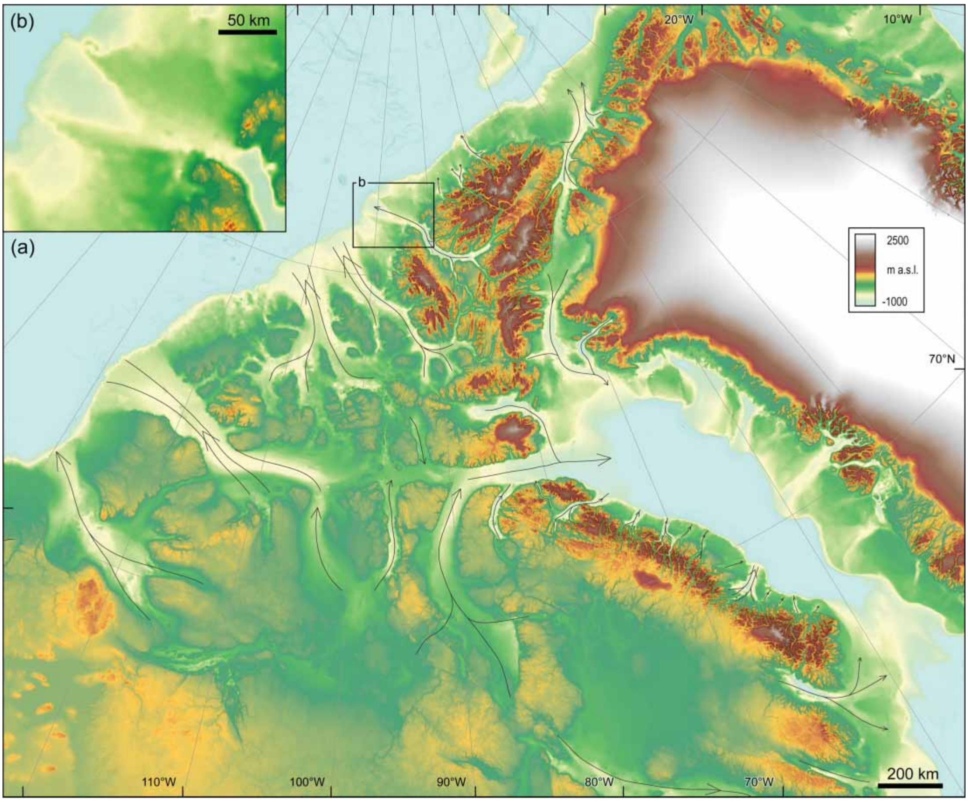

Figure 6. (a) The Canadian Arctic seen in IBCAO topographic data (see Figure 1 for location). Ice streams inferred from wide-scale topography are indicated. Notice the prominent shelf-crossing troughs, overdeepening of some of the channel and fjord floors, as well as sediment bulges (sedimentary depo-centres) built on the edge of the continental shelf. In the case of Nansen Sound (black rectangle), the cross-shelf trough is marked by extensive ridges. See panel (b) for a detail view.

Although our map represents the most complete to date, it is important to acknowledge that some ice streams may have operated, but their evidence has not been preserved. This may be especially true for short-lived ice streams flowing over resistant bedrock (Punkari, 1995; Roberts, Long, Davies, Simpson, & Schnabel, 2010).

4. Mapping results

The map contains 117 ice streams, which is almost three times more than previous inventories. These vary in size and shape, with some draining large portions of the ice sheet and others being rather minor features, typically draining ice through high-relief coastal areas. Note that we make no inferences on the timing of ice stream operation because very few of the mapped ice streams have any chronological control. However, it is clear that the mapped ice stream tracks represent a time-transgressive imprint of evolving ice stream trajectories, i.e. they cannot have all operated at once. Nevertheless, some broad spatial patterns emerge.

The northernmost part of the LIS covering the Canadian Arctic Archipelago and including the Innuitian Ice Sheet (Figure 1) was drained by a network of ice streams occupying the channels dividing the archipelago's islands and peninsulas. The location and pattern of these ice streams

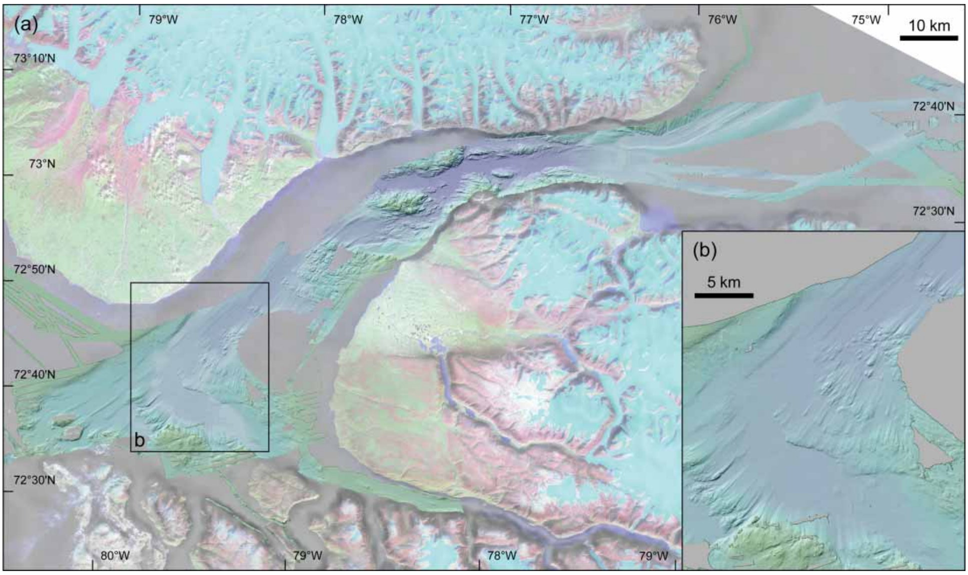

Figure 7. Eclipse Sound at the north coast of Baffin Island (see Figure 1 for location) – a deep sound that forms at a junction of numerous fjords. (a) a DEM-derived image draped with the Landsat Image Mosaic of Canada complemented by high-resolution swath bathymetry data that display well-developed mega-scale glacial lineations on the floor of the sound. See panel (b) for a detail of the onset zone of the streamlined terrain.

share characteristics with the Siple Coast ice streams of the West Antarctic Ice Sheet (Bennett, 2003; De Angelis, 2007b; Hughes, 1977). The northwestern, western and southwestern margin of the LIS displayed a more complex pattern of sinuous, sometimes cross-cutting, flow trajectories over a relatively flat bed that likely came into operation during different periods of ice sheet growth and decay. Moreover, these were predominantly land-terminating (terrestrial) ice streams. Large terrestrial ice streams also occupied the basins of the Great Lakes at the southern margin of the ice sheet. Further east, the continental shelf fringing the northeastern USA, Atlantic Canada and Labrador hosted a number of ice streams draining into the Atlantic Ocean. Ice streams have also been identified in areas that were close to the centre of a fully grown LIS. These ice streams presumably operated successively during deglaciation when the ice margin gradually retreated into the areas of the main domes in Keewatin, Labrador and Foxe Basin (Figure 1).

5. Conclusions

A map depicting palaeo-ice streams of the LIS has been produced using previously published hypotheses of their activity, together with new mapping from satellite imagery and digital elevation models, both onshore and offshore. In total, 117 ice streams have been identified, based on a variety of evidence and with some comparatively robust and others more speculative. The map only indicates the spatial distribution of ice streams within the LIS, without providing constraints on their timing of operation. Based on our review of the evidence (see list of sources on the main map), it is likely that the majority relate to the Late Wisconsinan, but we cannot rule out the possibility that some evidence has been preserved from pre-Late Wisconsinan ice sheets. Dating of these palaeo-ice streams is an obvious task for future research. This map, combined with better dating of ice stream operation, will allow for an improved understanding of LIS dynamics and its links to the atmosphere-ocean system. Such reconstructions will also extend the temporal record of ice stream activity, which is currently biased toward short-term observations of modern-day ice sheets.

Software

The mapping was carried out using Esri ArcGIS 10.1. The GEBCO data (Table 1) were exported for use with ArcGIS using the GDA Software Interface provided with the data. The Google Maps platform was used for displaying the high-resolution swath bathymetry data (Table 1). The final layout of the map was produced in Adobe Illustrator CS4.

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Supplemental data

Two shapefiles of LIS ice streams are enclosed: one with simplified polygons defining ice stream tracks and the other with polylines depicting lateral margins and ice flow directions. Supplemental data for this article can be accessed here. [10.1080/17445647.2014.912036]

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