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A map of large Canadian eskers from Landsat satellite imagery

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Meltwater drainage systems beneath ice sheets are a poorly understood, yet fundamentally important environment for understanding glacier dynamics, which are strongly influenced by the nature and quantity of meltwater entering the subglacial system. Contemporary sub-ice sheet meltwater drainage systems are notoriously difficult to study, but we can utilise exposed beds of palaeo-ice sheets to further our understanding of subglacial drainage. In particular, eskers record deposition in glacial drainage channels and are widespread on the exposed beds of former ice sheets. This paper presents a 1:5,000,000 scale map of >20,000 large eskers (typically > 2 km long) deposited by the Laurentide Ice Sheet (LIS), mapped from Landsat imagery of Canada, in order to establish a dataset suitable for analysis of esker morphometry and drainage patterns at the ice sheet scale. Comparisons between eskers mapped from Landsat imagery and aerial photographs indicate that, in most areas, approximately 75% of eskers are detected using Landsat. The data presented in this map build on and extend previous work in providing a consistent map of an unprecedented sample of eskers for quantitative analysis. It offers an alternative perspective on the problems surrounding ice-sheet meltwater drainage and can be used for: (i) detailed investigations of esker morphometry and distribution from a large sample size; (ii), testing of numerical models of meltwater drainage routing that predict esker characteristics (e.g. channel spacing, sinuosity), (iii) assessment of the factors that control esker location and formation; and (iv), a refined understanding of ice margin configurations during retreat of the LIS.

Keywords: eskers; glaciofluvial; meltwater; ice sheet; Laurentide; Canada

1. Introduction

Subglacial meltwater drainage systems are intimately linked with ice sheet dynamics (e.g. Boulton, Dobbie, & Zatsepin, 2001; Schoof, 2010; Stearns, Smith, & Hamilton, 2008). Given the increase in meltwater production as a result of increased warming in polar regions (e.g. Mernild, Mote, & Liston, 2011; Rignot, Velicogna, van den Broeke, Monaghan, & Lenaerts, 2011), a large amount of research has recently been directed at furthering our understanding of how the routing and arrangement of meltwater interacts with ice flow (e.g. Catania & Neumann, 2010; Parizek, Alley, Dupont, Walker, & Anandakrishnan, 2010; Schoof, 2010; Sundal et al., 2011). However, our current understanding of meltwater drainage systems beneath the Antarctic and Greenland ice sheets is limited by the difficulty in accessing their

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subglacial environments. To date, techniques designed to investigate the configuration of subglacial meltwater drainage (e.g. channelised versus distributed systems: see Mair, Nienow, Sharp, Wohlleben, & Willis, 2002; Walder & Fowler, 1994) are mostly remote or indirect and include, for example, radar sounding (e.g. Carter, Blankenship, Young, & Holt, 2009), dye-tracing (e.g. Schuler & Fischer, 2009), remote sensing (e.g. Fricker, Scambos, Bindschadler, & Padman, 2007) and/or numerical modelling (e.g. Lewis & Smith, 2009). An alternative approach is to use the geomorphological record of palaeo-ice sheets as an analogue for the meltwater systems of contemporary ice sheets (e.g. Aylsworth & Shilts, 1989a; Boulton, Hagdorn, Maillot, & Zatsepin, 2009; Delaney, 2001; Mäkinen, 2003; Margold & Jansson, 2012; Punkari, 1997). The most prolific landforms recording channelised meltwater activity are eskers: elongate, straight-to-sinuous ridges composed of glaciofluvial sand and gravel, formed by deposition in (predominantly subglacial) drainage conduits (e.g. Brennand, 2000; Price, 1969; Shreve, 1985a; Warren & Ashley, 1994).

The largest assemblage of eskers occurs on the bed of the former North American Ice Sheet complex, which covered most of Canada (Dyke & Prest, 1987; Dyke, Moore, & Robertson, 2003; Prest, Grant, & Rampton, 1968). Although there have been numerous investigations of individual esker ridges (e.g. Banerjee & McDonald, 1975; Brennand, 2000; Burke, Brennand, & Perkins, 2012; Gorrell & Shaw, 1991) and/or small regions of eskers from this ice sheet complex (e.g. in the form of surficial geology mapping; Aylsworth & Shilts, 1989a, 1989b; Hooke & Fastook, 2007; Menzies & Shilts, 1996; Shilts, 1984), much less research has focused on larger-scale patterns at the ice sheet scale, although there are notable exceptions. It is clear that this approach has much potential to lead to major advances in our understanding of esker formation and meltwater drainage (see Aylsworth & Shilts, 1989a; Clark & Walder, 1994). With this in mind, this paper builds on a significant legacy of previous mapping in Canada (e.g. Armstrong & Tipper, 1949; Aylsworth & Shilts, 1989b; Fulton, 1995; Klassen, Paradis, Bolduc, & Thomas, 1992; Prest et al., 1968; Shetsen, 1987, 1990) to present a new map of unprecedented detail (>20,000 eskers; see Supplementary Material). Although beyond the remit of the present paper, it is anticipated that the map will be used to improve our understanding of the formation of eskers and subglacial meltwater drainage at the ice sheet scale. Our aim is to provide a foundation for future work on the morphometry and spatial characteristics of eskers (similar to drumlins: see e.g. Clark, Hughes, Greenwood, Spagnolo, & Ng, 2009), as well as the factors controlling how and where they form in relation to ice margin retreat, with a view to ultimately providing a more robust model of how subglacial meltwater drainage systems operate on a large scale.

2. Previous mapping and purpose of the map

2.1. *Previous mapping*

Given that numerous eskers have already been identified and mapped in Canada, it is necessary to briefly outline previous work and explain the purpose of the map presented in this paper. As noted above, eskers have been the focus of detailed mapping for several decades, most notably in the numerous Geological Survey of Canada (GSC) Surficial and Quaternary Geology maps (e.g. Armstrong & Tipper, 1949; Aylsworth & Shilts, 1989b; Gravenor, 1959; Henderson, 1977; Veillette, 1987; Ward, Dredge, & Kerr, 1997). Many of these maps were created from aerial photograph analysis, often supplemented by fieldwork, and provide a high level of detail. However, this detailed approach necessitates that only relatively small regions can be mapped, although there are some notable exceptions of larger regions (e.g. Aylsworth & Shilts, 1989b).

Much of the early work was subsequently compiled on the Glacial Map of Canada (GMoC: Prest et al., 1968). This impressive synthesis and its more recent derivatives (e.g. Fulton, 1995)

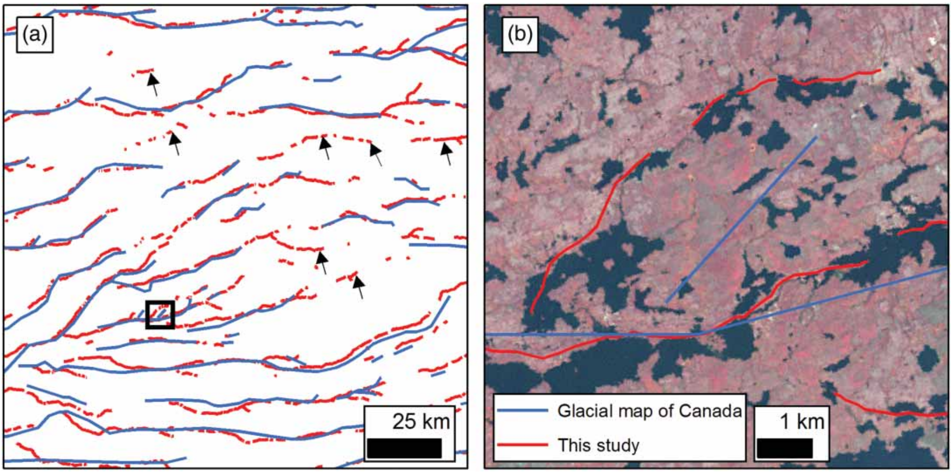

Figure 1. Eskers mapped in the GMoC and in the this paper. (a) Examples of eskers mapped in this paper but not mapped in the GMoC are indicated by arrows. The box indicates the area enlarged in B. See Figure 5 for location. (b) Landsat image (4, 3, 2) showing the cartographic simplification of eskers in the GMoC. Note that the gaps in the eskers are not represented in the GMoC and the locations of the esker ridges are relatively imprecise.

remains the only map showing the distribution of eskers for all of Canada. It shows a total of 7,026 eskers but the GMoC was printed at a scale of 1:5,000,000 and, as such, eskers were generalised from more detailed mapping, which appears to have necessitated a cartographic simplification of their form (Figure 1), e.g. straightening their plan form and exaggerating their continuity (perhaps ignoring small gaps). Thus, although these data are now available electronically (from http://geoscan.ess.nrcan.gc.ca/), extraction of measurements of esker morphometry may be difficult (e.g. sinuousity, which is an important parameter for modelling velocity through subglacial tunnels: Schuler & Fischer, 2009).

It is also the case that recent mapping (e.g. Aylsworth & Shilts, 1989b; Margold, Jansson, Kleman, & Stroeven, 2011; Shetsen, 1987, 1990; Veillette, 1987; Ward et al., 1997) portrays eskers in more detail than the GMoC and has sometimes identified eskers that may have been missed on the GMoC. In theory these more recent maps could be compiled and added to the GMoC but a potential draw-back is that these maps have been produced by different workers and are unlikely to be consistent in terms of their accuracy, scale or cartographic representation, notwithstanding differences in interpretation and the fact that some regions remain largely unmapped. Thus, our approach is to use these maps as a valuable ‘ground-truth’ and guide, but we chose to identify and map eskers from a consistent data source, in this case Landsat Satellite imagery (see Methods). As noted, a further advantage of our remote sensing approach is that all the data are ingested directly into a geographical information system (GIS) from which quantitative data can be easily extracted. This is an important advance on previous work and we now briefly outline the purpose of the map.

2.2. *Purpose of the map*

The purpose of the map is to fill a niche between high resolution maps of small areas, which provide a high level of detail but consequently lack the spatial coverage and sample size for assessment of regional/continental scale patterns; and the GMoC, which provides a continental

Table 1. Locations used to compare mapping from Landsat ETM+ imagery with mapping from high resolution aerial photographs. Esker detection rates in the Landsat ETM+ imagery, compared with the aerial photographs, is estimated and given as a percentage of total length. Locations are numbered in correspondence with Figure 5.

Location	No. and type of images (approximate resolution)	Area covered (km^2)	Number of eskers mapped on ETM+ imagery	Total length of eskers mapped on ETM+ imagery (km)	Number of additional eskers mapped	Total length of additional eskers mapped (km)	Esker detection rate in ETM+ imagery (%)
(1) Dubawnt Lake Area, Nunavut	847 aerial photographs (~2–3 m)	41,287	158	1138	57	186	85.91
(2) South and Central Alberta	30 aerial photomosaics (~5 m)	62,142	18	81	221	325	19.95
(3) Senneterre, Québec	449 aerial photographs (~2–3 m)	16,626	111	322	156	295	52.13
(4) Lac Aigneu, Québec	230 aerial photographs (~2–3 m)	12,981	46	137	63	99	58.02
(5) Lac Mistanukaw area, Québec	280 aerial photographs (~2–3 m)	14,131	260	555	206	265	67.61
(6) McCann Lake area, Northwest Territories	538 aerial photographs (~2–3 m)	11,511	215	863	131	120	87.76
(7) Gander Lake area, Newfoundland	373 aerial photographs (~2–3 m)	16,585	20	34	26	34	49.59
Total	2717 aerial photographs; 193 aerial photomosaics	175,263	810	3099	639	1002	75.57

coverage, but which necessitated a degree of cartographic generalisation. The result is a map that portrays >20,000 individual eskers ridges/segments, which is around three times the number on the GMoC. This increased number largely results because we refrain from interpolating gaps between separate esker ridges that are longitudinally aligned, but also because we identify some eskers that do not appear on the GMoC (Figure 1). Thus, it is anticipated that this map has the potential to advance understanding of ice sheet hydrology in four main areas, which are briefly highlighted below:

2.2.1. *Detailed investigations of esker morphometry and distribution from a large sample size*

The burgeoning availability of remotely sensed imagery and digital elevation data has increased capacity to map populations of glacial landforms at hitherto unprecedented sample sizes (Clark et al., 2009; Spagnolo, Clark, Hughes, Dunlop, & Stokes, 2010; Spagnolo, Clark, Hughes, & Dunlop, 2011; Spagnolo, Clark, & Hughes, 2012). This has generated statistically representative sample sizes of 10s of thousands of landforms (e.g. drumlins, ribbed moraine) which can be used to gain insight into their formation. For example, large sample sizes of drumlin measurements have been used to identify potential scales of bedform growth (Clark et al., 2009) and demonstrate that their size-frequency distribution is exponential, which is a potentially powerful constraint on numerical models of drumlin formation (Hillier, Smith, Clark, Stokes, & Spagnolo, 2013). A similarly large and statistically robust dataset of esker characteristics is currently not available and the data presented in the map (which will be made available as ArcGIS 'shapefiles' independently at a later date) fills this important gap and can be used to address important research questions, such as: what are the statistical distributions of esker length, sinuosity, density and spacing? How do these characteristics vary on different lithologies or during ice margin retreat? How do esker patterns evolve during deglaciation?

2.2.2. *Rigorous testing of numerical models of meltwater drainage routing*

The statistically robust data described above can also be used as a powerful constraint for numerical modelling. For example, large sample sizes of ribbed moraine measurements have been used to test numerical models of their formation (Dunlop, Clark, & Hindmarsh, 2008). As noted above, such data have hitherto not been available for eskers and the data presented in this map can be used to test numerical models that, for example, predict esker spacing (Boulton, Lunn, Vidstrand, & Zatsepin, 2007a, 2007b; Boulton et al., 2009; Hewitt, 2011) or make assumptions about, and parameterise, channel sinuosity (Schuler & Fischer, 2009). A key advantage of our dataset is that these numerical models can be tested against representative data from over 20,000 eskers, rather than being subject to the vagaries of smaller sample sizes. Indeed, the continental scale of our quantitative data is well suited to testing the subglacial routing of water predicted by large-scale ice sheet models (e.g. Le Brocq, Payne, Siegert, & Alley, 2009; Tarasov, Dyke, Neal, & Peltier, 2012; Tarasov & Peltier, 2006).

2.2.3. *Assessment of the factors that control esker location and formation*

Previous work has demonstrated that the large scale pattern of eskers can be used to gain insights into the factors that control where and when they occur under an ice sheet (Aylsworth & Shilts, 1989a; Clark & Walder, 1994; Menzies & Shilts, 1996; Shilts, Aylsworth, Kaszycki, & Klassen, 1987). Various (and sometimes inter-relating) factors have been suggested as being an important control on the location and formation of eskers. These include ice thickness (Shreve, 1972, 1985a, 1985b); sediment supply (Aylsworth & Shilts, 1989a); underlying geology (Clark & Walder,

1994) and groundwater characteristics (Boulton et al., 2009). Some of these controls have gained support from large-scale mapping on the GMoC (e.g. Aylsworth & Shilts, 1989a; Clark & Walder, 1994), but most are explored using smaller samples of eskers from specific regions of palaeo-ice sheets (Boulton et al., 2009; Shreve, 1985a). Our new data and map will add to this body of work in being able to demonstrate quantitatively how and where the distribution and pattern of eskers changes in relation to the ice sheet or sub-surface properties.

2.2.4. *A refined understanding of ice margin configurations during retreat of the Laurentide Ice Sheet*

Detailed mapping of eskers can be used to reconstruct ice margin retreat patterns (e.g. Clark, Hughes, Greenwood, Jordan, & Sejrup, 2012) and the GMoC and its derivatives (e.g. Fulton, 1995) have been used extensively, together with dating constraints, to reconstruct an impressive ice margin chronology for the North American Ice Sheet complex (Dyke et al., 2003). Although it is not the primary purpose of the present map, the increased density of eskers on our map may help to subtly refine aspects of the existing ice margin retreat pattern for North America.

3. Methods

Mapping glacial geomorphological features at the ice sheet scale necessitates a compromise in the level of detail which can be mapped because it is not efficient, financially or practically, to map entire ice sheet beds by field survey or analysis of aerial photographs. In this study, the majority of mapping was therefore based on the identification of eskers from Landsat 7 Enhanced Thematic Mapper (ETM)+ imagery. Landsat ETM+ imagery was chosen because it is freely available and has excellent spatial coverage and relatively high resolution (~30 m and ~15 m in the panchromatic band). This makes it an ideal resource for mapping large-scale glacial geomorphology (Clark, 1997).

3.1. *Data sources, mapping and map production*

A total of 678 Landsat images were downloaded from the Global Land Cover Facility (GLCF; www.landcover.org) in orthorectified GeoTIFF format. All images were projected into the relevant Universal Transverse Mercator (UTM) zones, referenced to the World Geodetic Datum (WGS84).The panchromatic band (band 8) provided higher resolution imagery which was used to aid detection and mapping. In some small areas (see Figure 2), no Landsat 7 ETM+ data were available and Landsat 5 Thematic Mapper (TM) images (comparable to Landsat 7 ETM+ images, with the exception of the absence of the panchromatic band) were used to fill these gaps. Figure 2 shows the individual images used and indicates the areas where only TM data were available.

The workflow involved in the production of the map is outlined in Figure 3. Firstly, images were visualised at a variety of scales and using different band combinations, but the most useful were typically a 4, 3, 2 (red, green, blue) or 7, 5, 2 composite. Eskers were then identified according to the criteria set out by Margold and Jansson (2012, p. 2364) who described their morphology as well-defined sub-linear ridges often accompanied by lakes and kettle holes that are often marked by shadows and/or by a different spectral signature due to the presence of glaciofluvial sediments (sands and gravels) and changes in soil moisture/vegetation cover. Esker crestlines were digitised as polylines in shapefile format in ArcGIS 10. To ensure minimal spatial distortion, they were mapped in separate shapefiles, corresponding to the local UTM zone of the Landsat

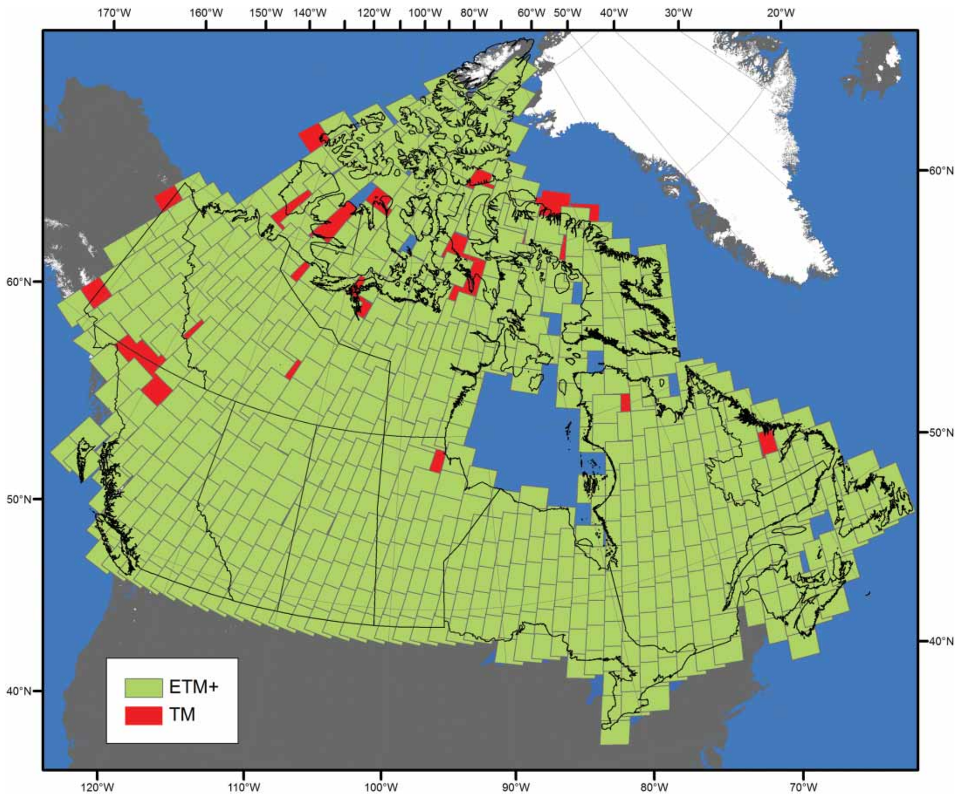

Figure 2. Map showing coverage of Landsat ETM+ Landsat TM imagery. Each image covers an area of approximately 125 km × 125 km.

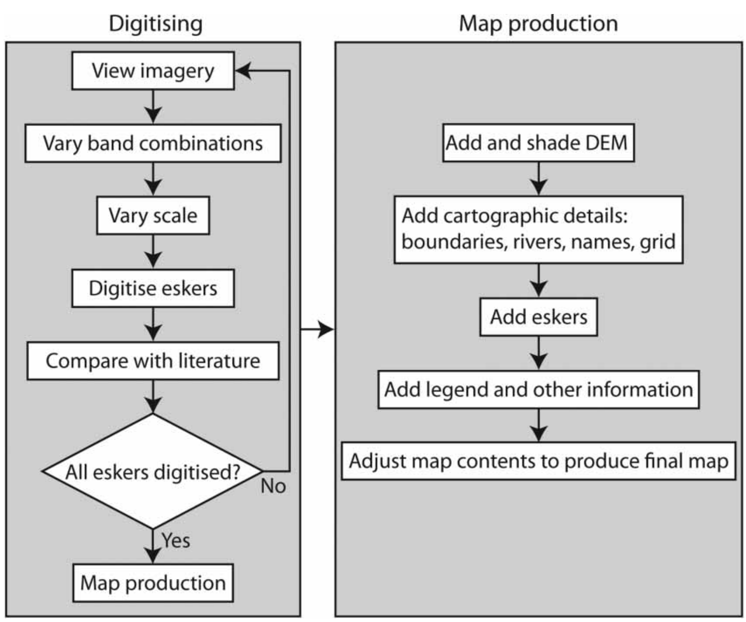

Figure 3. Flow chart showing the two stages of map development: digitisation and production of the final map.

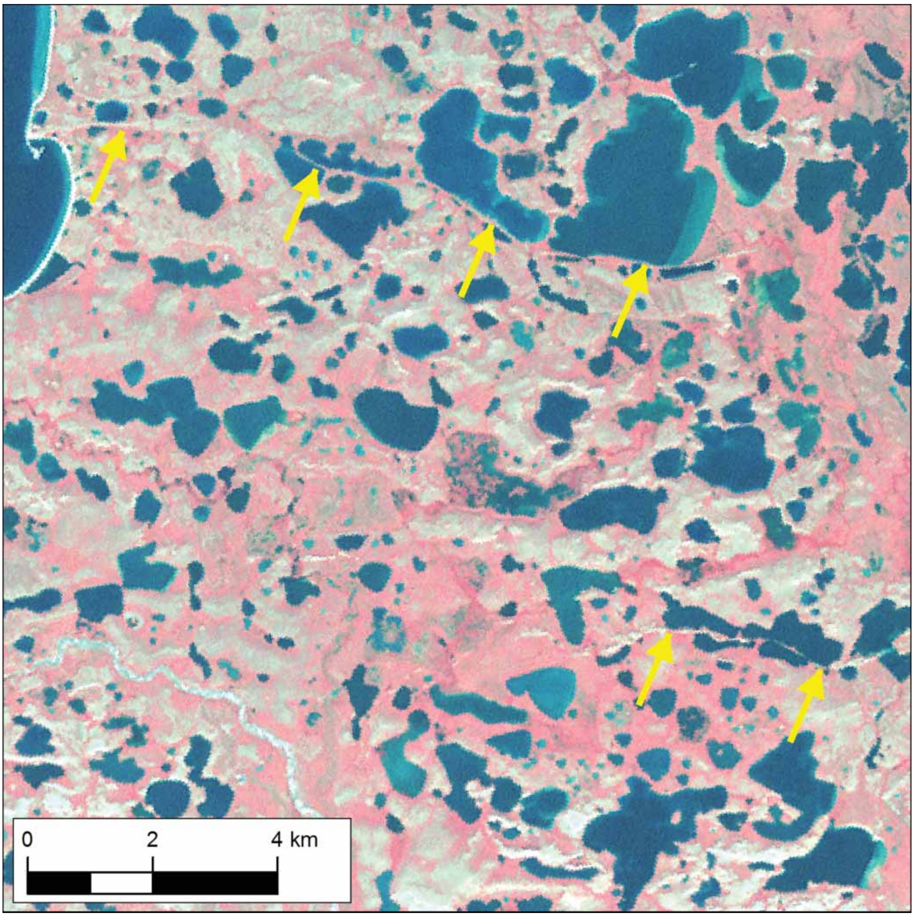

Figure 4. Two prominent eskers in Northwest Territories (also mapped as eskers by Brown et al., 2011). Note that these features were not included in the Glacial Map of Canada, in which the area was broadly defined as 'hummocky terrain' (Prest et al., 1968). See Figure 5 for location.

imagery. The shapefiles were then merged in ArcGIS 10 to produce a single shapefile, projected to the Canadian Lambert Conformal Conical projection, which was used for the final map.

Eskers were identified and mapped at a variety of scales. In the 30 m resolution imagery, eskers were typically identified at 1:80,000 and digitised at 1:40,000, to ensure that crestlines were portrayed as accurately and precisely as possible. In the panchromatic band (15 m resolution), smaller eskers were often identifiable at 1:30,000 scale. In some instances, features such as moraine ridges may be indistinguishable from eskers in remotely sensed images and mapping was therefore checked, where possible, against published geomorphological maps and other sources. In some instances, features have been mapped as eskers by some and moraine ridges by others (see Figure 4).

The Digital Elevation Model (DEM) used as a background for the map was produced from the GTOPO30 dataset (available from http://eros.usgs.gov), which has a spatial resolution of 30 arc-seconds. Contemporary ice cover data shown on the map were downloaded from the Atlas of the Cryosphere (available from http://nsidc.org/data/atlas/) and the Randolph Glacier Inventory (Arendt et al., 2012). Outlines of major lakes used for illustration were obtained from the North American Atlas (available from http://www.nationalatlas.gov).

3.2. *Errors and completeness*

Despite its advantages, a potential limitation of using satellite imagery is that some small features may go undetected (Margold & Jansson, 2012; Smith & Wise, 2007; Smith, 2011). Thus, in order to quantify this uncertainty and verify the detection of eskers on the Landsat imagery, seven small regions were also mapped from high resolution (~2–3 m) aerial photographs. This included 2,717 aerial photographs (and 30 aerial photomosaics), covering approximately 175,000 km^2 in seven contrasting locations (Figure 5). The locations were selected from a variety of situations: shield *versus* non-shield areas; areas significantly altered by human activity; zones of inferred fast *versus* slow palaeo-ice flow; areas of high/low esker density; and areas observed to be problematic when observed in Landsat imagery (Figure 5).The results of the aerial photograph comparison are presented in Table 1 and indicate that areas containing a high density of eskers are mapped the most completely on the Landsat imagery (see Figure 6). For example, detection rates of 86–88% are found for eskers emanating from the former Keewatin Ice Divide (areas 1 and 6: Figure 5) and indicate that the mapping from Landsat imagery is likely to be representative and captures most esker systems (Figure 7). Where there are fewer eskers, or in areas affected by human activity such as the St. Lawrence valley (area 3: Figure 5) and southern Alberta (area 2: Figure 5), the detection rate is lower, as would be expected for significantly modified terrain or regions containing less well preserved features. Closer inspection of the eskers that were missed by the Landsat imagery but detected on the aerial photographs (n = 639) shows

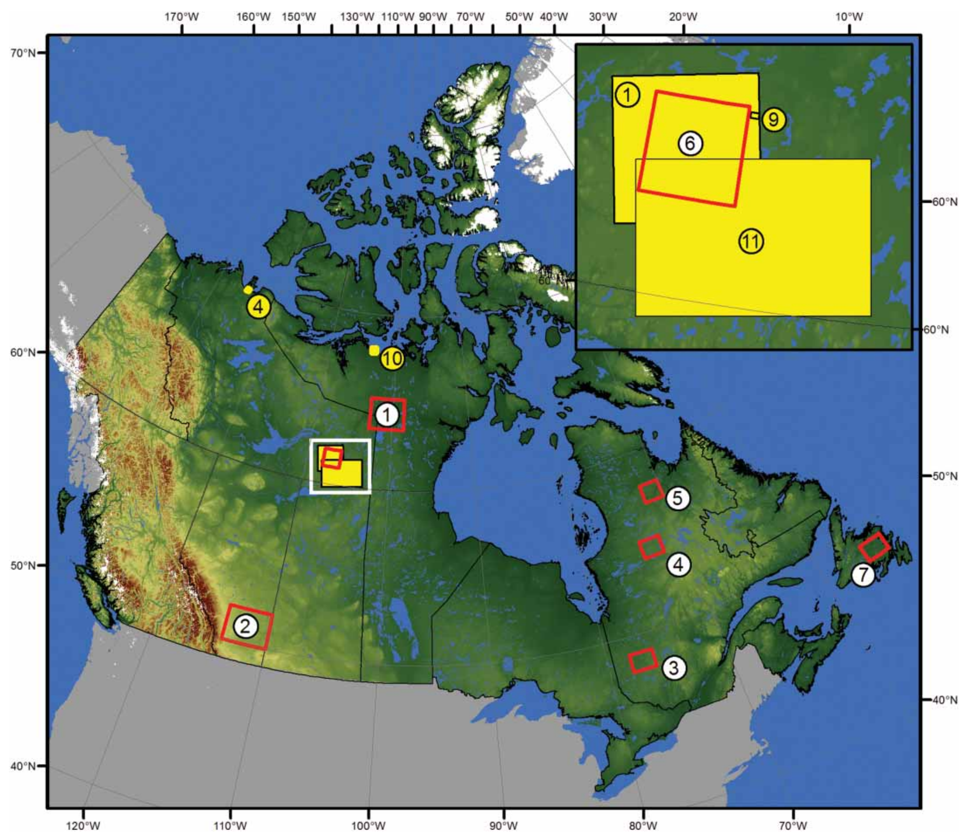

Figure 5. Locations of Figures 1, 4, 9, 10 and 11 (yellow) and areas mapped from aerial photographs (red boxes, white circles). See Table 1 for data. Inset is an enlargement of the area indicated by the white box.

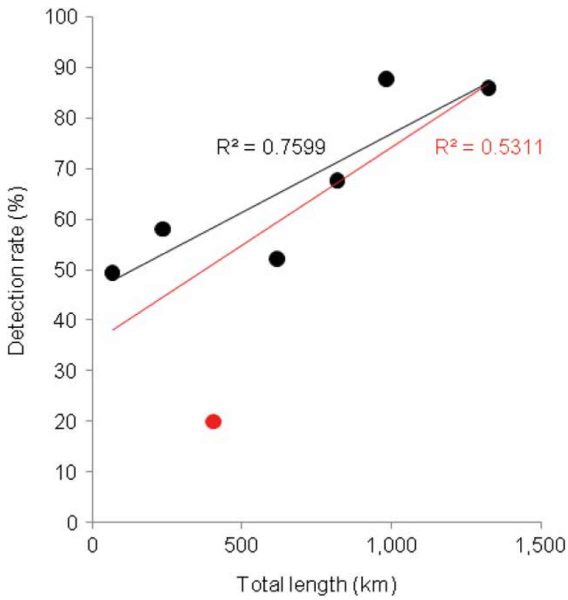

Figure 6. Total length of eskers from both Landsat and aerial photograph analysis in each study area, plotted against the observed detection rate. The red marker indicates the study area in southern Alberta (area 2: Figure 5), where the detection rate is significantly lower due to large-scale human activity. The red trendline takes this point into account, whereas the black trendline corresponds to the other six areas only. Areas containing a high proportion of eskers tend to result in the most reliable mapping.

that the vast majority (81%) are <2 km in length (see Figure 8). Thus, the map should be seen as a representation of large eskers (> 2 km) that captures the major drainage channels of the ice sheet. Finally, it should be noted that eskers exist in parts of the United States of America formerly occupied by the Laurentide Ice Sheet, but our mapping extends only to the Canadian border, partly because eskers are more difficult to detect in southern Canada and northern USA due to anthropogenic landscape modification. Thus, the map represents a systematic dataset of large (>2 km long) esker patterns at the ice sheet-scale, rather than a map of every esker on the ice sheet bed.

4. Results

4.1. *Esker morphometry*

A total of 20,186 individual esker ridges were mapped from Landsat ETM+ imagery of Canada, which is almost three times as many as appear on the Glacial Map of Canada (7,026). As noted above, the increased number largely reflects our conservative mapping approach, in that we refrained from drawing separate esker ridges as a single line feature. This is because it was not always possible to deduce whether a gap resulted from post-glacial modification/erosion or whether it represented a genuine lack of deposition within the palaeo-channel. Notwisthstanding this, we also identified numerous eskers that were not mapped on the GMoC (see Figure 1). The data will be released independently in shapefile format at a later date.

The map reveals that the morphology (e.g. length, sinuosity and spacing) of eskers varies throughout Canada and several types of esker were observed. Often, eskers displaying similar morphology occur together or are seen to merge into other types of esker. Following journal

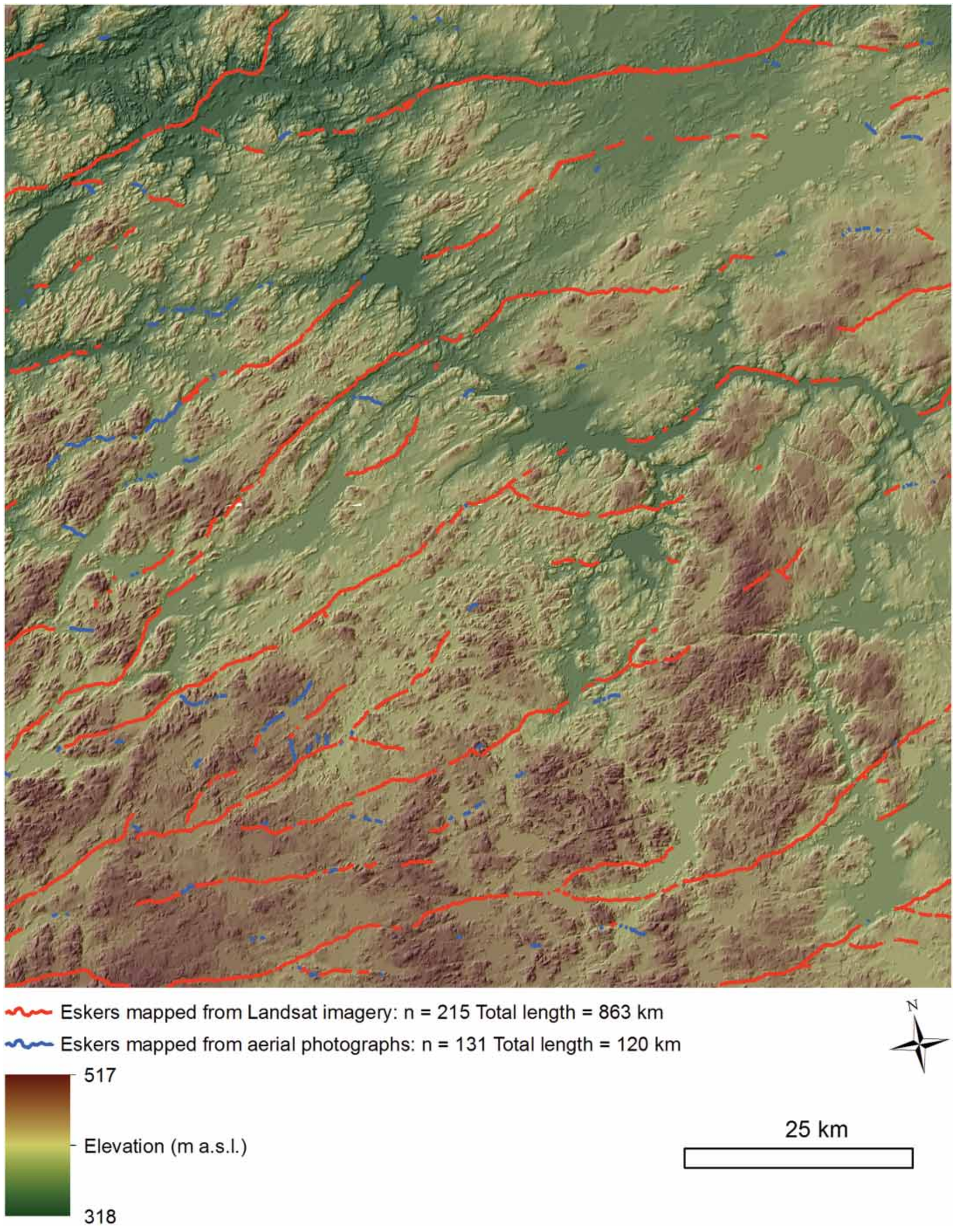

Figure 7. Eskers mapped from Landsat ETM+ imagery and aerial photographs in the McCann Lake area, Northwest Territories. See Figure 5 (area 6) for location.

guidelines, we refrain from an in-depth analysis in this paper, but some commonly observed variants are briefly outlined below.

The most common (and the classical) type of esker is a single, well-defined ridge displaying a straight-to-sinuous morphology. The area around the Keewatin Ice Divide provides exemplars of these eskers, where they are pervasive and are very well preserved (Figure 9). Some individual esker ridges extend without gaps for several tens of kilometres. The longest continuous ridge

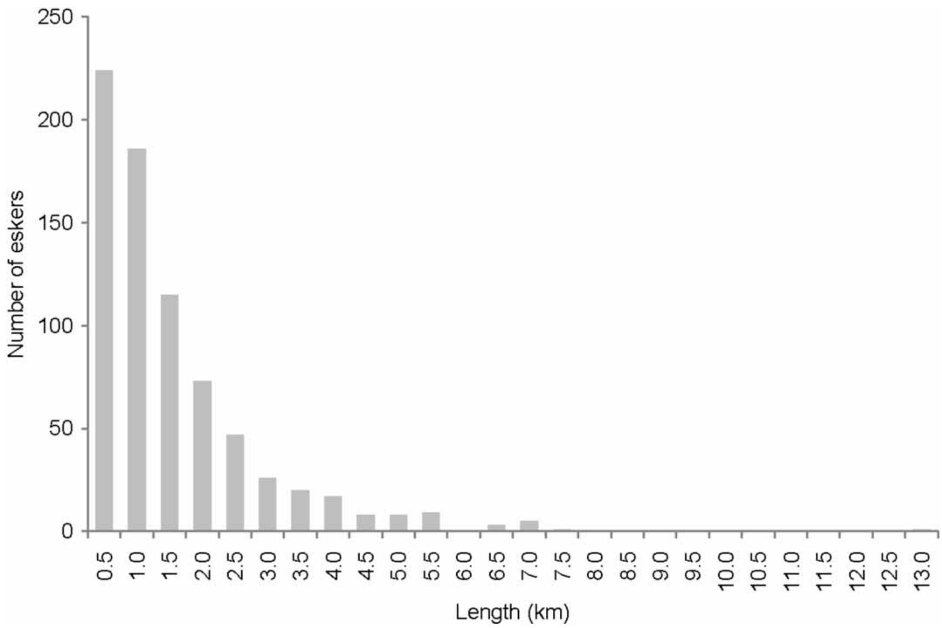

Figure 8. Histogram (intervals of 0.5 km) of the length of eskers detected in aerial photographs but not in Landsat imagery. Note that the majority of eskers are less than 2 km long.

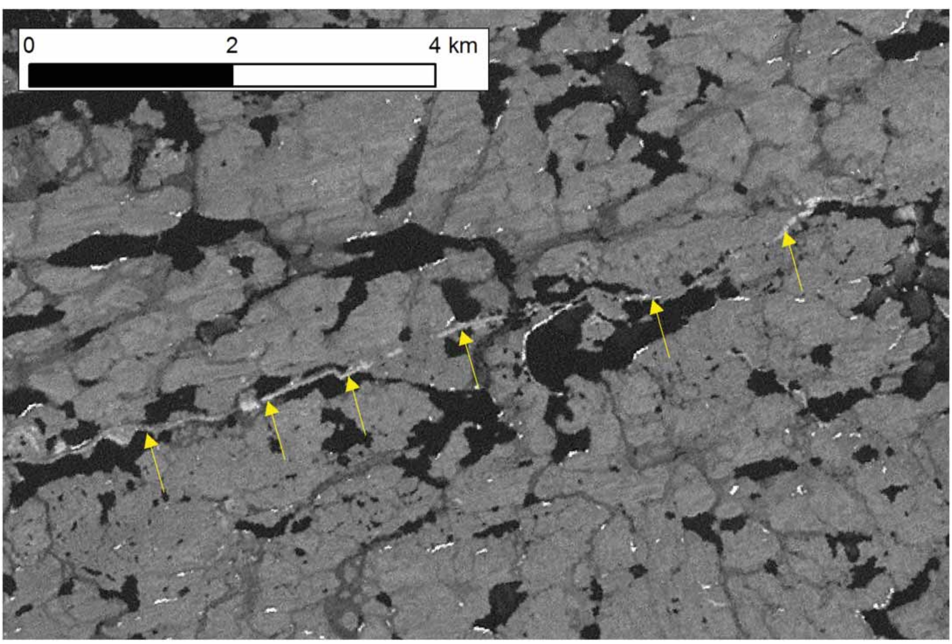

Figure 9. Landsat ETM+ image (band 8) of an esker in Nunavut. Note the very well-defined shape of the esker and the high continuity along its length. See Figure 5 for location.

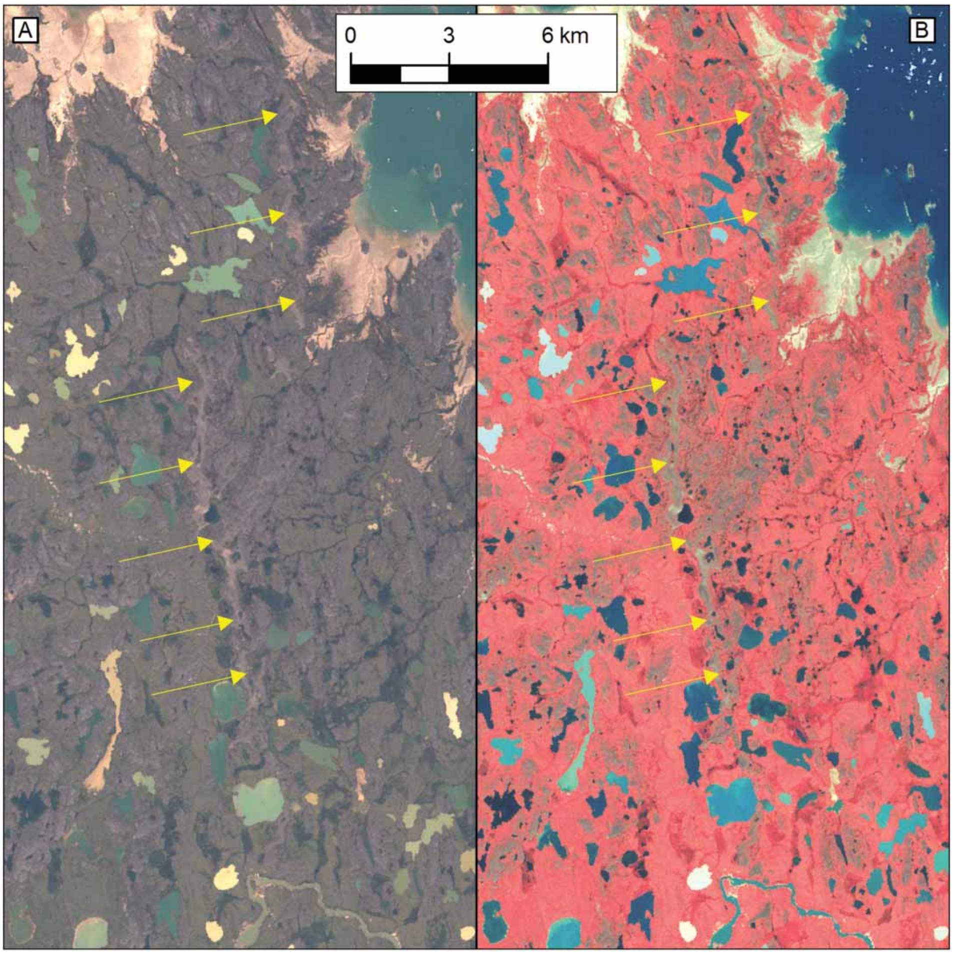

Figure 10. Landsat ETM+ image (3, 2, 1 in A; 4, 3, 2 in B) of discontinuous, 'patchy' eskers in Nunavut. Note poorly defined edges and presence of hummocky topography surrounding the eskers. See Figure 5 for location.

is measured at 97.5 km (in Ontario) and some systems can be traced for up to 760 km when gaps are taken into account. Indeed, eskers are usually found in fragments, reflecting either discontinuous formation, or post-depositional modification.

Though uncommon, esker ridges appear to be 'patchy' in some areas and do not display a coherent crestline, contrasting markedly with the classic Keewatin examples (Figure 10). Others consist of multiple ridges, which anastomose to produce complex patterns, although these eskers are usually confined to a relatively narrow 'swath'. In places, these swathes are marked by broader corridors of glaciofluvial sediment that appear as 'bright' patches on imagery and which some workers have called 'glaciofluvial corridors' (St-Onge, 1984; Utting, Ward, & Little, 2009).

4.2. *Esker distribution and pattern*

Several spatial patterns, visible at various scales, were recognised in the mapping. In general, the pattern of eskers is similar to that mapped by Prest et al. (1968) and clearly shows eskers radiating

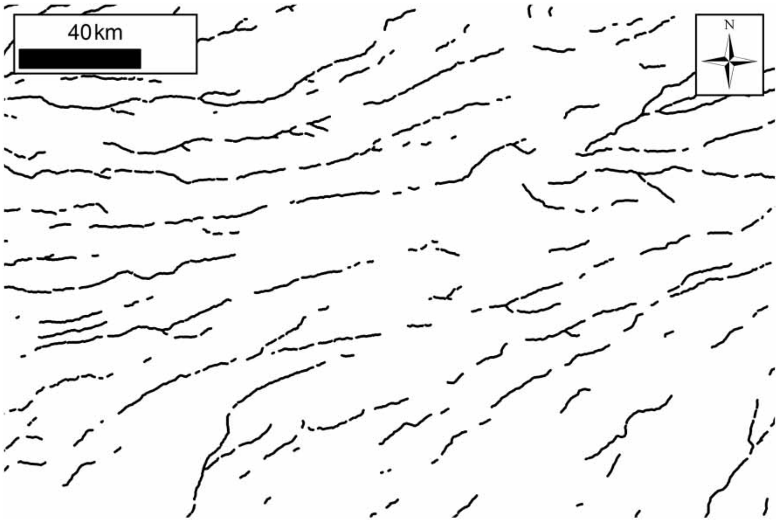

Figure 11. Digitised eskers in Northwest Territories exhibiting regular spacing (typically around 15 km). See Figure 5 for location.

away from the former location of major ice divides, for example in Keewatin and Ungava (cf. Boulton & Clark, 1990; Dyke & Prest, 1987; Menzies & Shilts, 1996). Beneath the former ice divides, however, eskers are conspicuously absent. As others have noted, integrated dendritic networks of eskers exist around the Keewatin Ice Divide (see Aylsworth & Shilts, 1989a), indicative of a well-connected drainage system.

In contrast, some areas display little or no recognisable pattern and eskers appear rather chaotic. This is particularly apparent off the Canadian Shield and over soft sedimentary rocks, e.g. north of Great Bear Lake in Northwest Territories, as well as on Victoria Island, where complex ice dynamics were recorded during deglaciation (Stokes, Clark, & Storrar, 2009). More generally, eskers are abundant on the Canadian Shield and are relatively sparse on the surrounding soft-bedded areas, as noted by Clark and Walder (1994), who hypothesised that eskers form preferentially on more resistant substrates.

In many places, eskers are relatively evenly spaced (typically from 10 to 20 km: see Figure 11), a phenomenon also observed in Finland and used as the basis of a hypothesis for groundwater control on esker spacing (Boulton et al., 2009). The map presented here could therefore be used as the foundation for a more in-depth analysis of esker patterns (and morphometry) and to test numerical models that predict esker spacing (e.g. Boulton et al., 2009; Hewitt, 2011).

5. Conclusions and implications

This paper presents a map of 20,186 large Canadian eskers mapped from Landsat satellite imagery. Analysis of aerial photographs in seven test areas suggests that approximately 75% of all eskers were detected using Landsat imagery alone, with most of those undetected being <2 km long, based on comparison to aerial photograph mapping. The morphometry of eskers was found to vary and several distinctive types were observed: classical, well-defined, single-ridge eskers; multiple-ridged and anastomosing eskers; and 'patchy' eskers. Eskers are predominantly preserved in fragments but systems of eskers can be interpolated from the patterns which often extend for several hundred kilometres. Eskers frequently conform to distinctive patterns at different scales, indicating highly organised systems. At the largest scale, eskers are seen to radiate away from former ice divides in Keewatin and Labrador. Within these radial esker systems, integrated networks of eskers can be seen with many tributary eskers. In some areas, eskers are very regularly spaced.

The map of eskers presented in this paper is well suited to a large-scale quantitative/statistical analysis of the morphometry of eskers (e.g. similar to that recently undertaken for drumlins: Clark et al., 2009; Hillier et al., 2013; Spagnolo et al., 2010, 2011, 2012) These data could then be used to test numerical models that predict the configuration of meltwater drainage beneath ice sheets (e.g. Boulton et al., 2009; Hewitt, 2011) and quantitatively test various hypotheses that seek to explain where and why eskers form (e.g. subglacial geology, groundwater characteristics, ice surface slope). Esker patterns can also provide new insights regarding the margin configuration of the former Laurentide Ice Sheet during deglaciation, since they typically form perpendicular to ice margins. This has significant implications both for our understanding of eskers and palaeo-glaciology, as well as for improving our knowledge of how large subglacial meltwater drainage systems operate under contemporary ice sheets.

Software

Landsat images were manipulated in Erdas Imagine 2011. Digitising and drafting of the map and figures was completed in ArcGIS 10 and Adobe Illustrator CS4.

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