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A quasi-annual record of time-transgressive esker formation: implications for ice sheet reconstruction and subglacial hydrology

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Abstract

We identify and map chains of esker beads (series of aligned mounds) up to 15 m high and on average ~65 m wide across central Nunavut, Canada from the high-resolution (2 m) ArcticDEM. Based on the close one-to-one association with regularly spaced, sharp crested ridges interpreted as De Geer moraines, we interpret the esker beads to be quasi-annual ice-marginal deposits formed time-transgressively at the mouth of subglacial conduits during deglaciation. Esker beads therefore preserve a high-resolution record of ice-margin retreat and subglacial hydrology. The well-organised beaded esker network implies that subglacial channelised drainage was relatively fixed in space and through time. Downstream esker bead spacing constrains the typical pace of deglaciation in central Nunavut between 7.2 and 6 ka ^{14}C BP to 165-370 m yr^{-1}, although with short periods of more rapid retreat (>400 m yr^{-1}). Under our time-transgressive interpretation, the lateral spacing of the observed eskers provides a true measure of subglacial conduit spacing for testing mathematical models of subglacial hydrology. Esker beads also record the volume of sediment deposited in each melt season, thus providing a minimum bound on annual sediment fluxes, which is in the range of 10^3-10^4 m^3 yr^{-1} in each 6-10 km wide subglacial conduit catchment. We suggest the prevalence of esker beads across this predominantly marine terminating sector of the former Laurentide Ice Sheet is a result of sediment fluxes that were unable to backfill conduits at a rate faster than ice-margin retreat. Esker ridges, conversely, are hypothesised to form when sediment backfilling of the subglacial conduit outpaced retreat resulting in headward esker growth close to but behind the margin. The implication, in accordance with recent modelling results, is that eskers in general record a composite signature of ice-marginal drainage rather than a temporal snapshot of ice-sheet wide subglacial drainage.

Introduction

Eskers record the former channelised drainage of meltwater under ice sheets. They typically comprise a slightly sinuous ridge of glaciofluvial sediments 10s–100s metres wide and 1–10s m high, and are widespread across the beds of the former Laurentide and Fennoscandian ice sheets (e.g. Prest et al., 1968; Aylsworth & Shilts, 1989; Boulton et al., 2001; Storrar et al., 2013; Stroeven et al., 2016). Their distribution and network geometry have been used to reconstruct past ice sheet retreat patterns and subglacial hydrological properties (Greenwood et al., 2016 and references therein). However, a key uncertainty is whether eskers, which often form networks that stretch continuously for hundreds of km, reflect an extensive synchronous drainage system (e.g. Brennand, 1994, 2000), or record in a time-transgressive manner the location of these segments of subglacial conduits under the ice margin as it retreated (e.g. Hebrand and Åmark, 1989; Mäkinen, 2003; Hewitt & Creyts, 2019).

Beaded eskers are characterised by a series of aligned mounds and are typically composed of ice-marginal sediments, deposited in either: (1) subaerial environments (Hebrand and Åmark, 1989); (2) subaqueous environments, as a delta or subaqueous fan at the mouth of a subglacial conduit in proglacial

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lacustrine or marine settings (Banerjee & McDonald, 1975; Rust & Romanelli, 1975; Cheel & Rust, 1986; Warren & Ashley, 1994; Brennand, 2000; Mäkinen, 2003); or (3) subglacial environments (Gorrell & Shaw, 1991). In the first two interpretations, the occurrence of esker beads implies time-transgressive esker formation. Indeed, several studies have suggested each beads consists of sediment from either one or a small number of melt seasons and therefore represents a quasi-annual signal of channelised drainage (e.g. Banerjee & McDonald, 1975; Mäkinen, 2003). Although detailed sedimentological investigations have improved our understanding of the processes and context of esker bead deposition (see above), what we can learn from such time-transgressive records about the past conditions of subglacial channelised drainage remains poorly understood. This includes the factors determining synchronous vs. incremental formation of esker ridges, palaeo-ice margin retreat rates and subglacial sediment fluxes.

In this paper we use the high-resolution (2 m) ArcticDEM v7 mosaic (Porter et al., 2018; https://www.pgc.umn.edu/data/arcticdem/) to identify and map nearly 5000 beads forming part of an extensive esker network NW of Hudson Bay, central Nunavut, Canada (Fig. 1). We use the distribution of the esker beads, their morphometric properties and their relationship with De Geer moraines to propose a quasi-annual, time-transgressive model of deposition and ice retreat, and we discuss the implications for understanding esker formation and subglacial drainage.

Study Area

The study area covers 87,500 km^2 of central Nunavut, around Chesterfield inlet, NW of Hudson Bay (Figure 1). North of Chesterfield Inlet the topography rises up to ~420 m a.s.l., but in general the area is low lying with relief rarely exceeding ~150 m a.s.l.. The region is predominantly composed of Precambrian Shield rocks of the western Churchill Province (mainly Archean gneiss and granites) (Paul, 2002) that are exposed at the surface in and around Chesterfield Inlet. To the north of the inlet the bedrock has a discontinuous veneer of till, whereas a thicker till (1-20 m) blankets the portion of the study area south of the inlet (Fig. 1). The till has been moulded into drumlins, flutes and crag-and-tails (e.g. McMartin & Henderson, 2004).

The study area partially straddles and is just to the southeast of the Keewatin Ice Divide (Fig. 1), which based on palimpsest glacial landform and sediment evidence, is thought to have been highly mobile throughout the last glaciation (e.g. Boulton & Clark, 1990a,b; Klassen, 1995; McMartin & Henderson, 2004). Regional ice-flow indicators including drumlins, striae and eskers suggest final ice flow during deglaciation was SE into Hudson Bay (Tyrrell, 1897; Prest et al., 1968; Shilts et al., 1979; Aylsworth & Shilts, 1989; Boulton & Clark, 1990a,b; McMartin & Henderson, 2004). Deglaciation of the area occurred between 7.2 and 6 ka ^{14}C BP (8 and 6.8 cal. ka BP), with the final vestiges of ice splitting into two small ice masses either side of Chesterfield Inlet (Dyke et al., 2003). Flights of raised marine strandlines indicate that final deglaciation involved a marine ice front calving into the Tyrrell Sea. Strandline elevations are variable across the region indicative of rebound under thinning ice cover, but typically range from ~130-170 m with the higher strandlines to the south (e.g. Shilts et al., 1979; Shilts, 1986; Randour et al., 2016).

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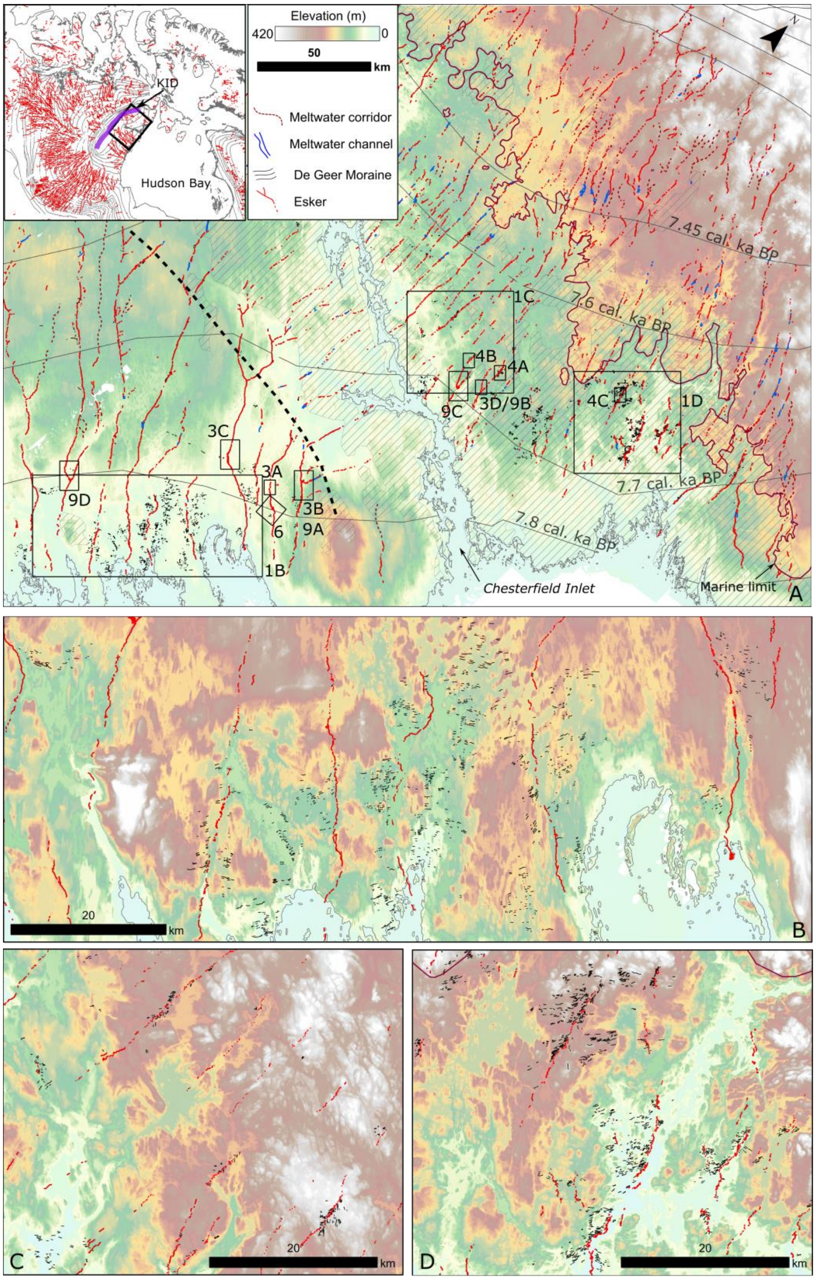

Figure 1: A. Glacial geomorphological map of meltwater features and De Geer moraines in central Nunavut, NW of Hudson Bay. Inset map shows location of study area, Keewatin Ice Divide (KID) (purple line) and previous mapping of eskers (Storrar et al., 2013). Black dotted line indicates the approximate axis of a re-entrant along which we interpret the two ice masses pulled apart. Solid black line is the marine limit modified and extended from Randour et al. (2016). Grey hatched lines are areas of exposed bedrock and solid grey lines are ice-margin positions extrapolated from Dyke et al. (2003). B-D. Zoom-ins show the relationship between De Geer moraines and eskers. DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

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Methods

Manual digitisation of eskers and other meltwater landforms (e.g. meltwater channels and subglacial meltwater corridors) was undertaken in ArcGIS 10.4 using hillshaded Digital Surface Models (DSMs) following standard practise outlined in Chandler et al. (2018). We used the 2 m ArcticDEM v7 mosaic, generated by applying stereo auto-correction techniques to overlapping pairs of high-resolution optical satellite images (Noh & Howat, 2015), to identify and map meltwater features. The outlines of esker beads were mapped as polygons at their break of slope, and esker ridge crestlines, moraine ridge crestlines, meltwater channel sides and subglacial meltwater corridor centrelines were mapped as polylines.

Esker bead area was calculated in ArcMap from the mapped polygons. Esker bead volume was calculated by removing the beads from the DSM; this included a 50 m buffer around the bead to avoid edge effects. The holes in the DSM were then re-interpolated using the function inpaint_nans in Matlab (written by John D'Errico: freely available at: https://uk.mathworks.com/matlabcentral/fileexchange/4551-inpaint_nans). The modified DSM with beads removed was then subtracted from the original DSM, and the summed elevation difference multiplied by 2 x 2 m (grid resolution) to calculate volume. Esker bead spacing was defined as the straight-line distance, d, between beads centre-points along the same meltwater axis and calculated as the average of both the bead upstream ($d+1$) and downstream ($d-1$) of it. Spacing distances of >1200 m (top 1% of spacing values, >5× median value) were removed to avoid biasing the statistics from breaks in deposition, submergence of beads in lakes or post-depositional erosion.

Results

Meltwater drainage imprint

Over 5000 esker ridge segments and 4700 esker beads were mapped across the study area, which together form a coherent esker and meltwater channel pattern converging into Hudson Bay (Fig. 1). There are two distinctive networks, a broadly N-S orientated set of quasi-regularly spaced (~6 km mean lateral spacing) eskers in the northern part of the study area and a larger and more widely spaced (~10 km lateral spacing) NW-SE trending network of eskers south of Chesterfield Inlet. After trending down the regional topography towards and across Chesterfield Inlet, the N-S orientated esker network becomes confluent with the NW-SE trending esker network. In the northern network, eskers above the marine limit (Fig. 1) tend to be more complex in planform, characterised by numerous tributaries and have orientations varying from NW-SE to N-S. These eskers typically comprise ridges rather than beads and often form in, and are connected to, subglacial meltwater corridors (e.g. Lewington et al., 2019). The southern section of this first network becomes increasingly fragmented, with beaded eskers dominating, and the general pattern is much simpler with few tributaries and a consistent N-S orientation with a remarkable degree of consistent parallel patterning. The southern end of this esker network connects with the second network of eskers, which, as described above, trends NW-SE. These eskers comprise a mix of beads and ridges, with beads more frequent on lower ground close to Hudson Bay and on the N-S tributaries emanating from the first network of eskers.

Esker bead distribution and morphology

Esker beads often form 'chains' across the landscape, with individual beads typically up to ~15 m high, having a median area of 4000 m^2 (~65 m wide), and their areas form a log-normal distribution with a large standard deviation (22,000 m^2) (Fig. 2A,B). Although the size of esker beads is variable, the largest beads tend to occur where the elevation is lower, close to the present-day coastline of Hudson Bay (Fig. 2A), and variations in size are gradual along individual eskers (p-value = 0.07) with ~30% of neighbouring esker beads similarly sized (Fig. 2C). 90% of beads are found <120 m a.s.l. within the

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marine limit, with the densest clusters on the till veneer and exposed bedrock north of Chesterfield Inlet and on the till blanket at the southeastern end of the NW-SE orientated esker system. Beads display a range of shapes, from mound-like forms (Fig. 3D) to wedge and fan geometries (Fig. 3C) and flow parallel and transverse ridges (Fig. 3A,B). Flat-topped esker beads are also observed (Fig. 3C), and tend to be more prevalent at the seaward end of the larger northwest-southeast esker network. Esker beads are often discrete features, but can also overlap or merge together, particularly when larger and/or closely spaced (Fig. 3B,C), or when they grade headwards into an esker ridge.

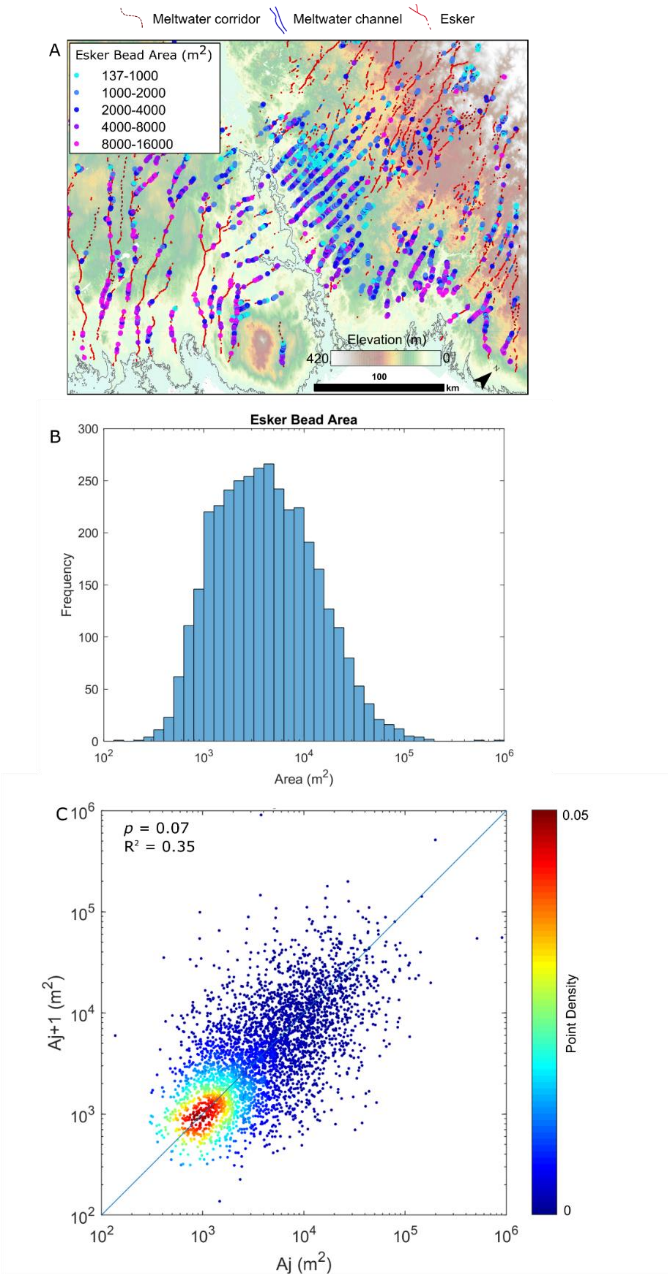

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Figure 2: Esker bead locations and area. A displays the spatial pattern. B Frequency histogram of bead area. C Leading order variogram, where A_j is the area of an esker bead and A_{j+1} is the area of its up-ice neighbour. Where neighbouring esker beads have the same area, the resultant point plots on the 1:1 line. Large deviations in area between successive beads result in a random spread of points. Point density is the number of other points lying within a circle of 400 m^2 radius, normalised by the total number of points. Note, the low p-value and clustering of points around the 1:1 line, which indicates a gradual transition in esker bead area along individual eskers. In addition, point density indicates that ~30% of neighbouring esker beads are similar (i.e. percentage of points within the cyan-yellow-red region). DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

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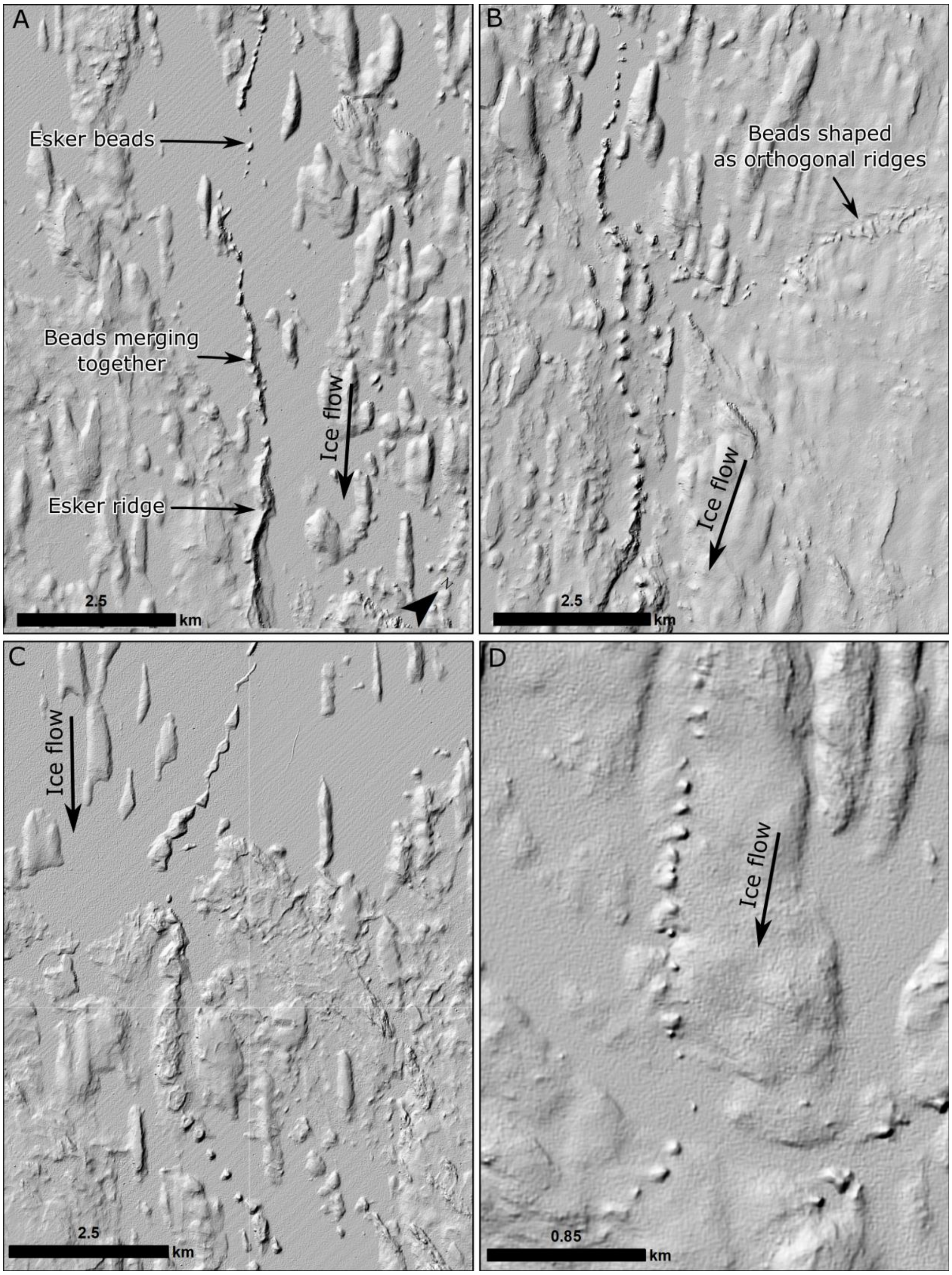

160 **Figure 3:** Examples of beaded eskers. (A) Transition between a classical esker ridge and esker beads, some of which are merging together to form a ridge-like form due to their large size and/or close spacing. Note how the beads range in shape from ridge-like (B) to triangular (C), flat-topped (C) and circular (D). Hillshaded ArcticDEM has 2 m horizontal resolution. Locations of beaded eskers displayed in Figure 1. DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

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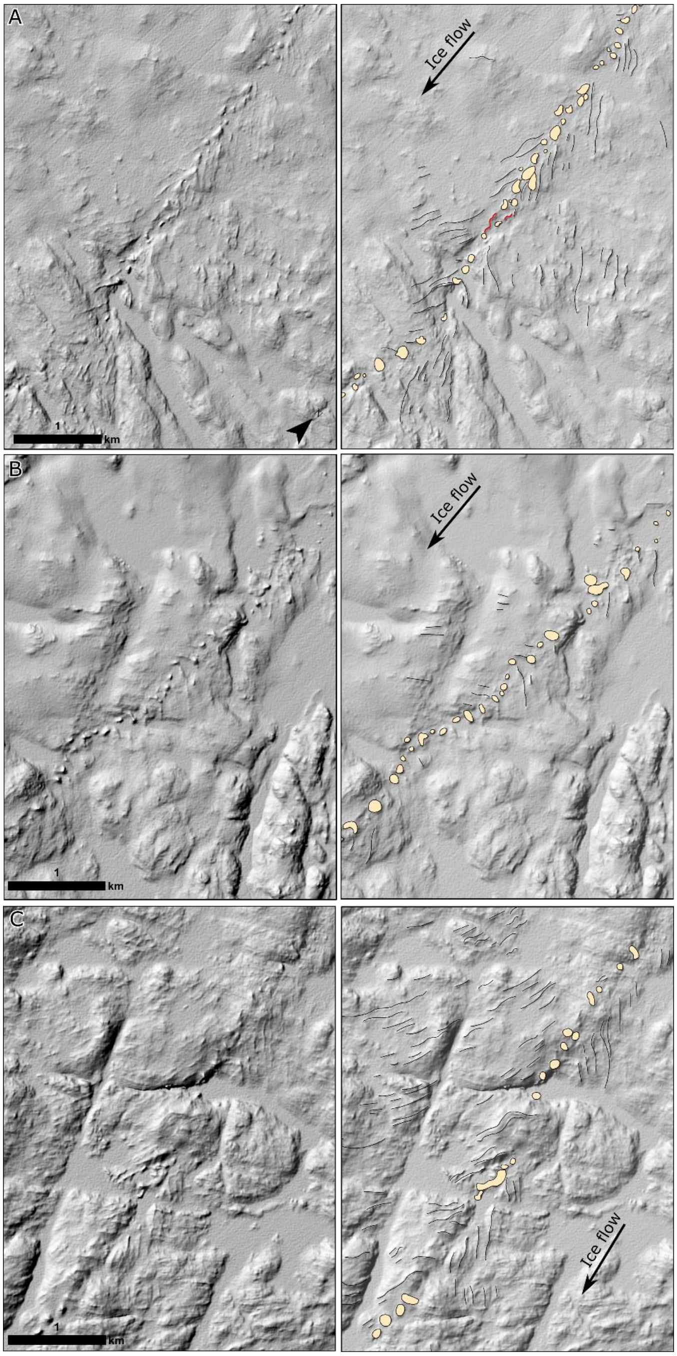

165 **Figure 4:** Relationship between esker beads and De Geer Moraine. Right hand column is the mapped (beads = yellow polygons; moraines = black lines; esker ridges = red lines) interpretation of A, B and C. Note how the De Geer moraines typically form a v-shaped geometry pointing up-ice, and the close association between individual moraines and beads. In some cases (e.g. 4A) the ridges originate from the beads. Hillshaded ArcticDEM has 2 m

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horizontal resolution. Locations are displayed in Figure 1. DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

Association with moraines

Below ~80 m a.s.l. esker beads are often intimately associated with parallel to sub-parallel, regularly spaced, sharp-crested moraine ridges, 1-3 m in relief, that drape the surrounding topography (Figs. 1B-D, 4). These ridges either occur transverse to the esker, or more commonly in a distinctive v-shaped arrangement (see also McMartin & Henderson, 2004), with the esker bead at the headward point and the ridges splitting downstream either side of the esker. This v-shaped arrangement typically only extends for no more than 1-2 km either side of the esker. Some moraine ridges appear to originate at the bead, resulting in a roughly one-to-one relationship between beads and moraines. Some beads even form a series of small flow-transverse ridge forms, like rungs on a ladder, suggesting they were modified when the ridge was formed (e.g. Fig. 3B – upper right quarter of panel).

A model for quasi-annual deposition of esker beads in an ice-marginal marine setting

Two principal hypotheses have been put forward for the formation of esker beads in the literature: (1) deposition at a retreat margin, with time-transgressive formation by sequential deposition of sediment debouching from subglacial conduits into a low energy subaqueous environment such as a lake or sea (e.g. Banerjee & McDonald, 1975; Rust & Romanelli, 1975; Cheel & Rust, 1986; Warren & Ashley, 1994; Mäkinen, 2003; Ahokangas & Mäkinen, 2014); and (2) entirely subglacial deposition with synchronous formation during periodic separation of the glacier from its bed causing sediment-rich water to spill laterally out from the main subglacial conduit (esker ridge) into neighbouring subglacial cavities (e.g. Gorrell & Shaw, 1991).

We interpret our esker beads to be quasi-annual deposits formed time-transgressively (hypothesis 1), predominantly in an ice-marginal marine setting (Fig. 5). This is based on their close one-to-one association with regularly spaced, sharp crested ridges (Fig. 4) that are interpreted as De Geer moraines (e.g. Lindén & Möller, 2005; Ottesen & Dowdeswell, 2006; Todd et al., 2007; Bouvier et al., 2015; Ojala, 2016). De Geer moraines are typically thought to occur at the grounding-line of calving glaciers (e.g. Ottesen & Dowdeswell, 2006; Flink et al., 2015), which is consistent with their occurrence only in areas below 80 m a.s.l., well within the proposed maximum marine limit of the Tyrrell Sea along the west coast of Hudson Bay (Shilts et al., 1979; Shilts, 1986; Simon et al., 2014; Randour et al. 2016). In addition, the v-shaped arrangement of the moraine ridges around the esker beads is consistent with embayments forming at the mouth of subglacial conduits (see also Hoppe, 1957; Strömberg, 1981; Lindén & Möller, 2005; Bouvier et al., 2015; Dowling et al., 2016) due to plume-enhanced melting and calving (e.g. Benn et al., 2007). In this configuration, local ice flow would be towards the embayment, which is supported by the convergent pattern of striations 3-4 km either side of esker ridges in this area (e.g. Fig. 6; McMartin, 2000). The morphology of the beads suggests to us that they did not form subglacially. In particular, some of the beads have a flat-top indicating sedimentation up to the water level, fan-shaped beads tend to be orientated down-stream rather than orthogonal to water-flow, where a bead grades into a ridge this occurs in an up-ice direction, and beads are strongly aligned (i.e. do not deviate from a central axis) (Figs. 3-4), all of which indicate ice-marginal deposition filling the accommodation space at the mouth of a subglacial conduit, rather than lateral deposition into a subglacial cavity flanking the main conduit. Likewise, given the arrangement of the De Geer moraines, their distribution within the marine limit and their association with esker beads, we consider alternative subglacial origins for their formation, such as in basal crevasses during surging (e.g. Zilliacus, 1989), to be unlikely.

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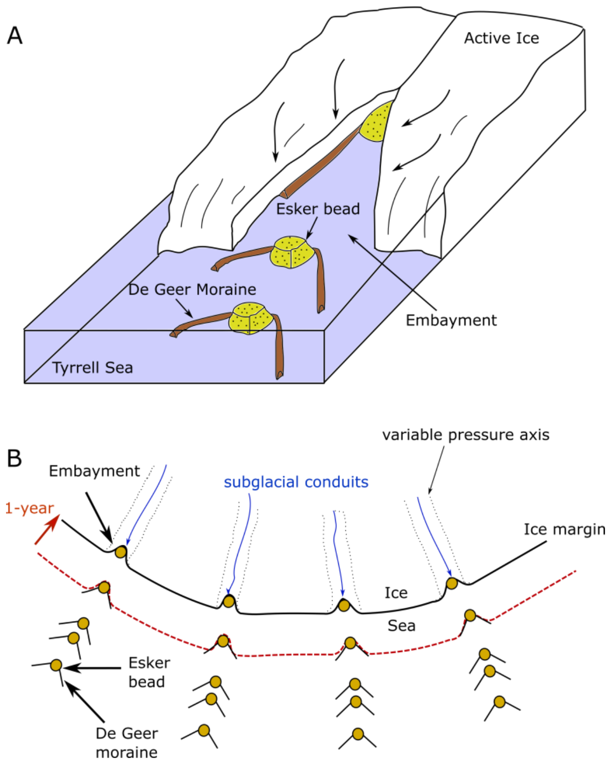

Figure 5: A. 3D schematic showing the proposed quasi-annual formation of esker beads and De Geer moraines in embayments at a marine grounding line (modified from Warren & Ashley, 1994). Note the flat-tops of the beads, which are determined by the water level B. Planview showing the annual deposition of esker beads at the mouth of a series of subglacial conduits. Note how variations in retreat rate affect the downstream spacing of esker beads, and that the lateral spacing between individual esker systems is a true measure of subglacial conduit spacing, at least near the palaeo-ice margin.

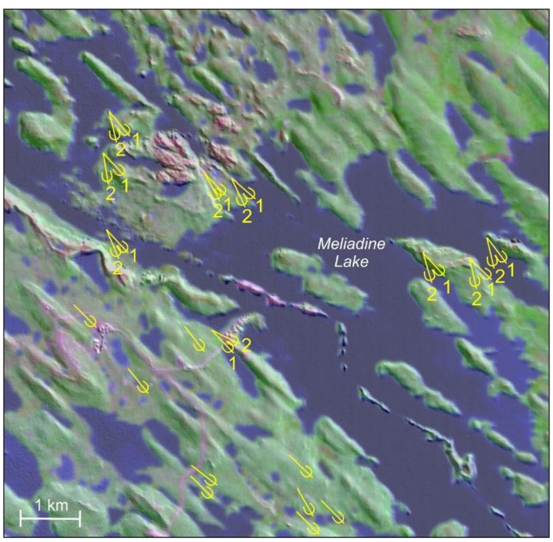

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Figure 6: Pattern of striations (yellow arrows) either side of the Meliadine esker beads, showing convergence towards the esker (#2 arrows). Background is a LANDSAT-8 satellite imagery (Bands 754) on top of the ArcticDEM.

Although De Geer moraines are traditionally thought to represent an annual signature with a ridge formed each winter as ice undergoes a minor re-advance (e.g. De Geer, 1940), intra-annual frequencies have also been proposed, with summer ridges associated with periodic calving (Lundqvist, 1958; Strömberg, 1965; Möller, 1962; Lindén & Möller, 2005; Ojala et al., 2015). Indeed, some ridges and beads could be the result of several years of deposition, with other ridges destroyed by a more extensive winter re-advance. Where intra-annual moraine ridges have been observed, they have tended to be smaller, less regular ridges nested amongst the larger, more regular annual ridges (Möller, 1962). However, we do not observe this bimodal population of moraine ridge sizes across the study area. If intra-annual calving events dominated the signal, we might expect to observe significant variation in sediment flux and retreat rate and consequently esker bead size and spacing over short distances imposed by the irregularity of calving events throughout the melt season. While there is some substantial deviation in bead size, variation is often gradual (e.g. Figs. 2C, 3A, 4C), and more typically beads exhibit consistent sizes down individual eskers (e.g. Fig. 2C, Figs. 3A-B, D, 4B-D). In addition, whilst there is a lot of noise, particularly where esker beads are widely spaced (likely due to breaks because of non-deposition / post-depositional modification), 35% of neighbouring esker beads are similarly spaced (Fig. 7C). Such observed sequences of variation in bead size and spacing is consistent with a background forcing comprising slow year-to-year changes in climate rather than quasi-random ice calving events.

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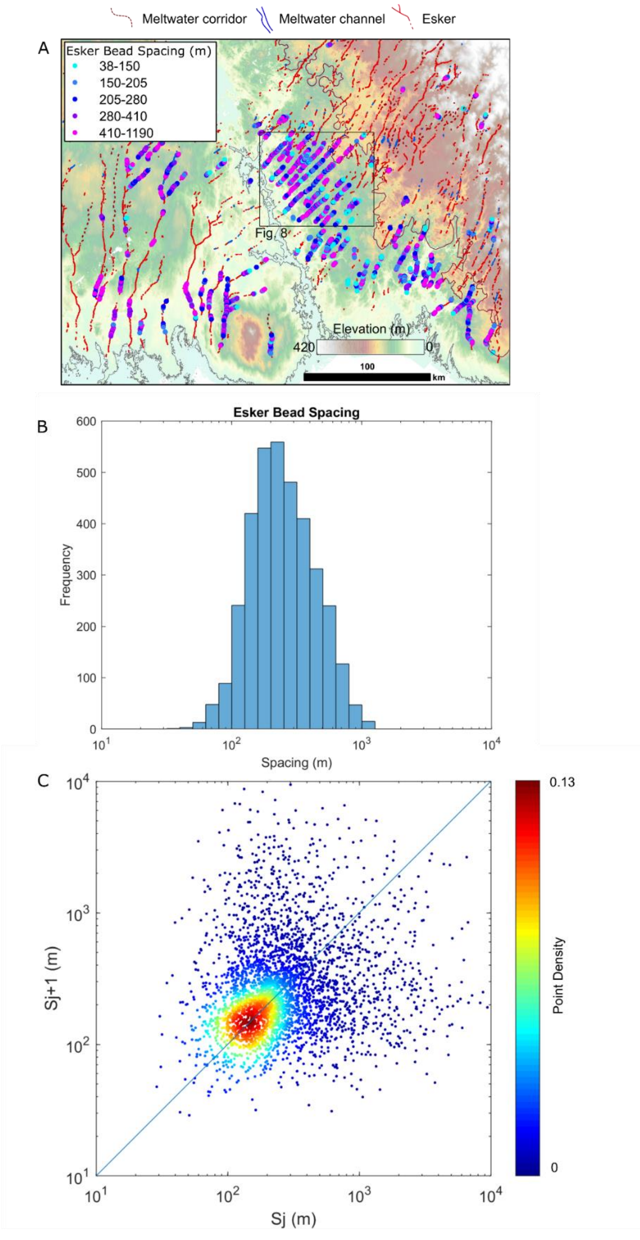

Figure 7: Along-esker bead spacing. A is the spatial pattern and B the frequency histograms. Black box is the location of Figure 8. The blackline in A is the marine limit. Median spacing is 240 m. C. Leading order variogram, where S_j is the spacing of an esker bead and S_{j+1} is the spacing of its up-ice neighbour. Where neighbouring esker beads have the same spacing, the resultant point plots on the 1:1 line. Large deviations in spacing between successive beads result in a random spread of points. Point density is the number of other points lying within a circle of 50 m radius, normalised by the total number of points. Although the p-value is not-significant and the R^2 is low, ~35% of successive neighbouring esker beads have a similar spacing (i.e. percentage of points within the cyan-yellow-red region). DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

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Although we prefer an annual origin to explain the regularly-spaced De Geer moraines, the traditional hypothesis that they formed each winter as ice underwent a minor re-advance (e.g. De Geer, 1940) is difficult to reconcile with their alignment next to rather than between esker beads (e.g. Fig. 4, and see schematics in Fig. 5) deposited during the summer melt season. In addition, De Geer moraines tend to be more common adjacent to eskers (within 1-2 km) and much rarer in intervening areas (Fig. 1). Together these observations either imply that there was sufficient sediment to deposit esker beads only towards the end of the melt season (i.e. a gap in deposition during the early melt season when the ice-margin was retreating), or that the De Geer moraines were formed during the summer melt season (i.e. when the esker bead was deposited). The second hypothesis would imply that meltwater was fundamental to De Geer moraine genesis. We therefore propose that meltwater flow along the variable pressure axis extending 1-2 km either side of a main subglacial channel could carry glaciofluvial sediment and facilitate widespread deformation and squeezing of saturated till to the ice margin (e.g. Price, 1970) producing local grounding line fans/wedges, and that this happens at the same time as the esker bead is deposited at the mouth of the subglacial conduit (Fig. 5).

The range of esker bead morphologies identified likely reflects variations in depositional environment and sediment supply (Figs. 3, 4). Fans and mounds are analogous to subaqueous fan deposition (Powell, 1990), while flat-topped beads suggest limited accommodation space, and therefore sedimentation in shallow water (e.g. delta) or beneath an ice shelf or conduit roof. About 10% of esker beads occur above the marine limit (Fig. 1). These beads more typically have a mounded appearance or occur as a sequence of short (<100 m) ridge segments, and are frequently interrupted by esker ridges. We interpret these to have been deposited subaerially or occasionally in proglacial lakes as outwash fans (mounds) or due to temporary clogging of the subglacial conduit (short ridge segments).

If esker beads are deposited approximately once per year, then their downstream spacing, like varves and De Geer moraines, could be used to produce a relative high-resolution, annual chronology of ice-margin retreat. Our data suggest that the downstream spacing of esker beads varies, with a strong positive skew, across the study area, from <50 m to >1200 m, with a median value of 240 m and interquartile range of 165-370 m (Fig. 7). This implies a typical retreat rate of 165-370 m yr^{-1} towards the Keewatin Ice Divide across a distance of >100 km. Although deglaciation is poorly constrained in this sector of the Laurentide Ice Sheet, reconstructed ice margins from Dyke et al. (2003) suggest that final retreat proceeded across a distance of ~85 km over 250 years, which equates to a mean retreat rate of ~340 m yr^{-1}. This is a rough figure given uncertainties in radiocarbon dating and poor age control in this region, however, it is of the same magnitude as that calculated from the esker beads.

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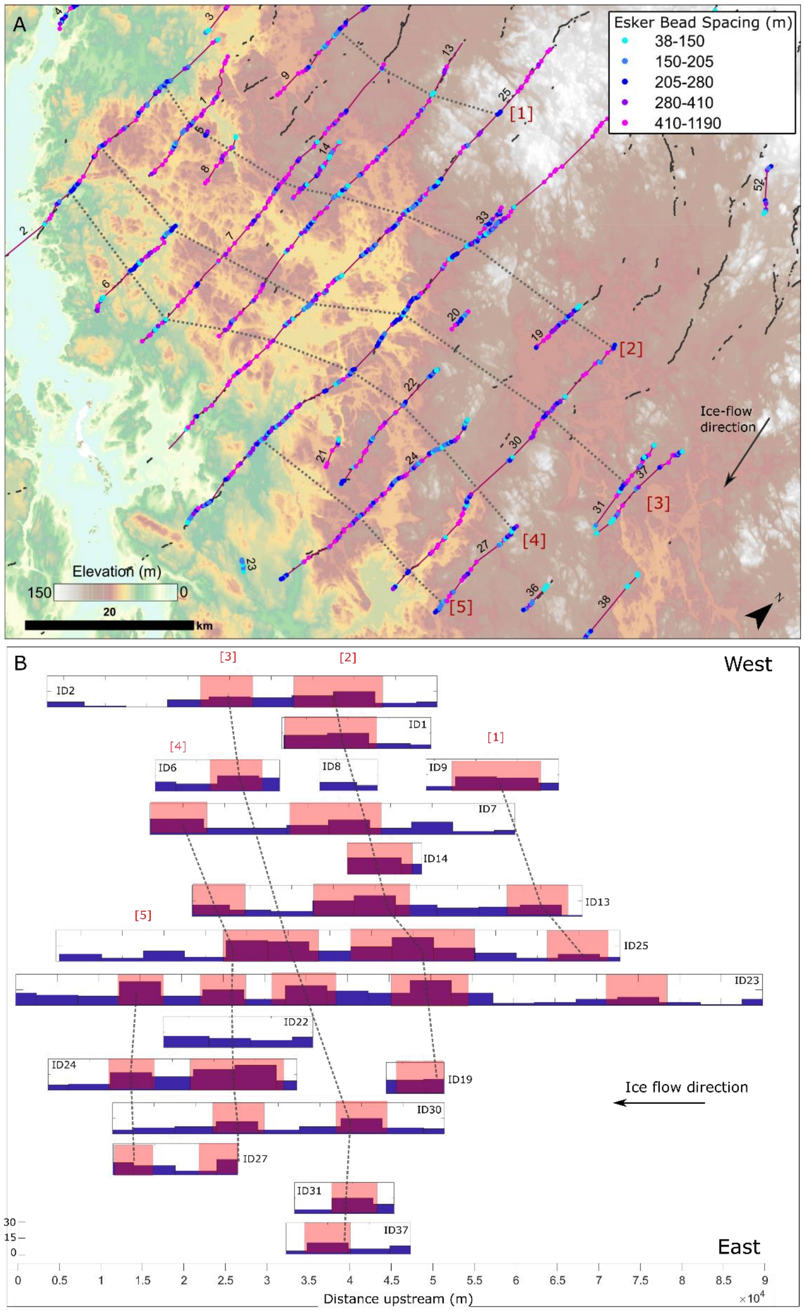

Figure 8: Esker bead downstream spacing-distance plot. A shows the spatial distribution of beaded eskers and average downstream spacing between two nearest beads (location shown in Figure 7). B is a frequency-density histogram of esker beads along esker axes (numerical ID labelled in black in A). Bins are 5 km. Coincidence of regions with closely spaced beads (high density) are traced by eye (red boxes and dotted lines) and plotted in A (red IDs). Note the consistent qualitative transverse relationship between closely spaced beads indicative of a common forcing. DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

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Variations in ice-marginal rate of retreat during regional deglaciation should result in a pattern of downstream spacing of esker beads that can be spatially correlated between eskers (e.g. Fig. 5B). Although this is complicated by uncertainty over the shape of the ice margin, local variations in retreat rate and fragmentation (e.g. due to hiatuses in deposition, post-depositional erosion or non-detection due to submersion in lakes), we are nonetheless able to identify coherent, broad-scale (data binned at 5 km) trends in esker bead frequency in the cluster of N-S trending eskers, just to the north of Chesterfield Inlet (Fig. 8). Five sections of more closely spaced esker beads corresponding to periods of slower ice retreat can be qualitatively identified across multiple eskers (Fig. 8A,B) and the resulting isochrones produce ice margins which appear realistic (i.e. they are transverse to the eskers and do not contain unusual lobes or indentations given the topography) (Fig. 8A). Thus, while we would certainly expect some local deviation from an annual signal, over a large area we suggest that the esker beads and De Geer moraines represent a roughly annual signature of ice retreat and meltwater drainage. This is consistent with other studies that have invoked an annual original for esker beads (e.g. De Geer, 1940; Banerjee & McDonald, 1975), but we suggest our data provides a more robust demonstration.

Implications for reconstructing the ice-marginal retreat history of central Nunavut

Annual esker bead deposition and De Geer moraine formation provides a high-resolution record of ice-margin retreat that can be used to better constrain the timing and rate of deglaciation in central Nunavut (Dyke et al., 2003). Our results suggest that the pace of deglaciation was on the order of 165-370 m yr^{-1}, punctuated by short periods of more rapid retreat (>400 m yr^{-1}) (Fig. 7). The distribution of beads and De Geer moraines indicate retreat of an initially marine terminating ice sheet (Shilts et al., 1979; Shilts, 1986) that became terrestrially grounded as it retreated northwards onto higher ground (>~130 m a.s.l.) (e.g. Fig. 1). Plume-enhanced melting and calving modified the grounding line, producing km-scale indentations (marine embayments) where water debouched from subglacial conduits (Fig. 5).

To explain the two distinct time-transgressive esker networks, orientated N-S and NW-SE, the ice sheet must have split into two ice masses with a large re-entrant to the south of Chesterfield Inlet (black dotted line in Fig. 1). This is consistent with fragmentation of the Keewatin Ice Divide into two small ice masses on either side of Chesterfield Inlet during the final stages of deglaciation (Dyke et al., 2003; Dyke, 2004). The more northerly ice mass must have migrated further northwards than envisaged by Dyke et al. (2003) to account for the extension of the esker network across the divide (see also McMartin et al., 2016, 2019). The interlobate zone along which the ice masses split is exemplified in Fig. 9A by two smaller N-S orientated beaded eskers joining a larger NW-SE beaded esker at acute angles. This larger esker likely demarcates the former interlobate zone into which water from the N-S trending ice-lobe was focused (e.g. Warren & Ashley, 1994; Mäkinen, 2003) (Fig. 1). Noteworthy in this example, is that the upper N-S orientated beaded esker turns E-W as it joins the larger esker (Fig. 9A), which is difficult to reconcile with a subglacial origin because drainage would have been up-glacier.

Implications for understanding subglacial drainage

The identification of beaded eskers as an annual imprint of ice-marginal conduit deposition is significant because the composite signature can be deconvolved to provide information on the spatial and temporal scales of subglacial drainage that have hitherto been difficult to reconcile. As such these findings provide much-needed constraints for testing subglacial hydrological models (e.g. Hewitt & Creyts, 2019). In particular, the assumption that the spacing of subglacial conduits is reflected by the lateral spacing of a given observed network of eskers (e.g. Hewitt, 2011; Storrar et al., 2014) is predicated on all eskers of that network having formed synchronously in the past. This condition is difficult to deduce from the esker ridges themselves, and different sets of eskers could have been deposited subglacially at different times during deglaciation to form the network observed today. In contrast, because the esker

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beads identified in this study formed time-transgressively at the ice-sheet margin, the set of all eskers must have formed together as one retreat episode. Thus, the lateral spacing of beaded eskers is a true reflection of subglacial conduit spacing at least near the palaeo-ice margin and so provides a more accurate set of observations for testing the esker-spacing theory.

The network of beaded eskers is well-organised and can be traced >100 km, spanning ~350 years of deposition (Fig. 1), indicating that subglacial channelised drainage was relatively fixed in space and through time in this region. Beaded eskers typically exhibit parallel drainage patterns, contrasting with areas dominated by ridges and subglacial meltwater corridors which tend to be more dendritic (Fig. 1). This could indicate that esker ridges are not formed right at the ice margin but can extend some distance up-ice, resulting in more complex drainage networks, and that tributaries may be largely transitory features, which tend to occur up-glacier of the retreating ice-margin. Alternatively, the increase in number of tributaries could indicate a transition to a shallower ice surface slope and thus shallower hydraulic potential gradient, or the higher roughness regions to the north may have resulted in more complex subglacial water flow. Where beaded esker tributaries are observed they tend to record re-entrants associated with unzipping of the two ice lobes (Fig. 9A). However, other tributaries with shallow-angled junctions also occur (Fig 9B-D) and in these cases it may be possible to determine whether these are true hydrologically functioning tributaries that emerge at the ice-margin during retreat, or apparent tributaries that arise as a single subglacial conduit splits into two during retreat. The tributaries in Fig. 9B and 9C do not appear to be controlled by bed topography and can only be traced for a short distance (~10 km in both cases) before one of the eskers disappears, and are therefore thought to represent slight re-organisations of the drainage network (e.g. due to a change in ice geometry). In Fig. 9D the esker tributaries are interpreted to have been strongly controlled by their alignment along topographic lows.

Finally, esker beads record the volume of sediment deposited each melt season, and can therefore be used to better constrain subglacial sediment fluxes. These fluxes should be considered minimum bounds since not all sediment will be deposited at the grounding line (much of the finer component will be transported away in plumes; e.g. Powell, 1990) and the beads have likely endured erosion since deposition. In addition, the spacing of eskers provides a bound on the width of the catchment of each subglacial conduit. Given the rough lateral spacing of beaded eskers is 6-10 km, these fluxes can be considered minimum sediment fluxes per year per 6-10 km width of the past ice sheet. The esker beads in central Nunavut produce minimum sediment fluxes that typically range between 10^3-10^4 m^3 yr^{-1} per bead (Fig. 10), which is a few orders of magnitude lower than sediment fluxes derived from the aggradation of present-day grounding line fans in southern Alaska (10^6 m^3 yr^{-1}: (Powell 1990; Powell & Molnia 1989). This is probably not surprising however, given the thin and patchy cover of sediment in central Nunavut (Fig. 1), which would have limited the supply of sediment, especially when compared to the more elevated and steeper terrain in southern Alaska. Indeed, there is a general qualitative correlation between the size of esker beads and bed substrate, with larger beads more prevalent south of Chesterfield Inlet in the zone covered by a thick till blanket, while the bedrock exposed area around Chesterfield Inlet is characterised by smaller beads that are more sporadic (Figs. 1, 2). The ubiquity of esker beads across this marine terminating sector of the former Laurentide Ice Sheet may therefore be a result of lower sediment fluxes that were unable to backfill conduits at a rate greater than the pace of ice-margin retreat. If so, the switch to more continuous esker ridges on higher ground to the north may reflect a slowdown in retreat as the ice became terrestrially terminating or an increase in sediment supply. Certainly, below the marine limit, esker ridges tend to be more common in thicker till and where esker beads are larger (e.g. see south of Chesterfield Inlet in Fig. 7A), implying that sediment supply is an important control. The logical conclusion is therefore that esker ridges also represent a time-transgressive signature, but that sediment backfilling of the subglacial conduit outpaced retreat allowing ridges to form in a headward direction behind the margin. This is in accordance with recent modelling results (Beaud et al., 2018; Hewitt & Creytts, 2019), and implies that eskers record a composite pattern of near-margin subglacial drainage.

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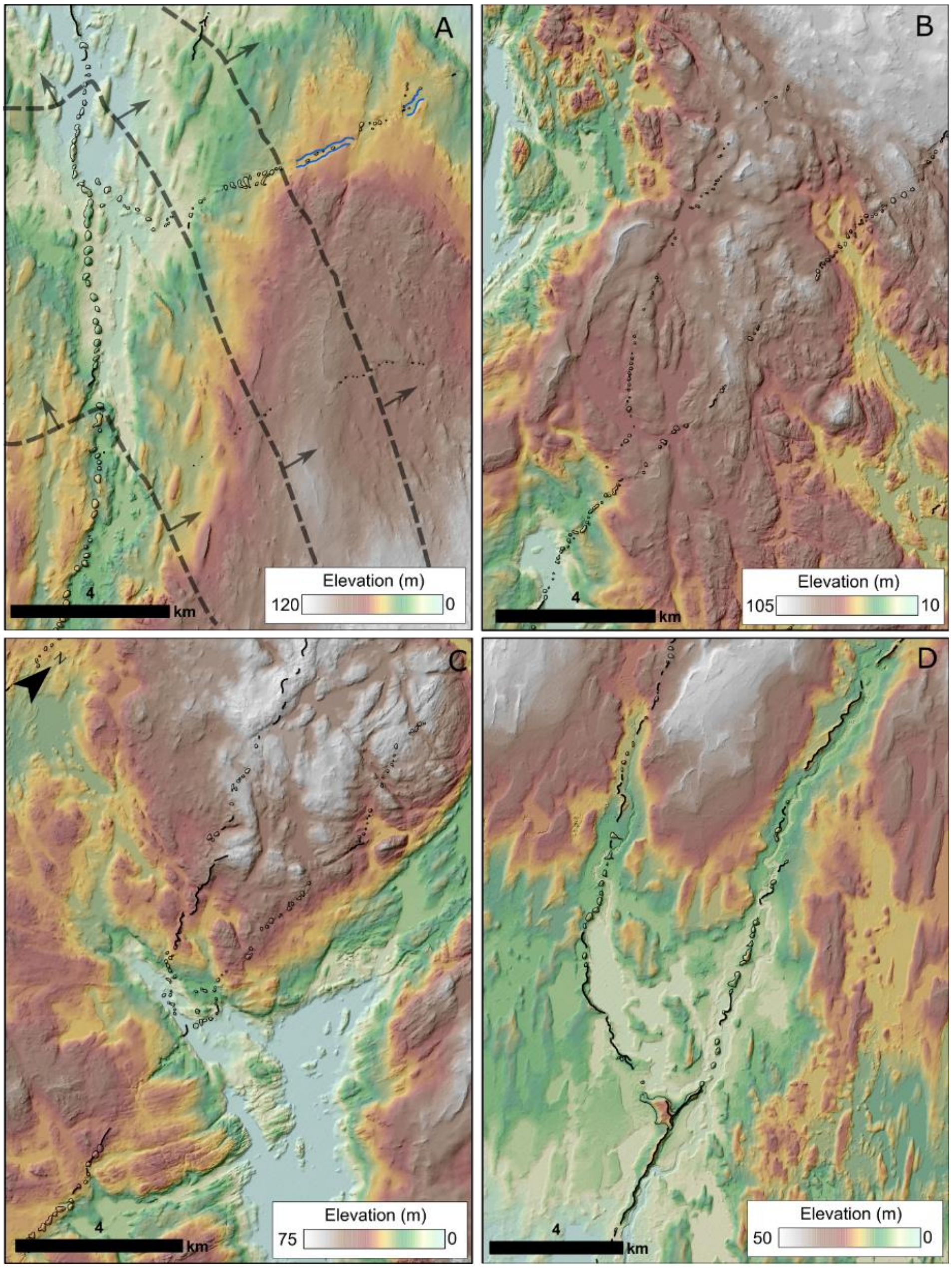

Figure 9: Examples of confluences between beaded eskers and influence of topography on drainage networks. Black lines are mapped esker ridges, blue lines are meltwater channel sides and black polygons are mapped esker beads. Hillshaded ArcticDEM is 2 m horizontal resolution. Locations are displayed in Figure 1. The black dashed lines in A represent interpreted margin positions demarcating the unzipping of two ice lobes, one retreating west and another north (arrows show direction of retreat). DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

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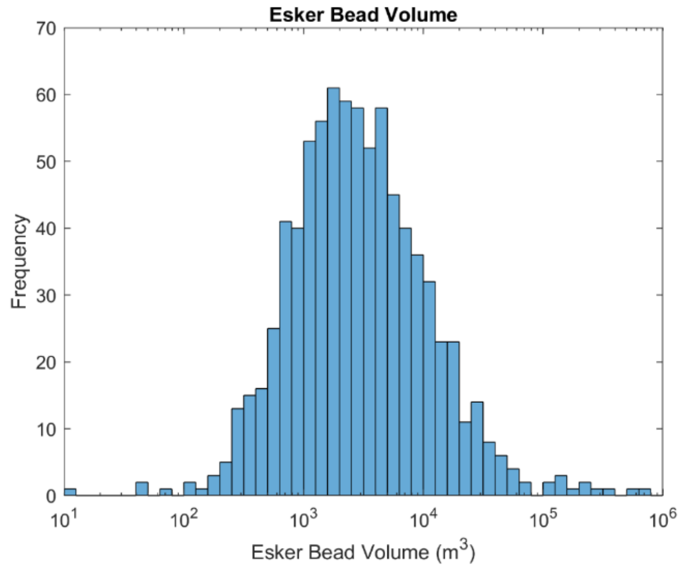

Figure 10: Esker bead volume. Because the beads are interpreted as quasi-annual and the lateral spacing of the eskers is thought to reflect the true spacing of the subglacial conduits, these volumes represent a minimum sediment flux per year per 6-10 km ice-margin width.

Conclusions

We mapped nearly 10,000 eskers beads and ridge segments from the high-resolution (2 m) ArcticDEM across an 87,500 km^2 area of central Nunavut, around Chesterfield inlet, NW of Hudson Bay. Mapping revealed nearly 5000 esker beads (series of aligned mounds), which because of their association with De Geer moraines are interpreted as quasi-annual ice-marginal deposits formed time-transgressively at the mouth of subglacial conduits during deglaciation. The majority of beads are below the former marine limit of the Tyrrell Sea and therefore likely represent subaqueous outwash fans/deltas. De Geer moraines display a striking v-shaped arrangement indicating the formation of embayments at the mouth of subglacial conduits due to plume-enhanced melting and calving. The relationship between De Geer moraines and esker beads hints that the former was also formed in summer and may indicate water flow either side of the main subglacial conduit (across the variable pressure axis) facilitating deformation and squeezing of till and deposition of glaciofluvial sediments to produce grounding line fans/wedges. The identification of esker beads as quasi-annual deposits has significant implications as they preserve a high-resolution record of ice-margin retreat and subglacial hydrology. This includes:

- The network of esker beads is well-organised (quasi-regularly spaced) and spans >100 km, implying that subglacial channelised drainage was relatively fixed in space and through time. Tributaries are thought to record re-entrants associated with unzipping of two ice lobes on either side of Chesterfield Inlet; stable drainage tributaries controlled by ice surface slope and topography have emerged at the ice margin during ice retreat.
- The downstream spacing of esker beads records a high-resolution (annual) record of ice sheet retreat in this sector of the former Laurentide Ice Sheet. Our results suggest that the pace of deglaciation was on the order of 165-370 m yr^{-1}, punctuated by short periods of more rapid retreat (>400 m yr^{-1}).

- In contrast to esker ridges, which could have been deposited subglacially at different times during deglaciation, the set of esker beads must have sequentially formed together during one retreat episode and therefore provide a true reflection of subglacial conduit spacing. Our data therefore provides an appropriate set of observations for testing the esker-spacing theory.
- Esker beads record the volume of sediment deposited each melt season, and therefore can be used to better constrain minimum subglacial sediment fluxes. The esker beads in central Nunavut produce minimum sediment fluxes in the range of 10^3-10^4 m^3 yr^{-1} per subglacial conduit, which drained meltwater across stretches of the ice sheet 6-10 km in width.
- There is a general qualitative correlation between the esker bead size and bed substrate, with larger beads more frequent in the zone covered by a thick till blanket. We suggest the prevalence of esker beads across this marine terminating sector of the former Laurentide Ice Sheet is a result of lower sediment fluxes that were unable to backfill conduits at a rate greater than the pace of ice-margin retreat. The switch to more continuous esker ridges on higher ground to the north may reflect a slowdown in retreat as the ice became terrestrially terminating or an increase in sediment supply. We therefore suggest that the esker ridges also formed time-transgressively, but that sediment backfilling of the subglacial conduit outpaced retreat resulting in headward esker growth close to but behind the margin. The implication, in accordance with recent modelling results (Hewitt & Creytts, 2019), is that eskers in general record a composite signature of ice-marginal not subglacial drainage, although we cannot rule out the latter sometimes occurring.

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