We thank Anna Hughes and the two anonymous reviewers for their comments on our paper. Their suggestions are very fair and have helped to improve the paper. In particular, reviewer 2 had two major comments, in response to which we have made significant changes. This includes, (i) expanding on the original pioneering work on esker beads by De Geer and removing reference to our study being the most robust demonstration of these beads as annual features; and (ii) modifying our explanation for the close relationship between eskers and De Geer moraine to remove reference to the terrestrial study by Price (1970) and instead focusing on the potential for winter re-advance of the ice margin or that ice-marginal advance/retreat is out-of-phase with the start/end of the melt season. We have also responded to the more specific comments by the three reviewers.

Our responses can be found below. Reviewer comments are in black and our replies in blue.

On behalf of all co-authors,

Kind Regards,

Stephen Livingstone

Reviewer 1

This is a well-crafted paper. The presentation is already very high quality, both in terms of writing and the visuals. The study is rigorous and the interpretations are well justified by the generated data and analysis. I particularly like how the authors present alternative interpretations that exist in the literature about esker formation, and frame their analysis around supporting one of these. The relationship between esker beads and de geer moraines makes their interpretation seem fairly clear. The beaded esker vs. continuous ridge esker seems to have implications in sediment supply and ice margin history (retreat rates), both topics that are very interesting and well explored.

Thank you for these kind comments.

11, I think “across central Nunavut” lets the reader imagine a much larger area than you actually studied, reword

We have changed to “in central Nunavut”

18, report ages in cal yr BP

Done.

24, no need to write “former” before Laurentide Ice Sheet. It is already defined as a former/Pleistocene ice sheet. Change here and throughout.

We have removed former and also searched and changed throughout the rest of the manuscript.

25, the tense of the writing shifts around. Already in the abstract, authors write in first person, here there is a switch to third person “are hypothesized” I suggest leaving all in first person.

We have changed to the first person here to be consistent with the rest of the abstract.

48, change beads to bead

Done.

66, relief does not have units of asl, that’s elevation

Deleted asl.

70, do crag and tails need bedrock, can they wholly form in till?

Crag-and-tails do need bedrock by definition. We have reworded to make this clearer.

73, awkward to say Keewatin Ice Divide and later say that its location shifts, reword

The Keewatin Ice Divide (KID) by definition represents the last position during deglaciation, not during the LGM. Lee et al., (1957) who defined the KID considered it as "the zone occupied by the last glacial remnants of the Laurentide Ice Sheet west of Hudson Bay". All the other ice divide positions are in Keewatin but cannot be termed "KID". To make this clear though we have rephrased as "the final location of the Keewatin Ice Divide.

Lee, H.A., Craig, B.G. and Fyles, J.G., 1957. Keewatin Ice Divide. Geological Society of America, Bulletin 68, 1760-1761.

79, This might be a stylistic thing in writing because it appears here and elsewhere, maybe it is a British thing (sorry, as an American I may follow different rules, subtle different), but is the word "on" required between "ice masses" and "either side"? I see this grammatical situation several times in this ms.

We have changed to include the "on" as per the suggestion.

115, I would find this paragraph more helpful if there was added clarification of patterns above and below marine limit. It is in there I think, or maybe it is in the next paragraph, but being clear about where the ML is and how features are different above and below – with just a touch more clarity – would be useful.

We agree that this could be more clearly defined, and have added an additional sentence in the paragraph below, where we clarify the differences in bead morphology and pattern above the marine limit – "Above the marine limit, beads are almost exclusively mound-shaped and tend to be smaller and form less coherent and more widely dispersed chains."

194, not "only" because you said previously that 10% occur above the marine limit

We have deleted "only".

201, "on" either side, as mentioned earlier.

Done.

203, sentence beginning with "In particular" needs some attention

To make this easier to read we have numbered the key lines of evidence and shortened it slightly with the final summary presented as a separate sentence.

261, "on" either side, as mentioned earlier.

Done.

274, "relatively" in place of "relative"

We mean relative in that that chronology cannot be tied to absolute ages; – it is a floating chronology. This idea of relative vs absolute chronology has precedent in glacial geomorphology (e.g. relative ages based on cross-cutting relationships of drumlins/lineations). However, we agree this maybe lacks clarity and so to make clearer have simplified the sentence by deleting relative and changing to "…could be used to produce an annual chronology of ice-margin retreat."

304, "provide" no s

Done.

319, "farther" better here than "further"

Done.

370, extra parenthesis

The extra parenthesis has been deleted.

371, check punctuation with use of however

We have modified to "This is probably not surprising, however, given…"

370, hereabouts, could mention (or not, your call) any implications about glacial erosion rates. Note of course that ultimately that's what is implied here, perhaps even more specifically quarrying rates (as opposed to abrasion, which produces fines that might leave the system as suspended load).

Although we would have liked to take this additional step to discuss erosion rates, on reflection, we think this would be too large a step as we do not know the size of the whole catchment area. Although we can say something about the width over which the conduit influences (based on esker spacing), we do not know how far up-ice the conduits extended (which might depend on ice thickness, water inputs, hydraulic potential etc.) as the beads only provide information about marginal deposition. We therefore prefer not to extend the analysis to erosion rates.

377, marine-terminating, no need of "former"

Deleted former.

380, would the broad ice margin here really slow down when it is above the marine limit – hard to imagine that water depths would have been deep enough to have a major influence on calving, nor that overdeepenings or pinning points (which typically come with high relief areas) would significantly offer significant control on ice dynamics?

Besides, can your method of reconstructing retreat rate not reveal rates of recession when the ice terminus was in water vs on land?

This is a good point although not one we can readily test as although beads do occur above the marine limit they are considerably more sporadic (esker ridges tend to dominate), making it challenging to derive accurate retreat rates in the terrestrial sector. In addition, even if the water were shallow, we might still expect the ice to melt faster compared to if it was terrestrially terminating (e.g. from observations of icebergs, where they often undercut at the waterline). We therefore retain the idea that the switch to a terrestrial margin could have caused a slowdown in retreat (based on the cessation of calving as a process for removing mass) but note that this is one of a number of reasons that could explain the switch in morphology.

402, esker beads instead of eskers beads

Done.

402, more mixed voice (first person and third person interspersed)

Done, we have moved to just first person here.

411, another "either side" grammatical thing

Done.

421, another "former" LIS

Deleted.

427, provides no s

Done.

428, deposited "during" each melt season

Done.

434, former

Deleted.

Reviewer 2

The paper by Livingstone et al. titled "A quasi-annual record of time-transgressive esker formation: implications for ice sheet reconstruction and subglacial hydrology" is presented in high quality concerning both the text and figures. The study uses new methods (ArcticDEM) to map and analyse a large number of esker segments over a wide area in central Nunavut, Canada, to discuss esker formation and the implications for reconstructing subglacial drainage. The paper is within the scope of, and well suited for, The Cryosphere. The authors present interesting new results on the morphometric properties of the eskers and their relationship with de Geer moraines. These finds have the potential to have important implications and significance for reconstructions of subglacial drainage and sediment transfer of ice sheets.

Thank you for these kind comments!

However, I do have some major concerns, both concerning the originality and the quality, of the interpretations of, and suggested models of formation for, esker beads and de Geer moraines which I would like to see addressed before I can recommend this manuscript for publication. My concerns and comments are specified below.

Originality of the proposed model of esker formation:
One of the main finds put forward in this manuscript is the identification of annual esker "beads". The authors do mention that esker beads being annual has been proposed in earlier studies but argue that their data "provides a more robust demonstration" (p. 15, line 304), a statement I strongly disagree with. The annual nature of such eskers beads were exemplified over 100 years ago based on many years extensive mapping and detailed sedimentological and stratigraphic work in Sweden, where such "beads" were correlated to annual ("de Geer") moraines and even individual glacial varves (see: de Geer 1897; 1905; 1910; 1940). The early works are published in Swedish (de Geer 1897; 1905) and German (de Geer 1910), but nonetheless they are well cited and by no means "hidden" in the litterature. There are also a more recent English translation of de Geer (1910) by Dullo & Hay (2002), and the works by de Geer is also summarized in English in de Geer (1940), which is actually cited in this manuscript. As a matter of fact in Sweden, and also in some Canadian work (e.g. Allard, 1974),

this type of eskers (with annual "beads") are referred to as De Geer type - eskers. The results presented in this manuscript are still new, interesting and important data from a remote and not so well studied area, but it is not more robustly or convincingly demonstrated in this manuscript that these beads are annual when compared to previous studies. If you disagree, please provide an explanation of why your data provides a more robust demonstration. I recommend adding some of the key references relating to the early pioneering works on beaded esker formation, i.e. de Geer (1897; 1910), and include a discussion how these relate to your findings. We should not let the hard and impressive work of our old heroes to fall into oblivion and take credit for "reinventing the wheel"!

This is a very helpful comment and we agree with the reviewer that we overstretched the originality of our work. In particular, signposting us to the English translation of De Geer (1910) was particularly helpful – we have not come across this before. To rectify this, as proposed by the reviewer, we have removed the statement "provides a more robust demonstration", included some of the key pioneering references of De Geer (see reply to specific comments below) and also expanded a few of the paragraphs. This includes, adding a description of how De Geer correlated esker beads to De Geer moraine and the varve record in Sweden (final paragraph of section on: 'A model for quasi-annual deposition of esker beads in an ice-marginal marine setting'), a sentence on the implications for esker ridge formation, which De Geer actually described in his 1940 paper (in section on: 'Implications for understanding subglacial drainage') and a note in the final bullet point of the conclusion making reference to how our work agrees with his pioneering work.

Esker bead- and De Geer moraine formation model:
In this manuscript, the annual nature of the esker beads are based on their relation to, assumed, annually formed de Geer moraines (similar to de Geer, 1910). De Geer moraines are assumed to be annually formed following the original hypothesis of them being formed during winter advances/standstill of the ice margin during overall retreat (de Geer, 1889), so far, so good. However, in this manuscript the authors then argue that, based on the relation between esker beads and moraines, the moraines are formed during summer melt seasons by deformation and squeezing of saturated till to the ice margin and refer to the process described by Price (1970). Price (1970) is, however, a study of a terrestrial ice margin on Iceland, so say that this process did produce the moraines, why do we not see De geer moraines above the marine limit (line 170)? and how can one still explain that they still are formed annually? How can you explain the gap between the moraines? What is there that speaks against the moraines simply being formed during winter advances that reaches the esker bead from the previous year, by the same process you describe on line 226-228? Or, that esker beads start to form prior to the onset of summer retreat from the moraines? Ice marginal advance/retreat is not necessarily in phase with the start/end of melt season as observed at present day ice margins (e.g. Schild & Hamilton 2013).

On reflection, we agree that a summer formation for the De Geer moraine is not the simplest explanation, particularly in light of reading Schild & Hamilton (2013), and the observation that De Geer moraine are not always associated with esker beads. We have therefore simplified the key paragraph, by removing the reference to Price (1970) and summer De Geer moraine formation, and concentrating on the options proposed by the reviewer. We have added the following section in place of the previous text: "This can be explained by the ice-margin re-advancing to the previous year's esker bead, and/or deposition of the esker bead prior to the onset or after summer retreat from the moraine. The latter suggestion is consistent with observations at present day ice margins, which indicate that ice-marginal advance (retreat) is out-of-phase with the start (end) of the melt season (e.g. Schild & Hamilton, 2003)."

Further comments (line number, followed by comment):

18, give calibrated ages and be consistent with the use of either "yr" or "a" (kyr/ka), here you use "yr" but further down in the manuscript you suddenly use "ka" change throughout the manuscript.

We have decided to stick to kyr and yr, and have corrected throughout the manuscript.

19, choose either kyr or ka

Done

22, choose kyr or ka

Done

41, here I miss a reference to the pioneering work by de Geer (1897). De Geer (1910) and/or de Geer (1940) would also suffice.

We have added in De Geer (1897, 1910, 1940).

85 (Figure 1), use either ka or kyr in the figure.

Done. We have used kyr to be consistent with the rest of the document.

139, how do you distinguish "till blankets"? From ArcticDEM or aerials? Geological maps? please specify.

We agree this is obtuse and have added a line in the methods where we state where these data are from, how they were derived and defined the key units referred to in this manuscript.

Figures 3-4, Beautiful figures!

Thanks.

184-185, as also mentioned above on line 41, here I miss a reference to the work by Geer concerning "hypothesis 1".

We have added a couple of the key De Geer references here – De Geer (1897, 1910).

Figure 5, See my comments on the proposed model for esker bead and de Geer moraine formation above.

We have removed reference to the variable pressure axis in light of the simplifications we have made to our proposed model and also modified the caption to make clear when the beads and De Geer moraine likely formed in relation to each other.

228-229, This view of these smaller interannual moraines proposed by Möller (1962) is not a generally accepted view. Please rephrase this sentence with e.g.: "proposed" or "suggested by Möller (1962).

We have rephrased this sentence along the lines proposed by the reviewer: "Möller (1962) suggest that…"

251-264, See my comments on the proposed model for esker bead and de Geer moraine formation above.

See reply to major comment above, we have adapted our model to keep the simplest idea that esker beads are formed in summer and De Geer moraine in winter.

273-275, This sentence reads like you are the first to come to this conclusion, please add a reference to e.g. de Geer (either 1910 or 1940), who suggested and showed that this was the case.

We agree and have added a reference to De Geer (1910).

277 & 281, use either “yr” or “a”

See above, we have decided to use kyr and yr throughout the manuscript and we have checked for consistency.

304, see my comments above concerning if your results are more robust.

We have deleted “…but we suggest our data provides a more robust demonstration” and also added in the 1897 and 1910 De Geer references.

309-310, use either “yr” or “a”

Done

329, “Identification” is a strong word. You have not proven that the beads are annual, you can however suggest that they are based on the assumption that the de Geer moraines are annual. Please rephrase.

We agree and have rephrased to “Our suggestion that beaded eskers are an…”

368 & 370, use either “yr” or “a”

Done

Figure 9, Please add north arrow to the maps.

Done.

409-412, See my comments on the proposed model for esker bead and de Geer moraine formation above.

We have removed the idea that the De Geer moraine formed in summer and replaced this sentence with: “The co-alignment between De Geer moraines and esker beads suggests that the ice-margin re-advanced to the previous years’ esker bead, and/or the esker bead was formed prior to the onset or after summer retreat from the moraine.”

420, To say that the beads “records a high-resolution (annual) record” is to strong. You infer them to be annual but have yet to prove that they are. Please rephrase.

Have rephrased to “We propose that the downstream spacing of esker beads records a high-resolution (quasi-annual) record…”

422-423, use either “yr” or “a”

Done

433, again, how do you know the thickness (and presence) of a till blanket?

See comment above, we have added in details of these data we used and how it was derived in the methods.

<u>Reviewer 3</u>

This paper presents new mapping of esker-bead chains in central Nunavut, Canada identified using the high-resolution ArcticDEM dataset. Consistent with previous research, the authors found the beads to be associated with De Geer moraines. Based on this association and the fact that De Geer moraines have an annual deposition cycle the authors reconstruct the rate of ice-margin retreat for this sector of the Laurentide Ice Sheet. Such precise quantitative information is relatively rare. A previous reviewer states that the finding that esker-bead chains have a regular deposition phasing is not new. This literature is cited by the authors. Nevertheless, the paper remains important as supports the previous findings in a new geographic location, thus confirming the regular phasing of these landforms and role to provide information on rates of retreat where they are found, when De Geer moraines may be absent. Figure 5 is excellent in this regard.

I found the paper to be well written and a pleasure to read. The description of the mapping methods and results are comprehensive and clear. Figures are high quality, although see comments below.

Thank you for these kind comments.

Figure 2/7: There is a lot of colour on A in these figures – which I appreciate, but I wonder if the figures have been checked for colour-blindness suitability. Some of the dots to indicate area (A) are overlapping, I wonder if these could have been displayed as relative size empty circles to account for this? Without testing, this may or may not improve things.

We agree there is a lot of colour in these figures, potentially making it difficult to decipher, and especially if you are colour-blind. We have therefore made the map panels (subpanel A) full page width so more detail can be seen, and made the background colour greyscale. When constructing the figures, we initially tried using relative size empty circles, but this becomes quite messy and difficult to identify patterns/colours so we prefer to stick with the filled dots even though we agree there is some overlap (we have made the dots partially transparent to help with this a bit).

Figure 8. There is a lot of information in this figure and it took me some time to understand. As for figure 2 and 7 the colour choice needs checking. For B the bin size of 5 km seems quite high considering most esker beads are <1 km apart. Although this would likely not change the conclusion that similarly-spaced beads are associated with the same retreating margin transverse to the orientation of the chains.

As with the above figures, we have changed the background to greyscale to make the coloured points easier to see. We prefer to stick to the 5 km bins – we chose these to try and reduce some of the noise to identify broad general trends.

95: practice 310: These appear to be reasonable (if relatively fast) retreat rates for a marine-terminating margin. Suggest that a citation is added here to make comparison to other former retreat rates in similar glaciological settings (either modern or palaeo).

This is a good idea and we have added the following sentence to put the retreat rates into context: “These retreat rates are consistent with, but towards the upper end, experienced by marine palaeo-ice streams (e.g. Winsborrow et al., 2010; Livingstone et al., 2012) and contemporary marine terminating outlet glaciers in Greenland (e.g. Howat & Eddy, 2011; Murray et al., 2015).”

343: suggest insert - ‘that spacing of subglacial channelised...’

Done

361: add - ‘accepting this interpretation’ or similar to caveat this statement

Done

# 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~~ in 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~~8.1 and 6.8 cal. kyr~~a~~ ~~$^{14}$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 from conduits 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. Conversely, we hypothesise that ~~E~~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 m~~etres~~ 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~~ close to the ice margin as it retreated (e.g. De Geer, 1897, 1910, 1940; 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 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 bead~~s~~ 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 conduit 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 in~~,~~ 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 above sea level (a.s.l.), but in general ~~the area is~~land lies below~~ 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~~2-20 m) blankets the portion of the study area south of the inlet (Fig. 1). The till has been moulded into drumlins~~,~~ and flutes and formed crag-and-tails in the lee of bedrock obstacles (e.g. McMartin & Henderson, 2004).

The study area partially straddles and is just to the southeast of the final location 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 that 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 kyr~~a~~ $^{14}$C BP (8.1 and 6.8 cal. kyr~~a~~ BP), with the final vestiges of ice splitting into two small ice masses on either side of Chesterfield Inlet (Dyke et al., 2003; Dalton et al., 2020). 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~~ and 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).

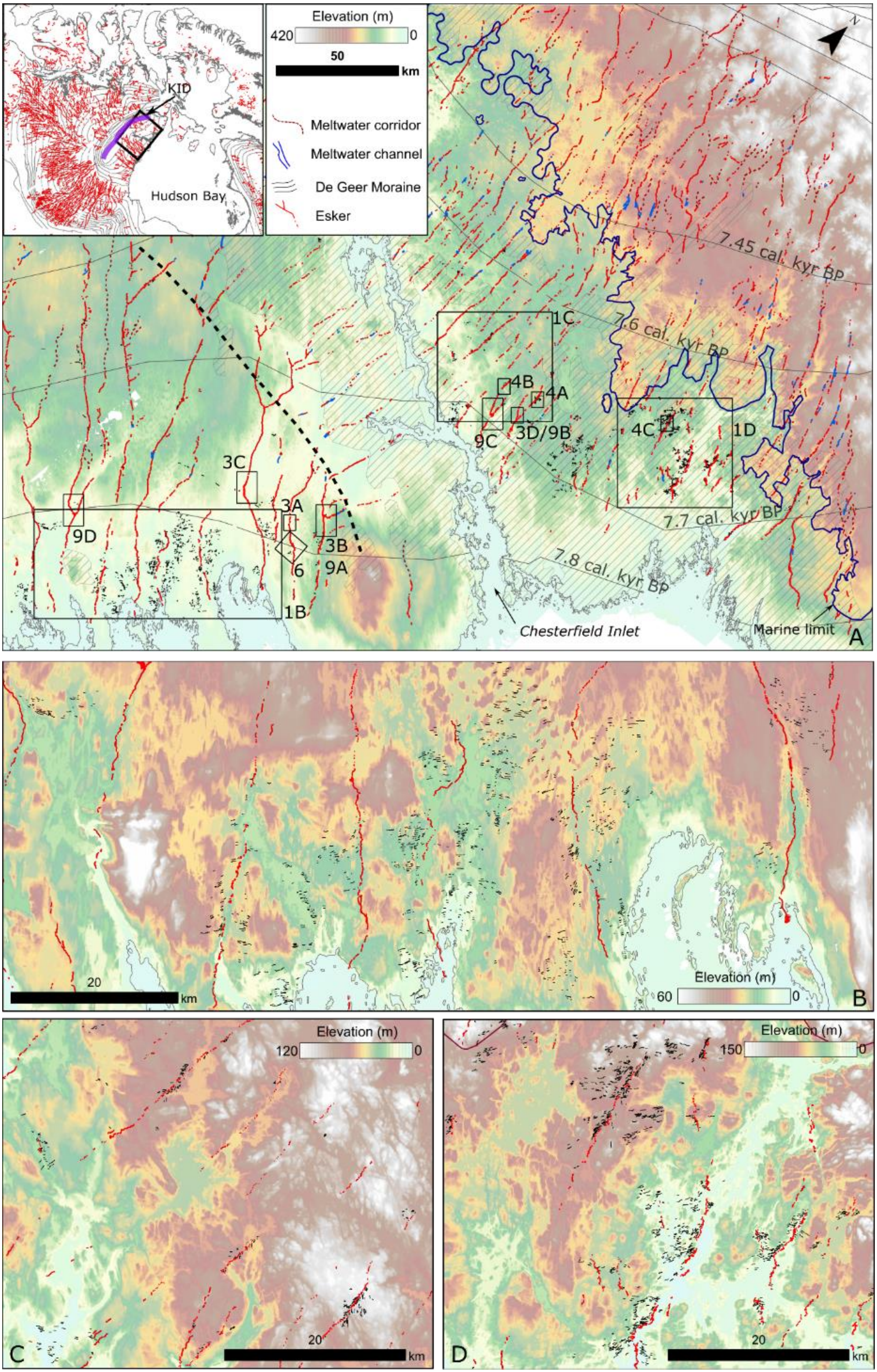

KID
Hudson Bay
Elevation (m)
420
0
50
km
Meltwater corridor
Meltwater channel
De Geer Moraine
Esker
N
7.45 cal. kyr BP
7.6 cal. kyr BP
7.7 cal. kyr BP
7.8 cal. kyr BP
1C
4B
4A
9C
3D/9B
4C
1D
3C
3A
9D
3B
9A
6
1B
Chesterfield Inlet
Marine limit
A
20
km
Elevation (m)
60
0
B
Elevation (m)
120
0
20
km
C
Elevation (m)
150
0
20
km
D

**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 regional mapping of eskers (Storrar et al., 2013). Black ~~dotted~~ dashed line indicates the approximate axis of a re-entrant along which we interpret the two ice masses pulled apart. Solid ~~black~~ dark blue line is the marine limit modified and extended from Randour et al. (2016). Grey hatched lines are areas of exposed bedrock and annotated solid grey lines are ice-margin positions extrapolated from Dyke et al. (2003). B-D. Zoom-ins showing the ~~relationship between~~pattern of De Geer moraines and eskers. DEMs created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

## 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. Surficial materials were taken from Fulton (1995), who mapped till thickness from aerial photographs (till veneer = <~2 m and till blanket = >~2 m).

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 successive beads' centre-points along the same meltwater axis and calculated, for a given bead, as the average of ~~both~~ its distance to the bead upstream ~~($d+1$)~~ and its distance to its bead downstream ~~($d$-$1$) of iteach~~. 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 proto-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 mean 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 here 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 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. Above the marine limit, beads are almost exclusively mound-shaped and tend to be smaller and form less coherent and more widely dispersed chains. 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.

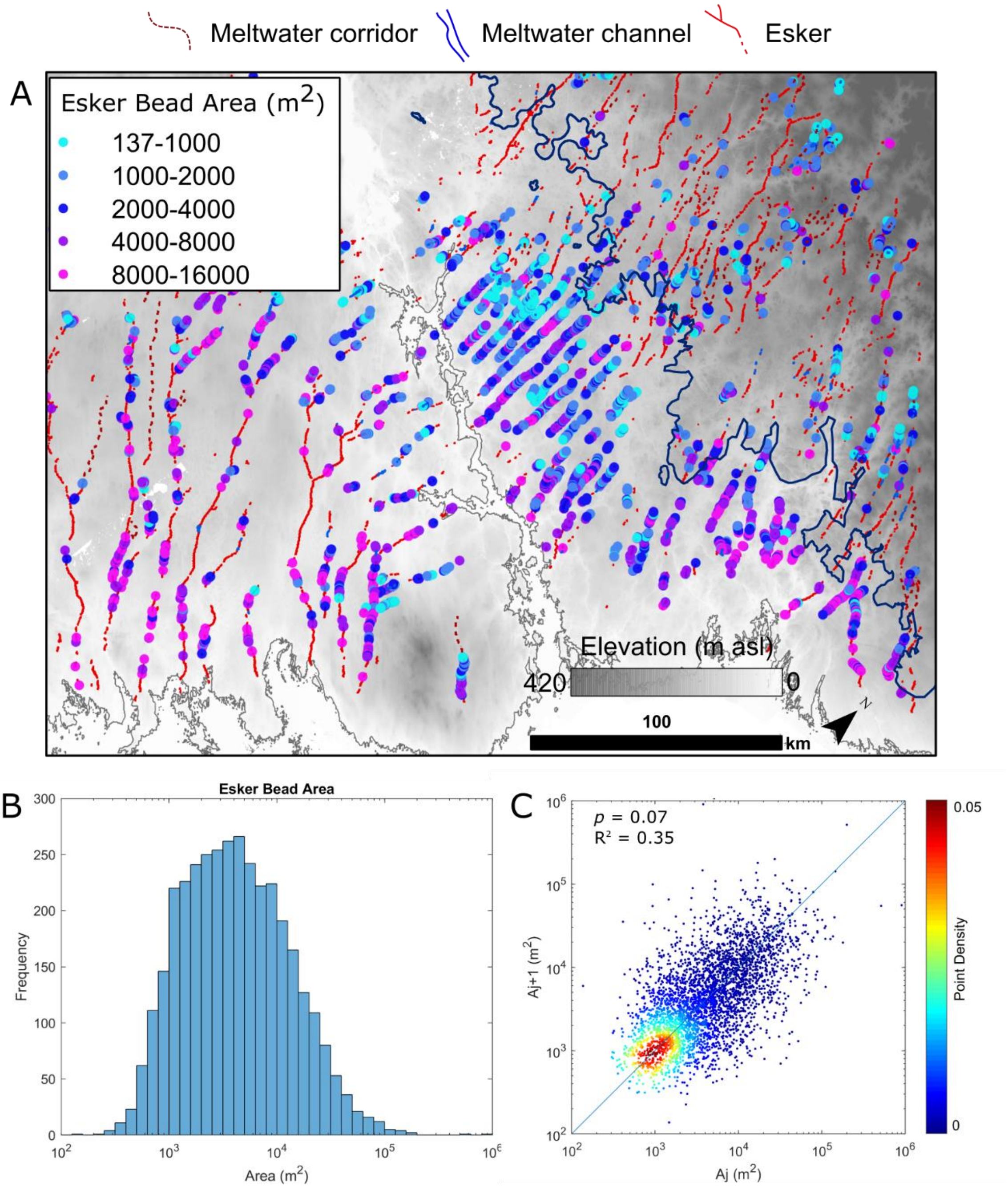


**Figure 2:** Esker bead locations and area. A displays their spatial pattern. The dark blue line is the marine limit. B Frequency histogram of bead area. C Leading order variogram, where $A_j$ is the area of an esker bead and $A_{j+1}$ is the area of its up-ice neighbour. Where neighbouring esker beads 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, t~~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.

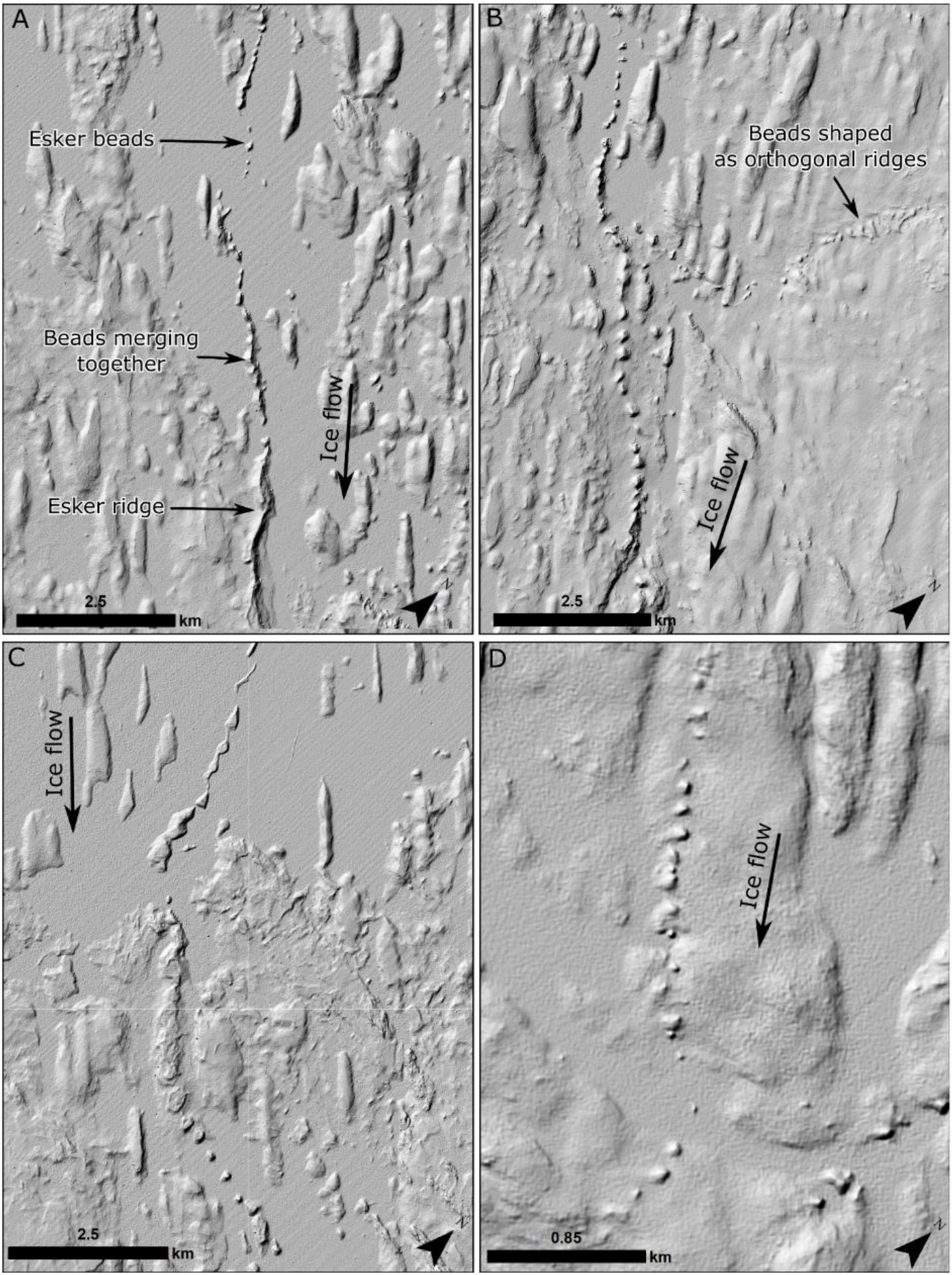


**Figure 3:** Examples of beaded eskers. (A) Transition between a classical esker ridge and esker beads, some of which are merging together to form a ridge-like form due to their large size and/or close spacing. Note how the beads range in shape from ridge-like (B) to triangular (C), flat-topped (C) 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.

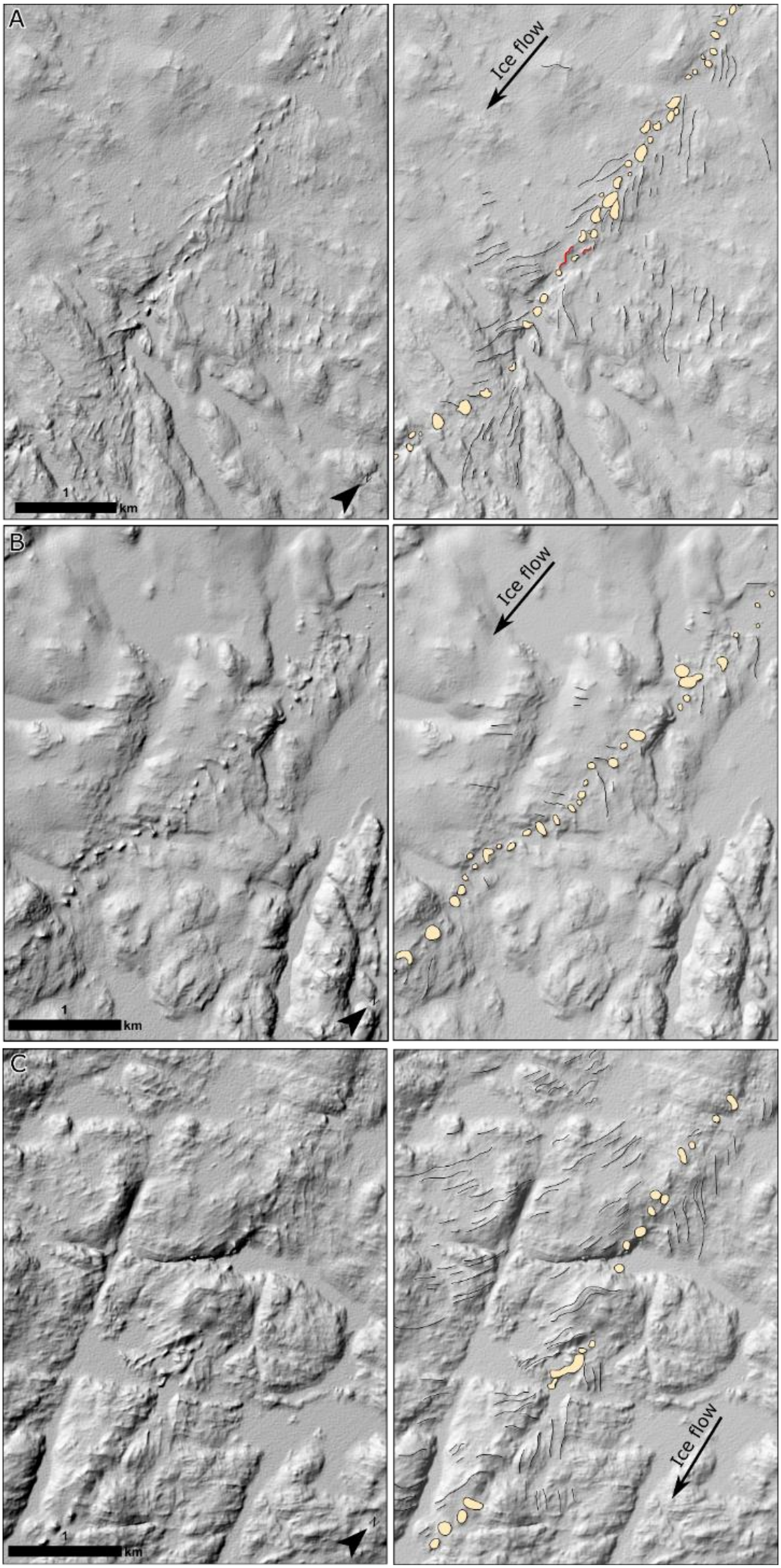

A
1
km
Ice flow
B
1
km
Ice flow
C
1
km
Ice flow

**Figure 4:** Relationship between esker beads and De Geer m~~M~~oraines. 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 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). Ridges observed on the ground are subtle, narrow features with no clear asymmetry and are commonly composed of sandy diamicton with a significant boulder cover. 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 retreating 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. De Geer, 1897, 1910; 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 12~~8~~0 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~~1-2~~4~~ km on 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, (i) some of the beads have a flat-top indicating sedimentation up to the water level; (ii)~~,~~ fan-shaped beads tend to be orientated down-stream rather than orthogonal to water-flow; (iii)~~,~~ where a bead grades into a ridge this occurs in an up-ice direction;~~,~~ and (iv) beads are strongly aligned (i.e. do not deviate from a central axis) (Figs. 3-4). Together, these~~, all of which~~ morphological observations 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.

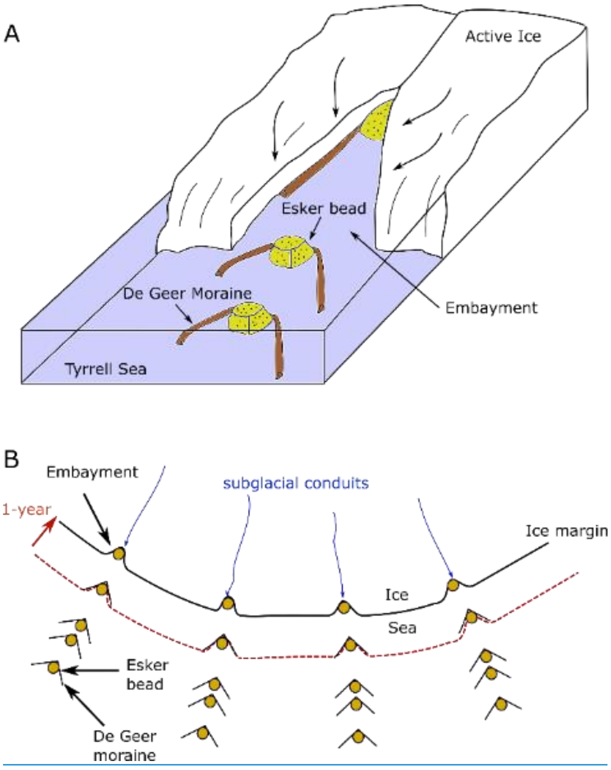


**Figure 5**: A. 3D schematic showing the proposed quasi-annual formation of esker beads and De Geer moraines in embayments at a marine grounding line (modified from Warren & Ashley, 1994). ~~Note,~~ De Geer formation likely occurred during subsequent winter ice re-advance-, and/or deposition of the esker bead prior to the onset or after summer retreat from the moraine. ~~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 inferred palaeo-ice margin.

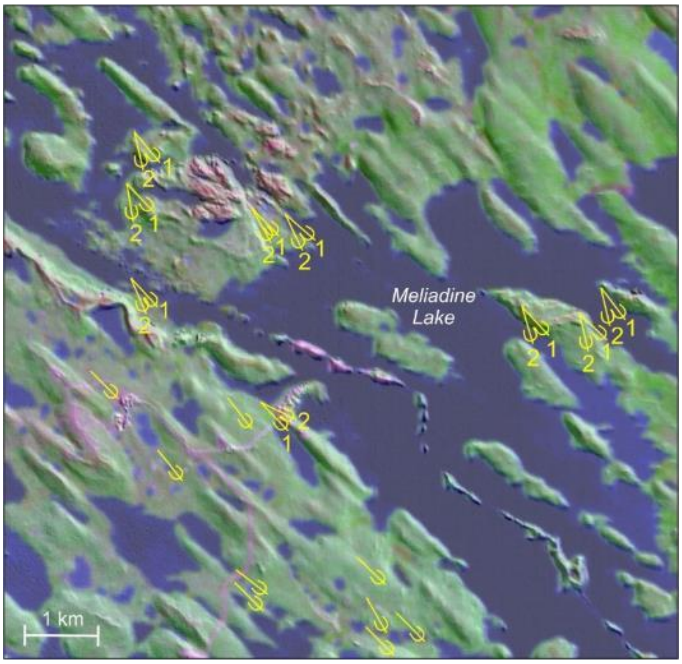


**Figure 6:** Pattern of striations (yellow arrows) either side of the Meliadine esker beads, showing convergence towards the esker (#2 arrows). Background is a LANDSAT-8 satellite image~~ry~~ (Bands 754) on top of the ArcticDEM.

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. Möller (1962) suggested that ~~Where~~ intra-annual moraine ridges ~~have been observed, they have tended~~tend 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 the 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 in the bead spacing measurements, particularly where esker beads are widely spaced (likely due to breaks because of non-deposition and/or~~/~~ 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.

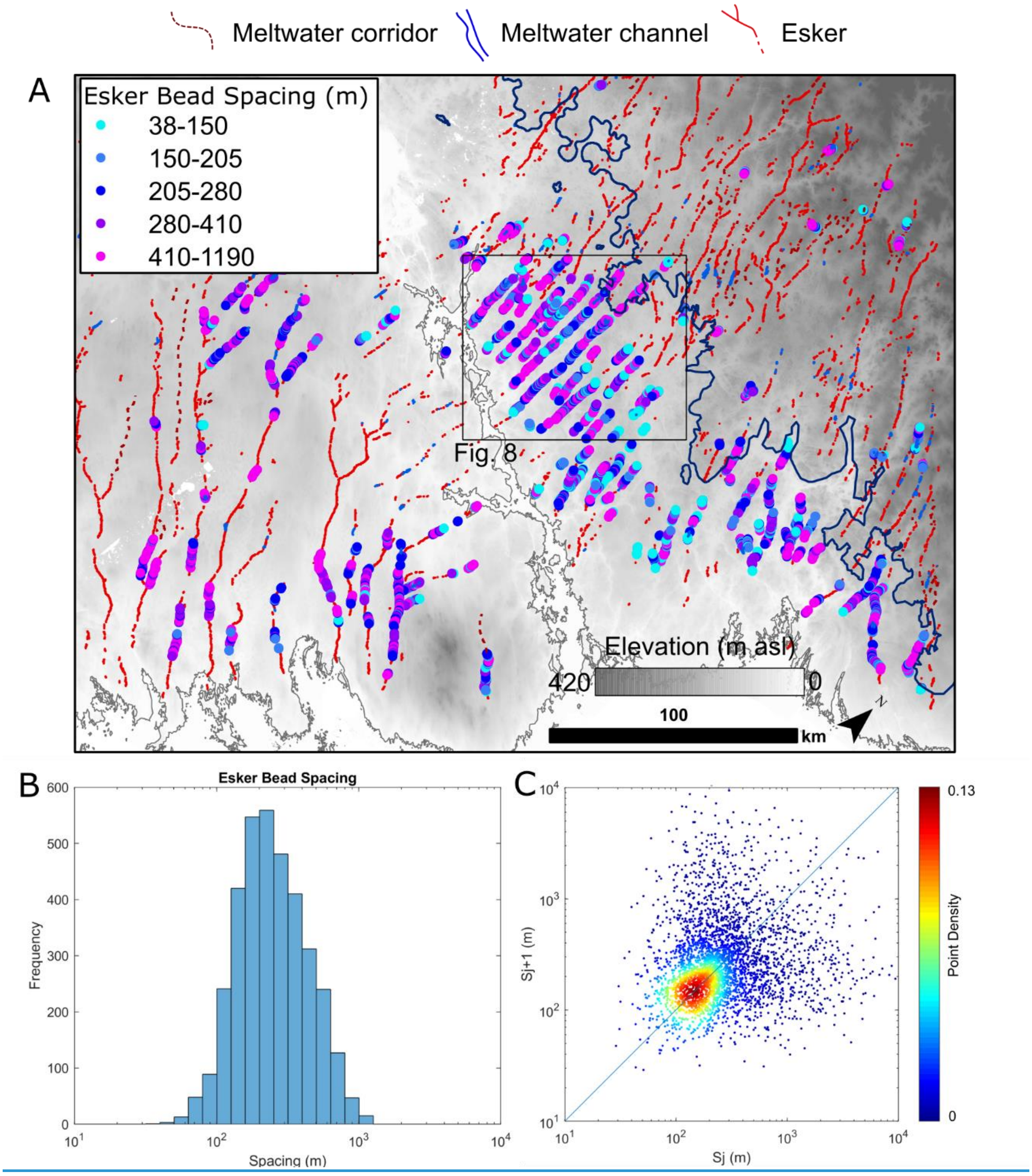


**Figure 7:** Along-esker bead spacing. A is the spatial pattern and B the frequency histograms. Black box is the location of Figure 8. The ~~black~~dark blue line in A is the marine limit.  Median spacing is 240 m. C. Leading order variogram, where $S_j$ is the spacing of an esker bead and $S_{j+1}$ 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.

Although we prefer an annual origin to explain the regularly-spaced De Geer moraines and their 1:1 relationship with beads, the traditional hypothesis that De Geer moraine~~they~~ formed each winter as ice underwent a minor re-advance (e.g. De Geer, 1940) ~~is difficult to reconcile~~needs to be reconciled 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~~This can be explained by the ice-margin re-advancing to the previous year's~~'~~ esker bead, and/or deposition of the esker bead prior to the onset or after summer retreat from the moraine. The latter suggestion is consistent with observations at present day ice margins, which indicate that ice-marginal advance~~/~~ (retreat) is out-of-phase with the start~~/~~ (end) of the melt season (e.g. Schild & Hamilton, 2003).

~~ 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 in the study region 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 an~~ relative high-resolution,~~ annual chronology of ice-margin retreat (e.g. De Geer, 1910). 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 final location of 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~~ Dalton et al. (~~2003~~2020) suggest that ~~final~~ retreat proceeded across a distance of ~~~85~~ 215 km over ~~250~~ 1.2 kyr~~years~~, which equates to a mean retreat rate of ~~~340~~ 180 m yr$^{-1}$. This is a rough estimate~~figure~~ given uncertainties in radiocarbon dating and poor age control in this region, however, it is ~~of the same magnitude as~~comparable to that calculated from the esker beads.

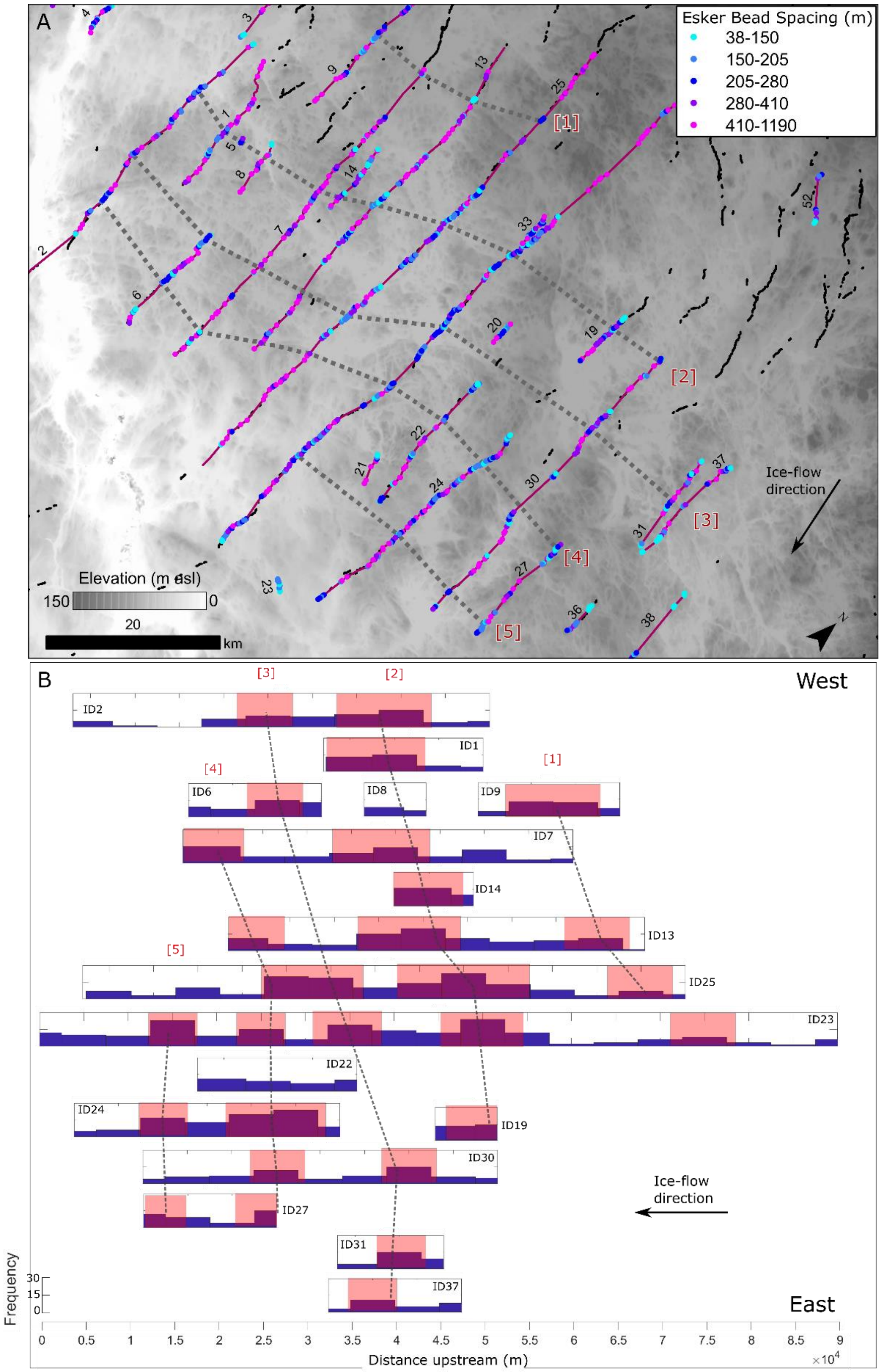


**Figure 8:** Esker bead downstream spacing-distance plot. A shows the spatial distribution of beaded eskers and average downstream spacing between two nearest beads (location shown in Figure 7). Black lines are esker ridges. B is a frequency-density histogram of esker beads along esker axes (numerical 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.

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 origin~~al~~ for esker beads (e.g. De Geer, 1897, 1910, 1940; Banerjee & McDonald, 1975)~~, but we suggest our data provides a more robust demonstration~~. In particular, De Geer (1897, 1910, 1940) was able to correlate esker beads to De Geer moraine and the annual glacial varve record in Sweden based on extensive mapping and detailed sedimentological and stratigraphic investigation.

## 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 (years to a few decades) of more rapid retreat (>400 m $yr^{-1}$) (Fig. 7). These retreat rates are consistent with, but towards the upper end, experienced by marine palaeo-ice streams (e.g. Winsborrow et al., 2010; Livingstone et al., 2012) and contemporary marine terminating outlet glaciers in Greenland (e.g. Howat & Eddy, 2011; Murray et al., 2015). 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~~ terminating 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).

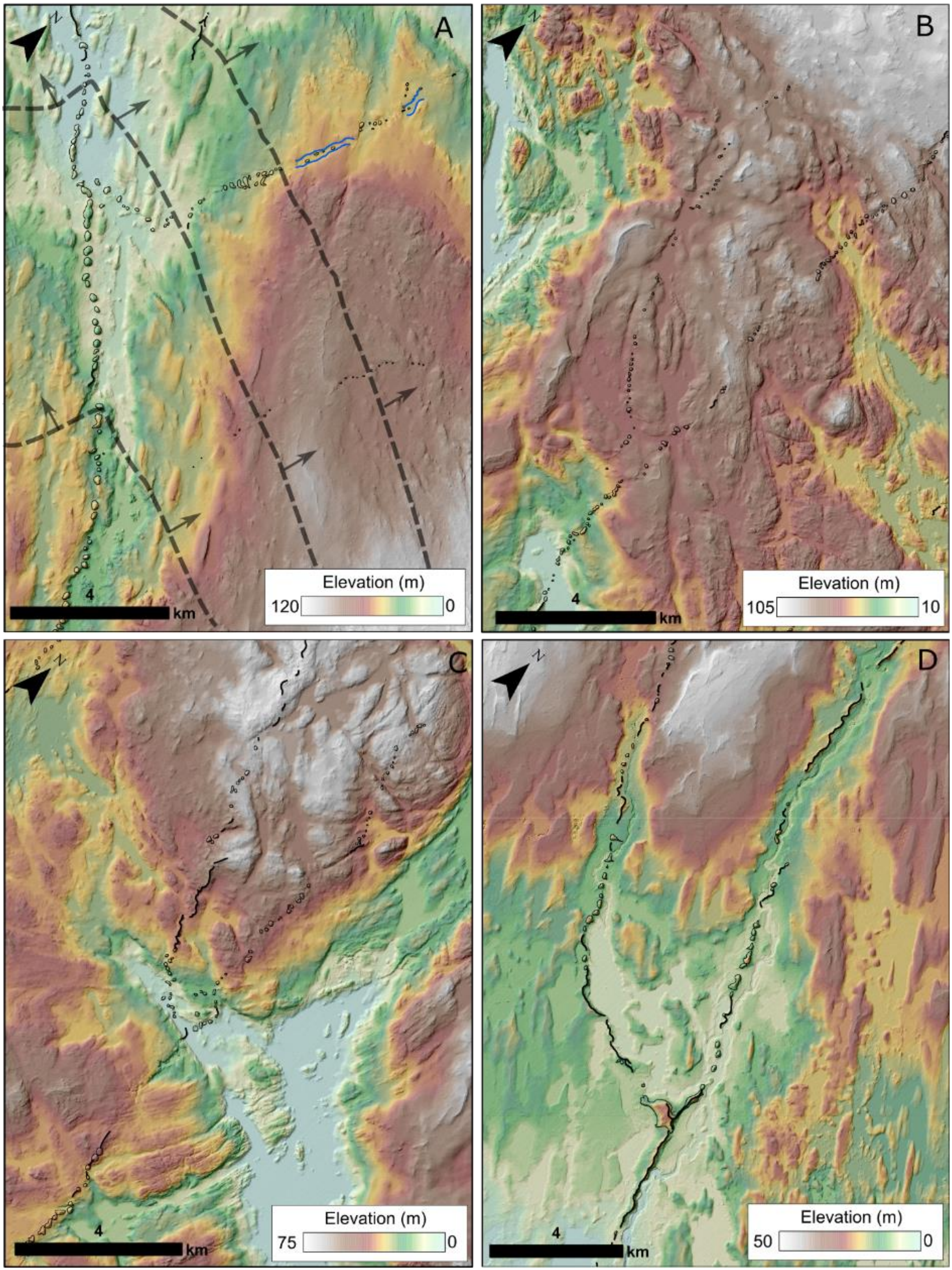
To explain the two distinct time-transgressive esker networks, orientated N-S and NW-SE, the ice sheet must have split into two ice masses with a large re-entrant to the south of Chesterfield Inlet (black ~~dotted~~ dashed line in Fig. 1). This is consistent with fragmentation of the ~~Keewatin Ice Divide~~ice sheet into two smaller ice masses on either side of Chesterfield Inlet during the final stages of deglaciation (Dyke et al., 2003; Dyke, 2004). The more northerly centre of ice ~~mass~~ dispersal must have migrated fa~~u~~rther 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~~ illustrated 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~~Our suggestion that ~~of~~ beaded eskers ~~as~~ are 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 ~~from the esker ridges themselves,~~ and will not be met if different sets of eskers ~~could have been~~were deposited subglacially at different times during deglaciation to form the network observed today. In contrast, because the esker 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~~Consequently, 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 for over ~~>~~100 km, spanning ~350 years of deposition (Fig. 1), indicating that spacing of 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, accepting this interpretation, esker beads record the volume of sediment deposited each melt season, and can therefore be used to better constrain subglacial conduit 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 esker 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~~These inferences are consistent with those of De Geer (1940), who identified esker ridges composed of a series of annual fans deposited on top of each other, and with recent modelling results (Beaud et al., 2018; Hewitt & Creytts, 2019), and implies that eskers record a composite pattern of near-margin subglacial drainage.



735 **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.

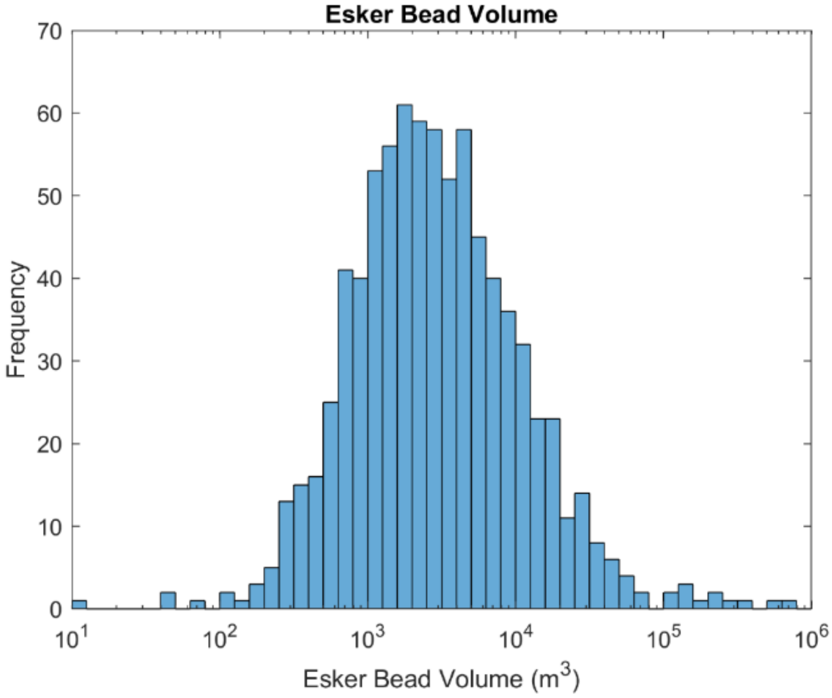


**Figure 10:** Esker bead volume. Because the beads are interpreted as quasi-annual and the lateral spacing of the eskers is thought to reflect the true spacing of the subglacial conduits, these volumes represent a minimum sediment flux per year per 6-10 km ice-margin width.

## Conclusions

We mapped nearly 10,000 esker~~s~~ beads and ridge segments from ~~the~~ high-resolution (2 m) ArcticDEM data across an 87,500 km$^2$ area of central Nunavut, around Chesterfield I~~i~~nlet, NW of Hudson Bay. Our ~~M~~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 located 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 co-alignment of~~relationship between~~ De Geer moraines and esker beads suggests that the ice-margin re-advanced to the previous year's~~'~~ esker bead, and/or the esker bead was formed prior to the onset or after summer retreat from the moraine. ~~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.
- We propose that ~~T~~the downstream spacing of esker beads records a high-resolution (quasi-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 provide~~s~~ an appropriate set of observations for testing the esker-spacing theory.
- Esker beads record the volume of sediment deposited during each melt season, and therefore can be used to better constrain minimum subglacial conduit 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 the pioneering initial work of De Geer (1897, 1910, 1940) and 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.

## Data availability

The mapping of meltwater features is archived at: XXX.

## Author contribution

EL discovered the esker beads. SJL carried out the mapping and analysis, with FN writing the code for Figures 2c and 7c and IM producing Figure 6. SL prepared the manuscript with contributions from all co-authors.

## Competing interests

The authors declare that they have no conflict of interest.

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