

Reviewer 1:

We thank the reviewer for their comments which have helped us to improve the manuscript. Their key issues were regarding our discussion of ice streams and with the relative timing and mechanism of landform formation. In response to this we have
5 discussed the possibility of a lack of preservation of geomorphic signatures beneath ice streams in addition to the possibility that the dominant drainage mode and the resultant signature may be different here. In terms of our discussion on ice streams and the potential for a highly channelised bed to moderate ice velocities, previous geomorphic studies (e.g. Storrar et al., 2014) and examples in the contemporary (e.g.
10 Sole et al., 2013; Williams et al. 2020) and modelling literature (e.g. Lelandais et al., 2018) support the concept that a well-drained bed (i.e. due to increased channelisation) has the ability to stabilise an ice sheet by regulating ice sheet velocity.

In response to the reviewer comments we have also improved the link between the proposed model and the geomorphic signature in the updated manuscript and have
15 better grounded this within a growing body of theoretical, experimental and contemporary evidence, which supports; (a) the occurrence of over-pressurisation of subglacial conduits; and (b) the potential ability for geomorphic work as a result. The very nature of large-scale geomorphic studies such as this focus on providing information on where drainage does or does not occur and how differing signatures
20 can be related to background controls. As such, we do not focus on finer resolution signatures and we believe that our updated manuscript now clearly explains the temporal aspect of formation within the model (i.e. corridors forming over 10's - 100's years within the ablation zone and eskers forming near the margin) and the assumptions involved when making comments about changes over time inferred from
25 changes over space. In addition to this, we have reduced our use of acronyms throughout to make the paper easier to follow.

Reviewer comments are in black and our responses are in green.

Kind regards,

Emma Lewington (on behalf of all co-authors).

The focus of the work was on the concentration of a variety of landforms of interpreted subglacial fluvial origin in corridors and then an explanation for this. Areas previously mapped as ice streams were noted to have fewer meltwater landforms. The suggestion that this was a matter of preservation potential of landforms in these locations was not addressed.

Thank you for pointing this out. We have now included a sentence considering the possible lack of preservation of features formed in this area due to enhanced erosion of fast flowing ice (e.g. Boulton, 1996). We also acknowledge that the presence of soft floored sediments may not result in the same geomorphic signature (i.e. water may be stored in till or organised into braided canals), and thus the absence of meltwater routes does not explicitly indicate the absence of efficient flow.

The timing of the formation of the landforms can be assumed by basic geologic principles. However, in this case, the authors suggested that the landforms represented approximately 1,000 years during deglaciation and were not overly concerned with a finer temporal resolution made possible by cross-cutting relationships or ice-marginal or ice-collapse features.

Within the study area we find no evidence of cross cutting of meltwater corridors or eskers. We do find eskers within meltwater corridors and have added in a section to make the temporal aspect of our model clearer - i.e. meltwater corridors were eroded within the ablation zone due to repeated pressure fluctuations over 10's to 100's years while eskers were most likely deposited near the ice margin. This paper presents a large-scale study and we are interested in the overall trend. We agree that more detailed morphology (e.g. esker splays and anastomosing esker sections) could be informative for high resolution ice margin retreat (e.g. Livingstone et al., 2020) but this is beyond the scope of this paper.

Without more geologic evidence, I was left with questions on: the contemporaneous nature and subglacial origin of features such as tunnels and similar-dimension positive-relief features; the subglacial origin and sedimentology of the hummocks; and the origin of splay landform which is similar to ice-marginal fans. I found the justification for their interpretations lacking. However, this is part of the very nature of a paper based on the cataloguing of land-forms from remotely sensed data: questions will

remain.

A subglacial meltwater origin has been established for meltwater channels and tracks within the literature (e.g. Rampton, 2000; Utting et al., 2009; Peterson and Johnson, 2018) and we are not the first to suggest a potential continuum between these features (e.g. Sjogren et al., 2002; Peterson and Johnson, 2018). However, we agree that we may have overstated the importance of eskers surrounded by lateral splays as a potential positive relief expression of this. Furthermore, we acknowledge that there are issues grouping eskers with lateral splays with the meltwater channels and tracks as some or all of these features may have formed subaerially or even supraglacially at the ice sheet margin rather than subglacially. Therefore, we no longer include eskers with lateral splays within the term meltwater corridor (Table 2).

Hypothesis for formation will need to be tested with observations of the materials at the very least. Measurements made on modern glaciers or demonstrated in experimental work would also help provide credibility to their interpretations that landforms vary with the pressurization of the subglacial water system.

We agree that our proposed model for formation of meltwater corridors will need to be tested and we hope that publication of our paper might prompt such work. In terms of modifications to the paper, we have updated the proposed model section to demonstrate the increasing evidence from contemporary and modelling studies, which support the occurrence of conduit over-pressurisation and the potential for this to access and erode sediment from the bed. This process has been inferred from simultaneous field observations of ice velocity and uplift, surface melt and proglacial river discharge in contemporary settings and we suggest is likely to have occurred in Keewatin, an area located on resistant shield bedrock that would have experienced high surface meltwater production rates during the time period covered by our study. Therefore, we think there is sufficient evidence to support the plausibility of our model as a simple explanation of a wide range of geomorphic signatures.

This is not a novel hypothesis, nor one that explains all observed features of the glacier bed but it is the primary interpretation of the paper.

We disagree with the first part of this statement and believe we now provide sufficient evidence from the geomorphic and contemporary ice sheet and alpine glacier

literature to support the conceptual model proposed within this study. We believe this paper and our proposed model provides support for viewing geomorphic evidence of subglacial meltwater landforms as a holistic signature and provides a more realistic understanding of the distribution of drainage beneath ice sheets.

We agree that our model does not 'explain all observed features of the glacier bed'; it would be a large task indeed to explain everything and we don't claim to.

The explanation for ice streams lacking meltwater features because of their low surface slopes is not the only plausible hypothesis; fast moving ice over deforming beds will destroy the evidence of channel formation.

We agree and this has now been modified (please see first comment response).

However, the authors emphasize that a well-drained bed results in more stable ice. This is simply reversing the emphasis typically presented in ice-stream papers but using similar reasoning for the bimodal behaviour of ice flow.

There is evidence from the contemporary literature, which suggests that gradual dewatering of the bed is occurring in response to increased surface melt and inferred subglacial channelisation, which results in an observed year-on-year reduction in ice sheet velocity (e.g. Sole et al., 2013; Tedstone et al., 2015) and vice versa (Williams et al. 2020). Although this a temporal relationship (i.e. when surface melt is higher and subglacial drainage more channelised, regional ice velocity is lower) and our argument for Keewatin is spatial (i.e. where there is evidence for more channelised drainage there are fewer ice streams (e.g. Storrar et al., 2014)), we are invoking the same mechanism. This idea is also consistent with modelling of Lelandais et al., (2018), who suggest that efficient drainage (i.e. the development of tunnel valleys) can shut down ice streams and may be crucial for stabilising ice sheets during periods of climate change.

Non-standard and casual punctuation is pervasive throughout the paper: and/or, presence/absence, substrate/geology, splay/glaciofluvial, meltwater track/meltwater channel, erosion/deposition, streaming/surging. Please choose a conjunction or a single word. Hyphens are used in noun strings but not needed with adverbs. I would avoid unnecessary complicated acronyms: MW subscript route(s); MW subscript

track(s), MW subscript corridors; VPA–variable pressure axis (a new one for me); GrIS for Greenland Ice Sheet (couldn't see where you defined that one). What is the point of using any of them in an online manuscript with no limits on characters or words? They are also not used consistently, e.g. line 516.

We understand that the use of acronyms may have been frustrating and made the paper more difficult to follow. We have now reduced the number of acronyms used and have made sure to state clearly what they refer to when using them for the first time. We have also amended the non-standard and casual punctuation throughout.

References:

- Boulton, G.S. The origin of till sequences by subglacial sediment deformation beneath mid-latitude ice sheets. *Annals of Glaciology*. 22: 75-84.
- Lelandais, T. Ravier, E. Pochat, S. Bourgeois, O. Clark, C. Mourgues, R. Strzeczynski, P. Modelled subglacial floods and tunnel valleys control the life cycle of transitory ice streams. *The Cryosphere*. 12: 2759-72. 2018.
- Livingstone, S.J. Lewington, E.L.M. Clark, C.D. Storrar, R.D. Sole, A.J. McMartin, I. Dewald, N. Ng, F.. A quasi-annual record of time-transgressive esker formation: implications for ice sheet reconstruction and subglacial hydrology. *The Cryosphere*. 2020.
- Peterson, G. Johnson, M.D. Hummock corridors in the south-central sector of the Fennoscandian ice sheet, morphometry and pattern. *Earth Surface Processes and Landforms*. 43: 919-29. 2018.
- Rampton, V.N. Large-scale effects of subglacial meltwater flow in the southern Slave Province, Northwest Territories, Canada. *Canadian Journal of Earth Sciences*. 37(1). 81–93. 2000.
- Sjogren, D.B. Fisher, T.G. Taylor, L.D. Jol, H.M. Munro-Stasiuk, M.J. Incipient tunnel channels. *Quaternary International*. 90. 41–56. 2002.
- Sole, A. Nienow, P. Bartholomew, I. Mair, D. Cowton, T. Tedstone, A. et al., Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers. *Geophysical Research Letters*. 40(15). 3940–44. 2013.

160 Storrar, R.D., Stokes, C.R. Evans, D.J.A. Increased channelization of subglacial
drainage during deglaciation of the Laurentide Ice Sheet. *Geology*. 42(3). 239–
42. 2014.

165 Tedstone, A.J. Nienow, P.W. Gourmelen, N. Dehecq, A. Goldberg, D. Hanna, E.
Decadal slow-down of a land-terminating sector of the Greenland Ice Sheet
despite warming. *Nature*. 526: 692 – 95. 2015.

170 Utting, D.J., Ward, B.C. Little, E.C. Genesis of hummocks in glaciofluvial corridors
near the Keewatin Ice Divide, Canada. *Boreas*. 38(3). 471–481. 2009.

Williams, J.J. Gourmelen, N. Nienow, P. Dynamic response of the Greenland ice sheet
to recent cooling. *Scientific Reports*. 10: 1647.

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Reviewer 2:

We thank Flavien Beaud for his very thoughtful comments; in response, we have made
180 significant revisions, which we think have helped us to clarify and refine the model,
and to improve the paper. The key suggestion was that the VPA model should be
dropped and the lateral migration theory expanded upon. This is based largely on
scepticism as to whether geomorphic work can occur across the VPA (i.e. whether
sediment can be eroded and removed). In response, we have made a number of
185 significant changes to bolster our argument and to make the case that both ideas are
compatible, including:

(i) Expanding on the modern glacial literature that provides evidence that
conduit over-pressurisation occurs on daily to seasonal timescales, and that
this can result in the conduit being overwhelmed and drainage reconfigured,
190 for example as a sheet flood (Russell et al., 2007) or as anastomosing or
braided channels/canals (e.g. Catania & Paola, 2001; Gulley et al., 2012;
Vore et al., 2019). The idea of over pressurisation resulting in braiding or
anastomosing is also consistent with the idea that conduits can transiently
migrate laterally and we therefore think that we are roughly on the same
195 page but that this was not well-explained in the original submission.

(ii) Engaging with the glacial erosion literature, which provides strong support
that over-pressurisation events can access and mobilise sediments beyond

- the subglacial conduit (e.g. see Delaney et al., (2018) who propose a similar mechanism to explain variability in subglacial sediment transport for two glaciers in the Swiss Alps), and that eskers scavenge sediments locally (e.g. Bolduc, 1992).
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- (iii) Better defining the timescales at which the observed features formed (10s to 100s of years), and the implication that they are therefore a composite signature produced by repeated pressure perturbations.
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- (iv) Clearly defining and consistently using the more descriptive term '*hydraulically connected distributed drainage system*' (we consider it to be the lateral limit of the influence of pressure variations that originate in a subglacial conduit that can result in water flow into or out of the conduit) instead of 'VPA' to provide greater clarity about what process we are referring too (and this clearly differentiates it from the weakly connected distributed drainage system where we don't expect geomorphic work to occur). To further help here we also discuss the different uses of the term in the literature in the introduction (e.g. 'VPA' in Hubbard et al., 1995; 'hydrological subcatchments' in Rada and Schoof, 2018; 'efficient core' in Davison et al., 2019).
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In addition to these arguments, we have further expanded the discussion on lateral channel migration, which we agree could occur, particularly where the hydraulic gradient is lower, higher up the ice sheet (e.g. see Vore et al., 2019). Indeed, this idea is also consistent with our model that during over pressurisations drainage can transiently reconfigure (e.g. by migrating laterally) (point i, above). We do, however, suggest that lateral migration of the principle channel is less likely to occur nearer the margin, based on modern observations of conduit stability (Vore et al., 2019) and the simple observation that eskers (relict conduits) and the surrounding meltwater corridors are straight and line up along-flow (e.g. see Storrar et al., 2014); if the conduit migrated extensively near the margin you would expect to find extremely sinuous eskers or esker sections that are offset. We therefore maintain that the more general VPA idea is the simplest explanation of the landform relationship we observe (although we also highlight the potential for conduit migration, which could occur as part of drainage reconfiguration, or instead of the VPA higher up the ice sheet), and fits with modern observations of frequent conduit over pressurisation (e.g. Bartholomew et al.,

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2011; Rada and Schoof, 2018), scales with modelling and observations of the width-range of the VPA in Greenland (e.g. Werder et al., 2013; Tedstone et al., 2015) and agrees with and helps explain sediment transport observations (e.g. Delaney et al., 2018).

235 By publishing this model, we hope to stimulate future modelling studies and palaeo and contemporary observations to test both our preferred model, and alternatives, which we do not rule out. We expand on these points below in response to the specific comments made by the reviewer.

Reviewer comments are in black and our responses are in green.

240 Kind regards,

Emma Lewington (on behalf of all co-authors)

A motivation for this work is to analyze different landforms together and recognize their intertwined nature. This is a welcome advance in glacial geomorphology enabled by the availability of the ArcticDEM, as studies of such landforms tend to overlook these interconnections. The authors perform a comprehensive mapping effort of the landforms and the relationships they find between different landforms will be essential in improving our understanding of their formation.

Thank you for these comments.

250 Generally, the literature cited is quite extensive, however, I think that the recent (past 5 years) literature on glacial processes has been a bit overlooked. For example, one the main point of the paper relies on the interactions between a subglacial channel and its surrounding drainage, topic that has been discussed a fair bit in recent papers (see Hoffman et al., 2016, Nature Communication; Stevens et al., 2015, Nature; Rada and Schoof, 2018, The Cryosphere; Andrews et al., 2014, Nature). While some of these papers are cited, their findings are not related in enough details.

Thank you for pointing this out, we have now expanded the section in the introduction discussing the three-system drainage model as the accepted current state of

260 understanding and have also expanded on the interactions occurring over a range of
timescales in more detail. To help this we have produced a new figure to highlight the
key terms.

In terms of sediment transport, bedrock erosion and tunnel valleys and esker
formations a few recent numerical modelling papers also offer some valuable insight
as to how to interpret the landforms of interest here and their results should be
265 discussed (see Beaud et al., 2016 Earth Surface Dynamics; Beaud et al., 2018, ESPL
and JGR, Delaney et al., 2019, JGR). While a number of these papers are my
research, I am not aware of any other study quantifying both sediment transport and
bedrock incision by subglacial water flow.

270 Thank you for these recommendations, we have now referred to these papers with
regards to the importance of seasonal water flows in the development of tunnel
valleys.

The current manuscript does not provide enough evidence to substantiate the claim
that the pressure fluctuations between a subglacial channel and its surroundings are
responsible for the formation of subglacial landforms shaped by water.

275 We agree that we may not have been sufficiently clear about how our proposed model
suggests water pressure fluctuations within the hydraulically connected distributed
drainage system contribute to landform formation. It is during periods when the conduit
connects to the hydraulically connected distributed drainage system that we expect
most geomorphic work to occur. Indeed, observations of subglacial fluvial sediment
280 transport (Swift et al., 2002) and lithological investigations of eskers (e.g. Bolduc,
1992) suggest that subglacial streams access sediment beyond the small fraction of
the bed they immediately occupy. In particular, and following similar observations at
other glaciers (e.g. Collins, 1990, 1996; Swift et al., 2002), Delaney et al. (2018)
observed increases in sediment discharge at two alpine glaciers during times when
285 water discharge increased rapidly (lake drainages and precipitation events). They
readily explain this by invoking the same mechanism proposed in our study (i.e., rapid
water inputs overwhelm the drainage system, creating high water pressures and
causing both increased access of water to sediment sources and high enough water
velocity to transport sediment). We therefore stick by our original supposition that

290 sudden variations in basal water pressure do result in geomorphic work, noting that
even precipitation events are able to cause an increase in sediment mobilisation
(Delaney et al., 2018), and that the corridors are a composite imprint formed over 10s
- 100s of years. We have now expanded the discussion to include a section on
subglacial fluvial erosion, where we discuss how our model fits with observations and
295 modelling from this wider literature.

I think that there is, in fact, more evidence to show that the lateral migration of
subglacial channels is a better candidate than the extent of the 'variable pressure axis'.
The variable pressure axis idea is used to describe a temporary phenomenon, and a
300 reversal in pressure gradient with respect to steady state conditions. As described in
Hubbard et al. (1995), the water that flows outward from the channel during a pressure
peak will subsequently flow back towards said channel. This mechanism cannot
explain a net transport in either direction. A similar idea that does not involve the
pressure gradient reversal is that channels tap into the surrounding distributed system
305 within a distance that is linked to the hydraulic conductivity of the distributed drainage
system (Hewitt, 2011, JoG; Hewitt, 2013, EPSL; Werder et al., 2013, JGR). This idea
is used by Delaney et al. (2019, JGR) to explain the transport of material created by
subglacial erosion toward a main channel, or by Hewitt and Creyts (2019) to determine
the spacing of eskers.

310 We disagree with these points. Firstly, a pressure reversal can cause net erosion if
the energy (i.e. ability to erode, transport etc.) of the water as it flows away from the
channel is different to when it flows back towards the channel. For example, if a
surface lake drains, the increase in water pressure in a connected subglacial channel
might occur over ~1 hour, and depending on the downstream hydropotential gradient,
315 the water pressure may then gradually decrease over tens of hours (e.g. inferred from
uplift plots in Fig. 3 of Doyle et al. 2013). The ability of water flow induced by the lake
drainage to erode and transport sediment will be much greater than that of the
returning water flow. Water also does not just flow laterally - when the conduit is
overwhelmed water will continue to drain towards the margin, but over a broader area
320 (e.g. Catania and Paola, 2001; Russell et al., 2007; Gulley et al., 2012; and see
comment below), analogous to when a river bursts its banks during a flood event. So,
sediment eroded at one point in the hydraulically connected distributed drainage

system will be transported down the regional hydraulic gradient towards the ice margin.

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We consider the VPA (now termed the hydraulically connected distributed drainage system) to be the lateral limit of the influence of pressure variations that originate in a subglacial channel. This lateral influence of the conduit on its surroundings therefore encompasses and supports the modelling ideas of Hewitt, Werder, Delaney and others, and also of a wide body of glacier and ice sheet observations demonstrating a hydraulic connection between the conduit and its surroundings (e.g. Rada and Schoof, 2018; Nanni et al., 2020). We have attempted to address these points in an expanded introduction that includes a new figure with key drainage terms defined, and a more complete description of this connection, including how the lateral limit varies depending on the magnitude of the pressure perturbation (determined by the volume and rate of meltwater input), antecedent conditions (e.g. the limit will decline on average through a melt season as the conduits become more efficient - see Rada and Schoof, 2018) and basal substrate.

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We agree conduit migration is certainly possible, and indeed, also consistent with the idea of transient drainage reconfiguration during over pressurisation (e.g. Catania & Paola, 2001; Gulley et al., 2012); we have expanded this section to discuss these points further and to better link to our overall model. In particular, there is some recent evidence that where the hydraulic potential is low (e.g. higher up the glacier) drainage occurs through multiple conduits, which migrate over time (see Vore et al., 2019). However, nearer the ice margin, where the hydraulic potential is steeper, the same research suggests the conduit is relatively stable in space, and this fits with the simple geomorphic observation that eskers (relict conduits) and the surrounding meltwater corridors are straight and line up (e.g. see Storrar et al., 2014 who found a median sinuosity of 1.04 for a sample of >20,000 Canadian eskers). To do this the conduit needs to be centred in a stable location. If the conduit migrated extensively you would expect to find extremely sinuous eskers or esker sections that are offset. In addition, the meltwater corridors themselves are relatively straight with a narrow width range.

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The size of the sediment transported in a distributed system is thought to be relatively small (Beaud et al., 2016, Earth Surface Dynamics), and may not be adequate to

transport the sediment of the size found in the targeted landforms. It is common to find gravel if not boulders in the till. The flow forming these landforms should thus be able to transport such sediment.

360 We agree that in a passive or weakly connected distributed drainage system sediment transport is generally likely to be low and dominated by or exclusively gravel or smaller. However, our model is focused on the impact of conduit over pressurisation on the hydraulically connected distributed drainage system. When the conduit becomes overwhelmed during rapid water pressure perturbations, the conduit is shown to
365 'connect' to this wider area (e.g. Hubbard et al., 1995; Bartholomew et al., 2001; Rada and Schoof, 2018). When it does so, flow is no longer thought to occur as 'passive' distributed drainage, but somewhere along a continuum between classical distributed and channelised drainage depending on the pressure gradient between the conduit and its surroundings. The amount of geomorphic work at that time likely depends on
370 where on this continuum the drainage event was (and of course we see a composite of many such events). Observations and modelling suggest this may range from cavity expansion, to conduit reconfiguration, to local sheet flood (e.g. Cowton et al., 2016; Catania and Paola, 2001; Russell et al., 2007; Gulley et al., 2012). To make this distinction clearer we have expanded the introduction section to more clearly define
375 the three-system drainage model (i.e. conduit, hydraulically connected and weakly connected drainage systems), and produced a new model figure that details the evolution of the VPA/ well connected drainage system to pressure perturbations (in Fig. 14 b1-b3). We have also carefully defined all our terms and used these consistently throughout. Please also see our above comment in regards to the ability
380 of these over pressurisation events to cause geomorphic work.

To explain the transport of significant amounts of sediment or clasts of large size, floods resulting from lake drainages are often involved. However, for a single lake drainage to create a flood throughout a channel until it exits the glacier, the lake size
385 has to be particularly large. For example, on the Greenland ice sheet lake drainages are unlikely to create large floods through a single channel as they are spread across a drainage catchment and may not drain at the same time (e.g. Bartholomew et al., 2012; Fitzpatrick et al., 2014). However, single drainage events will affect the bed in the vicinity (few kms) of the lake location (Stevens et al., 2015, Nature).

390 A supraglacial lake drainage may do significant geomorphic work locally, but once the
moulin is opened up, suddenly there is a direct connection to surface-generated water,
the amount of which varies substantially on diurnal etc. timescales. We know that this
variability in discharge (increases of up to 50 cumecs) does reach the margin because
we see it in proglacial discharge records (e.g. Bartholomew et al., 2011). This
395 variability clearly over pressurises the subglacial channel (and thus could lead to
geomorphic work) because it leads to hydrologically-driven diurnal ice velocity
variations (e.g. Bartholomew et al., 2012). In addition, the rapid increase in discharge
is sufficient to move cobbles and sometimes boulders as bedload in the proglacial
river. Although this may be more difficult subglacially due to accommodation space,
400 evidence of locally transient uplift of up to 1 m (e.g. Doyle et al., 2013) suggest that
significant bedload could be moved (see also reply to comment below).

Meltwater is transported to the ice bed by hundreds of moulins and crevasses (unless
it is stored in a lake) and so along the length of a subglacial channel, there will be
diurnal water pressure variations caused by surface-derived meltwater entering that
405 channel from the moulins and crevasses. Thus, the combined effect of all this water
reaching the bed is for there to be pressure variations sufficient to (probably) do
geomorphic work along the whole length (or the vast majority of the length) of a
subglacial channel.

Beaud et al. (2018, EPSL) further discusses the efficacy of floods of various magnitude
410 to incise bedrock, and find that seasonal meltwater production is more likely to produce
landforms like tunnel valleys. To remove sediment or incise bedrock and form a
negative-relief meltwater corridor, the water flow has to be able to produce shear
stresses that are sufficient to transport coarse sand and gravel which are typical from
glacial till. Therefore, the water flow velocities have to be sufficient and there should
415 be enough accommodation space for these particles to be transported. Sediment
transport in a macro-porous sheet has been modelled by Creyts et al. (2013, JGR)
and sediment transport capacity in a network of connected cavities is discussed in
Beaud et al. (2016 ESurf). In either study, the size of sediment that can be readily
transported in a distributed system is small, i.e. on the order of size of coarse sand. I
420 believe there is a strong body of evidence to suggest that the lateral migration of a
subglacial channel across a melt water corridor is responsible for its formation. Gulley

et al. (2012, JoG) find that the location of moulin has a large control on the location of the drainage channel and as a result of moulin advection, the said drainage channel changed paths from one year to the next. In the tunnel valley review presented in
425 Kehew et al. (2012), there is ample evidence that the fill of tunnel valleys is constituted of numerous smaller individual channels, hinting a migration rather than a process occurring in a channel surroundings. Experiments of water flow under pressure over a sediment bed, show the braided nature of the resulting sediment channels (Catania and Paola, 2000, Geology) or the migration of single sediment channels (Lelandais et
430 al., 2016, JGR).

We acknowledge that we may have induced some confusion due to a lack of consistency in our terms used in the original paper. However, we are not suggesting that the high amounts of sediment erosion or transport occur within the weakly connected distributed drainage system (i.e. the passive system) but instead within the
435 hydraulically connected distributed system during periods of over pressurisation when water is forced out of the conduit and into the surrounding distributed system, resulting in drainage reorganisation in the form of anything from cavity expansion to a local sheet flood. In this scenario, consequent local hydraulic jacking of the ice would generate accommodation space (up to 1 m locally – Doyle et al. 2013) and sufficient
440 water velocities to erode and entrain sediment (i.e. forming the meltwater corridors probably through repeated drainages over 10s to 100s years). In the weakly-connected distributed drainage system (i.e. areas in between the meltwater corridors with passive distributed drainage) we agree that we do not expect to see any visible evidence of fluvial erosion, and indeed we see this from the glacial geomorphological
445 imprint.

Please see above our detailed comments about the role of conduit migration in the formation of these features. While we do not discount this as a possibility, we suggest that the processes within the VPA model are supported by more evidence from contemporary ice sheets and fit with the geomorphological observations. We do note
450 that the work of Gulley et al. (2012) and Catania and Paola (2000) references here seem to support our model that during periods of over pressurisation drainage can reconfigure to form anastomosing or braided conduit networks (see comments above). Although it is true that the location of moulins are thought to be a key control on

455 drainage pathway, there is strong evidence that moulin typically reset to approximately the same location as streams are captured upstream of the existing moulin by new crevasses which occur in the same position as the original moulin formed (due to constant stresses in the ice over the timescale of moulin formation) (see e.g. Catania and Neumann, 2010; and the Gulley paper also makes this point).

460 Finally, in this study, eskers are not necessarily at the center of a MWcorridor, whereas, in an isotropic medium and following the proposed VPA theory, they should. In an anisotropic medium, they should still be systematic characteristics on either side of a drainage channel likely dependent on the conductivity or the roughness of the substrate in this area.

465 We would suggest that the fact that we are dealing with reality and not a model (isotropic medium) contributes additional complexities, so that we would not expect the eskers to always (or ever) sit in the centre of a corridor. We would expect the lateral extent of the VPA to vary depending on the regional and local hydraulic potential surface. If the pre-existing hydraulic gradient is steep and positive away from one side of the channel, the VPA on this side would be narrow. If the pre-existing hydraulic
470 gradient on the other side is positive but shallow, the VPA on this side would be relatively wide. To reuse our above analogy; a subaerial river whose channel lies closer to one valley side will have an uneven flood extent on either side of the channel.

In summary, I believe that the VPA origin of landforms should be dropped, unless the authors are able to provide convincing evidence that it can produce sediment transport
475 and bedrock erosion. However, I believe the author can make a strong case for subglacial channel migration being the responsible for the width of MWcorridors. Such migration has seldom been studied and the present study could thus open the door for the use of MWcorridor width as a proxy for glacial conditions. It is likely that the migration is limited by a combination of bed topography, ice surface topography,
480 effective pressure (ice over- burden minus water pressure) and location of moulin.

We have not dropped our case for the VPA origin of landforms, but have instead clarified our phrasing and added additional evidence to support the proposed model (see above comments for more detail). We now think that the VPA model is clearer and more convincing and is supported by a range of observations (of over-

485 pressurisation and sediment transport) from contemporary ice sheet and alpine
settings. We acknowledge that conduit migration probably also plays a role in the
formation of these features (particularly where the hydraulic gradient is shallower) and
actually think this is consistent with our model and one possible outcome of conduit
490 over pressurisation as part of a spectrum of possible responses (covering cavity
expansion, braiding, anastomosing and sheet floods).

In addition, the spacing between MWcorridor is a more complete description of the
esker or channel spacing proposed by Hewitt (2011) and Hewitt and Creyts (2019).
Thus, the current results could actually be used to infer more robustly the spacing of
drainage networks and thus inform the conductivity of the distributed drainage
495 networks that should be used in numerical models.

We agree and think that this is an exciting key output of this paper. Our results suggest
that surface meltwater inputs influence between 5 - 36 % of the bed (meltwater corridor
coverage) which is 25 times more than conduits (eskers) alone (~ 0.5 % in this area).
This has implications for understanding the impact of surface meltwater inputs on ice
sheet velocity and for sediment access and removal at the bed. The fact that not all
500 meltwater corridors contain eskers supports the idea that eskers are a minimum map
and that including additional lines of evidence (i.e. a holistic drainage map) is likely to
generate a more realistic impression of the true drainage coverage. Finally, we have
added a new figure which shows that the centreline mapping results from this study
505 are within the range of other studies (many of which are in the Keewatin area), which
have relied on eskers alone, but that our mean (8.1 km) is towards the lower end of
this range. Interestingly, the average spacing appears to decrease with studies over
time, perhaps indicating that increased resolution datasets (and in this case detailed
mapping of all visible subglacial meltwater features) and large scale mapping studies
510 are reducing the perceived spacing between meltwater routes.

Title change: the title should be modified to something that focuses more on the
method and results than the interpretation of the results.

We agree that the title does not currently reflect the paper as well as it could and have
thus changed it to 'A model for interaction between conduits and surrounding
515 hydraulically connected distributed drainage system based on geomorphological

evidence from Keewatin, Canada.’ Although this still focuses on the interpretation of the results, we now make clear in the title that this is a model, which we hope will stimulate future modelling studies and palaeo and contemporary observations to test.

520 Throughout the text there is copious use of comparatives, but they are not always compared to something specific. In general, please try to quantify these comparisons with numbers so that they are less subjective. It seems a bit weird to put eskers with splays and eskers at odds during the explanations. These are both positive relief features in opposition to the other negative relief landforms. Also, it seems circular to
525 say that esker with splays are connected to eskers, since their name suggests they are eskers too. Please add some explanation of these choices in the manuscript.

We agree that we may have overstated the importance of eskers surrounded by lateral splays as a potential positive relief expression of the negative relief landforms and have reduced the discussion on this (please see more detailed comments in response
530 to reviewer one on this). We have also made an effort to be less subjective in our comparisons.

Many of the figures display text that is too small, or the maps show an area that is too large to see features clearly. Many figure panels also lack letters to reference them. Please add some to make the figure more intelligible.

535 We have amended these concerns.

At the beginning of the paper show examples of the different landforms and their manifestation on the DEM. I understand this is was the point of the Lewington et al., 2019 paper, but it is necessary to show this here again. Define splay around the esker in more details.

540 We have now added a new figure with zoomed in examples of each of the geomorphic expressions of subglacial meltwater flow that we discuss in the introduction.

Specific comments:

Thank you very much for the detailed comments on the manuscript these have been

545 addressed as follows:

14. Please define acronym when first used

We have now done this.

15. "Eskers exhibit key similarities with [...] association with eskers"? Types of what? That sentence should be reworded to be more clear.

550 We have now done this.

23. The sentence construction in the abstract is a bit confusing and sometimes convoluted. Please rewrite to make it more direct.

We have re-written much of the abstract to make it clearer.

45. I think the wording is not quite right. The efficient drainage can have a relatively
555 large effect on ice motion, but that effect is to reduce sliding rather than enhance it.

We have re-written this sentence as follows: 'The configuration of the subglacial hydrological system is key to this, with a hydraulically efficient drainage system able to accommodate and evacuate an equivalent water flux without causing spikes in basal water pressure which have been linked to transient ice accelerations (e.g.
560 Tedstone et al., 2013).'

53. I think it is worth including more recent literature like Hoffman et al. (2016, Nature), as it tackles that idea that the system is not binary. Hoffman is referred to in the next paragraph, I believe it should be done earlier though. The paper by Rada & Schoof, should also be discussed here. I general the literature cited in this paragraph should
565 described a bit more extensively to reflect their findings. The main point is that the connectivity of the distributed drainage has a key effect on overall water pressures and sliding speed. I believe this is relevant for this study.

We have expanded this section significantly in the introduction and have included the key references you have recommended. We now make it clear that the subglacial
570 drainage system is comprised of three main components: (i) a moulin connected channelised system; (ii) an active hydraulically connected distributed system influenced by the channelised system and; (iii) a weakly connected distributed system

largely isolated and rarely influenced by surface meltwater (e.g. Andrews et al., 2014; Hoffman et al., 2016; Rada and Schoof, 2018).

575 We have also added in a new schematic to conceptualise this.

83. Beaud et al. (2018, ESPL) and Beaud et al. (2018, JGR) use numerical models to explore the formation tunnel valleys and eskers respectively. While it may be weird to point to my own work, these two papers are the only studies I am aware of that explores the processes responsible sediment transport and erosion by water flow under glaciers in details. The findings are directly relevant to the interpretations made in this study.

We agree and have referenced both papers in this section.

112. over-pressurization with respect to what? over atmospheric pressure or over ice-overburden pressure?

585 We have rephrased to 'during periods of high water pressure within the conduit'

123. Please also look at Catania & Paola (2000) and Lelandais et al 2016, where tunnel valley development is explored with physical experiments.

Thank you for these recommendations we have now included both in our introduction to tunnel valleys.

590 129. Beaud et al. 2016/ 2018 propose, 3) that floods are unnecessary, because subglacial water pressure gradients are large enough with seasonal meltwater flow to produce shear stresses that can explain sed transport and incision.

We have added the following to address this: 'iii) formation from seasonal meltwater flow (Beaud et al., 2016, 2018b).'

595 135. I think the distinction between features typical from bedrock or sediment substrates should be more clear or at least discussed. The processes of subglacial water flow expected are vastly different as a function of said substrate.

We have modified the section discussing tunnel valleys to acknowledge this: 'Tunnel valleys typically occur on soft substrate and are observed to occur at various

600 developmental stages from mature and clearly defines to indistinct valleys often
associated with hummocky terrain or as a series of aligned (e.g. Kehew et al., 1999;
Sjogren et al., 2002). Bedrock carved tunnel valleys are rarer and tend to be narrower
and more V-shaped in cross-profile (Van der Vegt et al., 2012).'

137. Sediment and ice-walled conduits have fundamentally different characteristics. If
605 blended under the same term, this should be explained in details.

We are clarifying terminology not process understanding here and thus have decided
not to expand into a discussion here.

163. I think it is worth recognizing that, in particular for tunnel valleys many of them
might be buried under sediment, i.e. their current topographical expression is not
610 necessarily representative of their actual presence.

We have added in the following sentence to address this: 'Importantly, we note this is
a minimum map as some landforms – particularly tunnel valleys – may be fully or
partially buried (e.g. Jørgensen and Sandersen, 2006).'

615 172. Please give some quantification of 'low' here.

We have rephrased this sentence to say 'local negligible relief'. Shilts et al., (1987)
suggest that the relief rarely exceeds 95 m and is generally subdued.

173. Resistant to what? The quantification of the 'resistance' of bedrock can also be
difficult if thought of in term of erosion. A number of studies show that fracture density
620 rather than lithology controls how easily bedrock can be removed by geomorphic
processes. Please clarify.

The Shield area is commonly described as being composed of resistant crystalline
lithologies resulting in minimised glacial erosion and limited debris production (e.g.
Shilts et al., 1987).

625 174. What is 'thin' and 'thick'? Please give some sort of quantification to adjectives
used throughout the text.

We have clarified that thinner till veneer is typically < 2m and thicker till blankets are

typically > 2m.

630 177. I believe the text in the caption is a bit too small. All the text in each map should be clearly readable, including the disclosures of where the data comes from.

We have made the text larger in all figures.

180. Is the study area with in the black polygon in (b)? if so this should be clearly stated.

635 It is stated in the figure caption and within the figure (identified as 'study area' in upper right of polygon) – this has been made larger so as not to miss it.

195. I believe these dashes should be longer?

We have made the dashes longer.

211. The sentence should not start with an acronym

640 Thank you, we have changed this to start as follows: 'High-resolution digital elevation data, made available through the ArcticDEM (10 m)...'

233. Adding a figure (or referring to, but I couldn't find a fig showing that, maybe Tab 2) that show the concept of the methodology explained here would be extremely useful. I think I understand where the authors are going, but with the current material I can't be sure.

645 We have now included an additional figure which shows the ice margin isochrones (Dyke et al., 2003) across the area and demonstrates how they are used as transects for sampling the meltwater routes.

282. Is it really a point if a width can be extracted? replace by 'location'?

We have changed this to location.

650 287. Please explain what the roughness at that scale is expected to be relevant for.

We have now updated the methodology and the resultant figure and have included a paragraph which justifies the parameter selection. This is based on the literature which

discusses the transfer of bed topography to the surface (e.g. Gudmundsson, 2003; Ignéczi et al., 2018).

655 303. 'wider' than what? Or is it just to say vast majority eskers are part of MW routes network?

We have rephrased this to indicate part of the same network.

314. The maps in Figure 3 have too large of a scale to actually make that point. Consider choosing smaller areas to make that point.

660 Here we meant that the updated meltwater routes map is denser than the initial esker map, suggesting that the holistic mapping captures a more complete picture of the drainage. We believe that this figure demonstrates this at the scale it is at.

315. updated compared to what? Just say clearly which map is referred to.

665 We have added in a sentence to explain that we have updated Storrar et al., (2013) mapping: 'Esker mapping by Storrar et al., (2013) was updated in the study area. Due to the higher resolution data available and the smaller spatial area covered, smaller features which may have been missed could be included.'

316. Wider than what?

670 We meant this in reference to the fact that features in the scale of 100s – 1000s m (i.e. meltwater channels, meltwater corridor or esker splays) are recorded at a vast majority of sample locations. We have made this clearer and removed the subjective description.

326. Define L and U quartiles.

We have done this.

675 326. Add centerline spacing, to make it more obvious to the reader.

We have done this.

329. Avoid starting sentence with acronym. Also the subject of the sentence should be the attribute of the feature (length or width) not the generic name of the feature

itself.

680 We have done this and removed a significant number of the acronyms from the paper all together.

333. This isn't clear. Around what part of the ice sheet.

We have changed this to across the study area.

685 335. This needs to be clarified as well. The sentence talks to spatial changes, and the link between spatial and temporal involves some assumptions about landform formation.

We have added in the sentence: 'If these landforms are assumed to have formed time-transgressively, this would suggest no clear trend in width during deglaciation.'

690 337. What is that range? Note that the range from models is directly tied to the range of conductivity values used in these models which in essence is rather arbitrary and tuned to match field observations. Perhaps, best to remove the models from this paragraph.

695 To make this clearer we have added in a new figure (modified from Storrar et al., 2014), which demonstrates the range of spacings presented in earlier studies and this one. Only one of the 11 samples included is from a model (the rest are observations), and this is included just for comparison.

339. Again, the step from spatial to temporal involves a number of assumptions and interpretation. It is best to keep to the spatial interpretation in the results and develop the importance for expected temporal evolution for the discussion.

700 We have kept this in the results section but have added 'if we assume a time transgressive formation' as we believe this is an important observation.

345. Please put number on each panel or make it clear that the figure is separated in 3 rows. The meaning of column is clear looking at the figure, not that of the rows.

We have added this in and now what each panel shows is clearer.

705 350. I can't find these locations in Fig. 2. Also the caption of Fig. 2 only points to Fig 4

and 5, not 3. Are these the unlabelled black squares in Fig.2? Please update with clear labels for each locations.

We have updated the figure to make it clearer where each location is.

710 359. I think section 4.2 can be removed. It repeats what has been said before and brings no new information.

We think that this is useful for contextualising this work so have included part of the paragraph but have consolidated it and combined it with the esker mapping section.

367. what does definition mean here? It's the first time it's used in this context. Please keep same names and descriptions as earlier or define terms.

715 We have changed this to make the description on relief quantifiable.

381. Please make sure the features you describe in the text to make your points are visible in the figure. Esker and esker splays are really hard to visualize here, and in some cases hummocks too. Consider zooming in the panels or adding a figure if the whole area needs to be displayed for other purposes as well.

720 Thank you for pointing this out, we have redone this figure zooming in to key geomorphic signatures which are important in this paper. We have also put this figure in the introduction (now figure 2) so as to provide the reader with a clear understanding of what is being discussed from the start.

725 381. Use numbers in the topo elevation scale. High and low mean nothing here as the relief described here are all low compared to alpine or fjord type glacial landscapes.

The elevation scale bar has been removed as we now use greyscale hillshades to better visualise the features.

730 382. Add delineation of MW routes on figure. Where is north? What were the local ice flow direction? Where are these regions from with respect to the general map? Are they the colored dots?

Please see answer to 381.

393. Many redundancies in this paragraph, please consolidate.

We agree and have consolidated this.

735 400. Where are these examples? Where is north? Give numbers for elevation scale It would be useful to the outlines of the landforms on the DEM as well to clearly see the topography and better understand the analysis. Ice flow vector and text should be larger.

740 We have now added lat/lon to each image, a north arrow and ice flow direction. The images have been redone using greyscale hillshade to better visualise the features.

420. Are these statistics for the whole study area? It would be great to have the location of the mean marked on the plot (in addition to the number given) and it might be useful to add the median as well given the nature of the populations.

745

Yes, they are from the whole study area, we have added this to the figure caption. We have also marked the mean and median on each plot.

432. Because of the redundancy of labels in the panels, it would make the figure if the same labels were only written once per column or row and that the font be made bigger. Is there a meaning for the different color used? if so please explain. The authors might also want to make a color choice that is suitable for people with colored impaired vision.

750

755 Thank you for this recommendation, we have updated the labels. We have used the colours blue to represent over representation and red to indicate under representation.

432. For consistency it would be useful to have the panels for each landform in the same order as in Fig. 6. Also each sub-panel should be labelled to make the back and forth between figure and text easier.

760

We agree and have changed the ordering of these panels to match the figure above.

765 442. I'm not sure I understand the display of the std dev of the topography. If a moving window is used, then that results in a map of topography std dev. So where do the 1 to 5 std dev come from? Why is it not just the value of the std dev that is displayed on the map?

770 We have now changed this figure completely so there is just one map with the roughness standard deviation surface (please see comment 287 for parameter selection) with the meltwater routes overlain on this. This demonstrates that the area with the highest roughness (at a scale expected to be relevant for bed to surface transfer), coincides with the area with the densest subglacial meltwater routes.

775 446. I think it would be worth expanding a bit more than 2 sentences on figure 9.

We have done this.

780 450. what is the std window used in panel (a)? or is the coloring the density of MWroutes?

Please see comment 442.

785 450. This figure is too small. Where is north? What is the scale? perhaps put lat-long lines? Why not display the MWroutes on all panels?

Please see comment 442.

473. Figure needs to be bigger and font larger.

790 We have redone this figure. As well as making the figure and font larger, we have added an inset to show the distribution of ice streams across the Canadian Shield at a larger scale. We have also sampled meltwater route density in boxes across ice stream and non-ice stream areas and have compared these quantitatively using a two-sample t-test. This confirms that there is a significant difference between density of meltwater routes in and out of ice streams.

795

490. Make the colored line thicker, they are really hard to see.

We have made the coloured lines thicker.

800 490. Thank you for adding number on till cover! Currently the colors for veneer and blanket are hard to differentiate though.

We have changed the colours so they are easier to differentiate between.

805 491. Where do these example come from in other maps? Is the distance along the ice flow? why are not all the panels labelled? Why sample at 5km and not at shorter interval?

810 We have coloured the long profiles in our locations map (now Fig. 5) to show where the examples are from.

Yes, this is the distance along flow, we have added this to the figure axis to make this clearer.

815 We have now resampled along each meltwater route at 1 km intervals. This captures more of the variations in landform expression (i.e. meltwater track to meltwater corridor transitions) as well as the more fragmented esker ridges.

570. While the general idea is right, it necessary to break down and explain a bit more how these different papers and method infer or calculate large pressure in subglacial conduits. Also, the recent study by Rada and Schoof (2018, The Cryosphere) is perhaps the most comprehensive documentation of borehole water pressure to date and is worth discussing with regard to the context of the current study.

820

Thank you for this recommendation. We have now included this within the updated paper.

825 References:

- Bartholomew, I. Nienow, P. Sole, A. Mair, D. Cowton, T. Palmer, S. Wadham, G. Supraglacial forcing of subglacial drainage in the ablation zone of the Greenland ice sheet. *Geophysical Research Letters*. 38(8). 2011.
- 830 Bolduc, A.M. The formation of eskers based on their morphology, stratigraphy and lithologic composition, Labrador, Canada (Unpublished Ph.D thesis). Lehigh University. 1992.
- 835 Catania, G. Paola, C. Braiding under glass. *Geology*. 29(3): 259-62. 2001.
- Collins, D.N. Seasonal and annual variations of suspended sediment transport in meltwaters draining from an Alpine glacier. *International Association of Hydrological Sciences Publication*. 193: 439-46.
- 840 Collins, D.N. A conceptually based model of the interaction between flowing meltwater and subglacial sediment. *Annals of Glaciology*. 22(1). 224-32.
- 845 Cowton, T. Nienow, P. Sole, A. Wadham, J. Lis, G. Bartholomew, I. et al., Evolution of drainage system morphology at a land-terminating Greenlandic outlet glacier. *Journal of Geophysical Research. Earth Surface Processes*. 118. 29-41. 2013.
- 850 Cowton, T. Nienow, P. Sole, A. Bartholomew, I. Mair, D. Variability in ice motion at a land-terminating Greenlandic outlet glacier: the role of channelized and distributed drainage systems. *Journal of Glaciology*. 62(233): 451-66.
- 855 Davison, B.J. Sole, A.J. Livingstone, S.J. Cowton, T.W. Nienow, P.W. The influence of hydrology on the dynamics of land-terminating sectors of the Greenland Ice Sheet. *Front. Earth Sci*. 7:10. 2019.
- 860 Decaux, L. Grabiec, M. Ignatiuk, D. Jania, J. Role of discrete water recharge from supraglacial drainage systems in modelling patterns of subglacial conduits in Svalbard glaciers. *The Cryosphere*. 13: 735-52. 2019.
- 865 Delaney, I. Bauder, A. Werder, M.A. Farinotti, D. Regional and annual variability in subglacial sediment transport by water for two glaciers in the Swiss Alps. *Frontiers in Earth Science*. 6: 175. 2018.
- Doyle, S.H. Hubbard, A.L. Dow, C.F. Jones, G.A. Fitzpartrick, A. Gusmeroli, A. Lindback, K. Pettersson, R. Box, J.E. Ice tectonic deformation during the rapid in situ drainage of a supraglacial lake on the Greenland Ice Sheet. *The Cryosphere*. 7: 129-40. 2013.

- 870 Gudmundsson, G.H. Transmission of basal variability to a glacier surface. *Journal of Geophysical Research: Solid Earth*. 108(B5). 2003.
- 875 Gulley, J.D. Grabiec, M. Martin, J.B. Jania, J. Catania, G. Glowacki, P. The effect of discrete recharge by moulins and heterogeneity in flow-path efficiency at glacier beds on subglacial hydrology. *Journal of Glaciology*. 58(211). 2012.
- Hubbard, B.P. Sharp, M.J. Willis, I.C. Nielsen, M.K. Smart, C.C. Borehole water-level variation and the structure of the subglacial hydrological system of Haut Glacier d'Arolla, Valais, Switzerland. *Journal of Glaciology*. 41(139). 572–83. 1995.
- 880 Ignéczi, A. Sole, A.J. Livingstone, S.J. Ng, F.S.L. Yang, K. Greenland ice sheet surface topography and drainage structure controlled by transfer of basal variability. *Frontiers in Earth Science*. 6: 101. 2018.
- 885 Kehew, A.E., Piotrowski, J.A. and Jørgensen, F. Tunnel valleys: Concepts and controversies - A review. *Earth-Science Reviews*. 113(1–2). 33–58. 2012.
- Nanni, U. Gimbert, F. Vincent, C. Graff, D. Walter, F. Piard, L. Moreau, L. Quantification of seasonal and diurnal dynamics of subglacial channels using seismic observations on an Alpine Glacier. *The Cryosphere*. 14: 1475-96. 2020.
- 890 Rada, C. Schoof, C. Channelized, distributed, and disconnected: subglacial drainage under a valley glacier in the Yukon. *The Cryosphere*. 12: 2609-36. 2018.
- 895 Russell, A.J., Gregory, A.R., Large, A.R., Fleisher, P.J. and Harris, T.D. Tunnel channel formation during the November 1996 jökulhlaup, Skeiðarárjökull, Iceland. *Annals of Glaciology*, 45, 95-103. 2007.
- 900 Shilts, W.W. Aylsworth, J.M. Kaszycki, C.A. Klasson, R.A. Canadian Shield. In: Graf, W.L. (Ed.), *Geomorphi Systems of North America*. Geological Society of America, Boulder, Colorado. pp. 119-61. Centennial Special Volume 2. 1987.
- 905 Storrar, R.D. Stokes, C.R. Evans, D.J.A. Morphometry and pattern of a large sample (> 20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. *Quaternary Science Reviews*. 105: 1 – 25. 2014.
- 910 Swift, D.A. Nienow, P.W. Spedding, N. Hoey, T,B, Geomorphic implications of subglacial drainage configuration: rates of basal sediment evacuation controlled by seasonal drainage system evolution. *Sedimentary Geology*. 149. 5-19. 2002.

Tedstone, A.J. Nienow, P.W. Gourmelen, N. Dehecq, A. Goldberg, D. Hanna, E.
Decadal slow-down of a land-terminating sector of the Greenland Ice Sheet
despite warming. *Nature*. 526: 692 – 95. 2015.

915 Vore, M.E. Bartholomaus, T.C. Winberry, J.P. Walter, J.I. Amundson, J.M. Seismic
tremor reveals spatial organisation and temporal changes of subglacial water
system. *Journal of Geophysical Research: Earth Surface*. 124: 427-46. 2019.

920 Werder, M.A. Hewitt, I.J. Schoof, C.G. Flowers, G.E. Modeling channelized and
distributed subglacial drainage in two dimensions. *Journal of Geophysical
Research: Earth Surface*. 118(4). .2140–58. 2013.

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945 **A model for interaction between conduits and surrounding hydraulically**
connected distributed drainage based on geomorphological evidence from
Keewatin, Canada.

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955 **Abstract**

960 We identify and map visible traces of subglacial meltwater drainage around the
former Keewatin Ice Divide, Canada from high resolution Arctic Digital Elevation Model
(ArcticDEM) data. We find similarities in the characteristics and spatial locations of
landforms traditionally treated separately (i.e. meltwater channels, meltwater tracks
and eskers) and propose that creating an integrated map of ‘meltwater routes’
captures a more holistic picture of the large-scale drainage in this area. We propose
the grouping of meltwater channels and meltwater tracks under the term ‘meltwater
corridor’ and suggest that these features in the order of 10s – 100s m wide, commonly
surrounding eskers and transitioning along flow between different types, represent the
interaction between a central conduit (the esker) and surrounding hydraulically
connected distributed drainage system (the meltwater corridor). Our proposed model
is based on contemporary observations and modelling which suggest that connections
between conduits and the surrounding distributed drainage system within the ablation
zone occur as a result of over pressurisation of the conduit. The widespread aerial
coverage of meltwater corridors (5 – 36 % of the bed) provides constraints on the
extent of basal uncoupling induced by basal water pressure fluctuations. Geomorphic
work resulting from repeated connection to the surrounding hydraulically connected
distributed drainage system suggests that basal sediment can be widely accessed and
evacuated by meltwater.

975

1. Introduction

980

Variations in the configuration of subglacial hydrological systems are key to understanding some of the most dynamic ice sheet behaviour at a range of spatial and temporal scales (e.g. Zwally et al., 2002; Das et al., 2008; Joughin et al., 2008; van de Wal et al., 2008; Shepherd et al., 2009; Palmer et al., 2011; Fitzpatrick et al., 2013; Doyle et al., 2014). Once water reaches the bed, its impact on ice flow is determined by the hydraulic efficiency of the subglacial hydrological system. Theory developed at alpine glaciers suggests that increasing water pressure results in enhanced ice motion owing to reduced ice-bed contact (Lliboutry, 1968; Bindschadler, 1983) and where sediment is present, enhanced sediment deformation (e.g. Engelhardt et al., 1978; Hodge, 1979; Iken and Bindshadler, 1986; Fowler, 1987; Iverson et al., 1999; Bingham et al., 2008). Water pressure at the bed depends on water supply to, storage within and discharge through the subglacial hydrological system (Iken et al., 1983; Kamb et al., 1985; Nienow et al., 1998). The configuration of the subglacial hydrological system is key to this, with a hydraulically efficient drainage system able to accommodate and evacuate an equivalent water flux without causing spikes in basal water pressure which have been linked to transient ice accelerations (e.g. Tedstone et al., 2013).

995

Traditionally the subglacial hydrological system has been conceptualised as a binary model comprising (i) inefficient distributed drainage - taking the form of thin films of water (Weertman, 1972), linked cavities (Lliboutry, 1986; Walder, 1986; Kamb, 1987), groundwater flow (Boulton et al., 1995) and / or wide shallow canals (Walder and Fowler, 1994); and (ii) efficient channelised drainage with conduits cut either up into the ice (Rothlisberger-channel) or down into the bed (Nye-channel) (e.g. Rothlisberger, 1972; Shreve, 1972; Nye, 1973; Hooke et al., 1990). These two systems interact with each other over a range of spatial and temporal scales (e.g. Andrews et al., 2014; Hoffman et al., 2016; Rada and Schoof, 2018; Downs et al., 2018; Davison et al., 2019), resulting in: (i) a moulin-connected channelised system which remains hydraulically connected to surface meltwater inputs throughout the melt season; (ii) an active hydraulically connected distributed system strongly influenced by the channelised system and therefore surface inputs across a range of spatial and temporal scales (e.g. Hubbard et al., 1995) and; (iii) a weakly-connected distributed system largely isolated from the channelised system and only rarely – if ever - affected

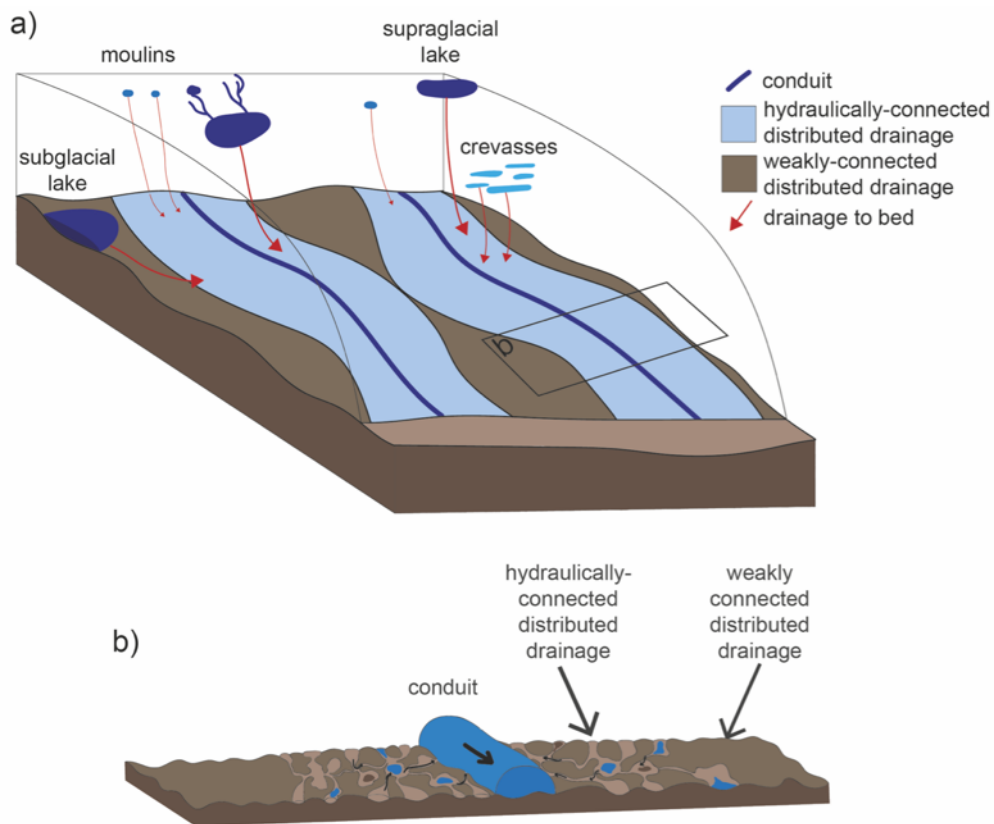
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by surface meltwater inputs (Andrews et al., 2014; Hoffman et al., 2016; Rada and Schoof, 2018).



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Figure 1. Ice sheet hydrological system with varying surface and basal inputs (a) and a three-system drainage model (b). In the three-system drainage model, the hydraulically connected distributed drainage system (light blue in a), is influenced regularly by surface meltwater inputs through the conduit. The weakly-connected distributed drainage system (dark brown) is largely isolated and rarely or never impacted by surface meltwater inputs. At present, the relative coverage of each is not yet known, nor the precise configuration or relation between each component.

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In theory, in a steady-state system, water flows from surrounding high pressure distributed regions into lower pressure conduits. Borehole measurements of subglacial water pressure, modelling and ice velocity proxy data (e.g. Hubbard et al., 1995; Gordon et al., 1998; Bartholomaus et al., 2008; Werder et al., 2013; Tedstone et al., 2014) suggest, however, that given a sufficiently large and rapid spike in water delivery to a subglacial conduit, the hydraulic gradient can be reversed such that water is

1035 forced out of and laterally away from the conduit into the hydraulically connected distributed drainage system. This has been variously termed a Variable Pressure Axis (VPA) (Hubbard et al., 1995), efficient subsystem (Rada and Schoof, 2018), efficient core (e.g. Davison et al., 2019) etc. Here, we use the term hydraulically connected distributed drainage which we consider to be the lateral limit of the influence of pressure variations that originate in a subglacial conduit and cause the flow of water in or out of the conduit. This mechanism has implications for overlying ice sheet dynamics, for example, overpressurisation overwhelms the conduit and can elicit ice flow acceleration and ice sheet surface uplift (e.g. van de Wal et al., 2008; Bartholomew et al., 2011; Doyle et al., 2013; Tedstone et al., 2015). The extent of this dynamic effect is much greater than the area of the bed directly affected by the meltwater.

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1055 Beyond the hydraulically connected distributed drainage system, the remaining distributed drainage system – likely composed of linked cavities – is largely isolated or disconnected from surface meltwater inputs (Andrews et al., 2014; Hoffman et al., 2016; Rada and Schoof, 2018). This area may exhibit some slow leakage into the hydraulically connected distributed drainage system (Hoffman et al., 2016; Rada and Schoof, 2018) and it is possible that pressure perturbations within the conduit also increase connections between these weakly connected parts of the bed and the hydraulically connected distributed drainage system. Weakly connected drainage areas potentially cover a large percentage of the bed and their gradual drainage over time is hypothesised to reduce regional basal water pressure, thereby increasing ice-bed contact and reducing ice velocity (e.g. Sole et al., 2013; Andrews et al., 2014; Bougamont et al., 2014; Tedstone et al., 2015; Hoffman et al., 2016).

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1065 Although we now have a better appreciation for the heterogeneous nature of the subglacial hydrological system, a lack of direct observations means that the reality of this interaction – its spatial and temporal occurrence, its expression and impact – remains speculative. For example, is the transition between the connected and isolated parts of the distributed drainage system abrupt (e.g. Hoffman et al., 2016) or transitional (e.g. Hubbard et al., 1995; Downs et al., 2018); how does the extent of the hydraulically connected distributed drainage system vary over space and time; does

the forcing of pressurised water out of the conduit have implications for sediment erosion rates?

1.1 Palaeo-meltwater landforms

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Palaeo–meltwater landforms have been fundamental in inspiring and guiding conceptual and numerical models of how water self-organises into drainage systems beneath present day ice masses because they can be easily observed and investigated ([Fig. 2](#)). Such landforms are therefore key to contextualising spatially and temporally limited contemporary observations and are commonly used to support and develop the theory of ice sheet hydrological systems (e.g. Shreve, 1985; Clark and Walder, 1994; Boulton et al., 2007a, [2007b](#); 2009; [Beaud et al., 2018a; 2018b](#); Hewitt and Creyts, 2019). Much of this focus has been on landforms such as eskers, meltwater channels and tunnel valleys which indicate efficient channelised subglacial drainage (e.g. Shreve, 1985; Brennand, 1994, 2000; Clark and Walder, 1994; Punkari, 1997; Boulton et al., 2007a, [2007b](#), 2009; Storrar et al., 2014a; Livingstone and Clark, 2016). We will now discuss each of these in more detail.

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1.1.1 Eskers

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Eskers are linear depositional landforms made up of glaciofluvial sand and gravel deposited from meltwater flowing through or beneath an ice mass in conduits metres to tens of metres in width and height. They exist as individual segments that often align to form networks extending up to several hundreds of kilometres (e.g. Shreve, 1985; Aylsworth and Shilts, 1989; Brennand, 2000; Storrar et al., 2014a; Stroeven et al., 2016) and are typically taken to record the former position and characteristics of Röthlisberger-channels (R-channels) thermally eroded into the base of the ice by turbulent water flow. While most studies reduce esker mapping to a single crest-line and consider the ‘classic’ single straight-to-sinuuous undulating ridge to be pervasive, more complex esker morphologies also occur (e.g. Banerjee and McDonald, 1975; Rust and Romanelli, 1975; Hebrand and Amark, 1989; Gorrell and Shaw, 1991; Warren and Ashley, 1994; Brennand, 2000; Mäkinen, 2003; Perkins et al., 2016; Storrar et al., 2019). These include fine-grained sandy fan shape elements or ‘splays’, alongside and associated with the coarse gravelly central ridge (e.g. Cummings et al.,

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1100 2011a; Prowse, 2017). These splays are an order of magnitude wider and more gently
sloped than the main ridge (Cummings et al., 2011a). They are proposed to form in
proglacial environments, representing subaqueous outwash fans deposited by
sediment laden plumes exiting a subglacial conduit into a proglacial lake (e.g. Powell,
1105 1990; Hoyal et al., 2003; Cummings et al., 2011b), supraglacial environments (e.g.
Prowse, 2017) and subglacial environments, with sedimentation in subglacial cavities
alongside the main esker ridge during periods of high water pressure within the conduit
(e.g. Gorrell and Shaw, 1991; Brennand, 1994).

1.1.2 Meltwater channels and tunnel valleys

1110 Erosional subglacial meltwater channels, or Nye-channels (N-channels), incised
into bedrock or sediment substrate range in size from metres to tens of metres wide
(e.g. Sissons, 1961; Glasser and Sambrook Smith, 1999; Piotrowski, 1999) to large
tunnel valleys several kilometres in width and tens of kilometres long (e.g. Kehew et
1115 al., 2012; van der Vegt et al., 2012; Livingstone and Clark, 2016). Tunnel valleys are
observed to occur at various developmental stages from mature and clearly defined
to indistinct valleys often associated with hummocky terrain or as a series of aligned
depressions (e.g. Kehew et al., 1999; Sjogren et al., 2002). Their formation has been
linked to subglacial meltwater erosion at the ice-bed interface (c.f. Ó Cofaigh, 1996;
1120 Kehew et al., 2012; van der Vegt et al., 2012) with the assumption that channels
transported large volumes of sediment and water. However, their precise mechanism
of formation is still debated with the main arguments focussing on i) catastrophic
outburst formation with rapid erosion following the release of sub or supraglacially
stored water (e.g. Piotrowski, 1994; Cutler et al., 2002; Hooke and Jennings, 2006;
1125 Jørgensen and Sandersen, 2006); ii) gradual steady-state formation with headward
erosion of soft-sediments in low water pressure conduits (e.g. Boulton and Hindmarsh,
1987; Mooers, 1989; Praeg, 2003; Boulton et al., 2009); and iii) formation from
seasonal meltwater flow (Beaud et al., 2016, 2018b).

1130 Here, we use the term meltwater channel to refer to palaeo-evidence of erosional
channelised flow preserved on the ice sheet bed (i.e. the outline of the path the water
took) at all scales from N-channels through to tunnel valleys. We use the term conduit

to refer to the active channelised flow beneath a contemporary ice mass (i.e. the enclosed (sediment or ice walled) pipe carrying water at the ice-bed interface).

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1.1.3 Meltwater tracks

Detailed mapping in northern Canada and Scandinavia has identified the presence of linear tracks variously termed ‘hummock corridors’, ‘glaciofluvial corridors’, ‘washed zones’ and ‘esker corridors’, typically a few hundred meters to several kilometres wide and a few kilometres to hundreds of kilometres long (e.g. St-Onge, 1984; Dredge et al., 1985; Rampton, 2000; Utting et al., 2009; Burke et al., 2012; Kerr et al., 2014a, 2014b; Sharpe et al., 2017; Peterson et al., 2017; Peterson and Johnson, 2018; Lewington et al., 2019). These features often contain eskers and hummocks which vary in size, shape and relief (Peterson and Johnson, 2018) as well as ‘patches’ of glaciofluvial deposits and areas of exposed bedrock. While a subglacial meltwater origin is largely agreed upon, their precise mode of formation is not yet known. These features are collectively termed meltwater tracks hereon in.

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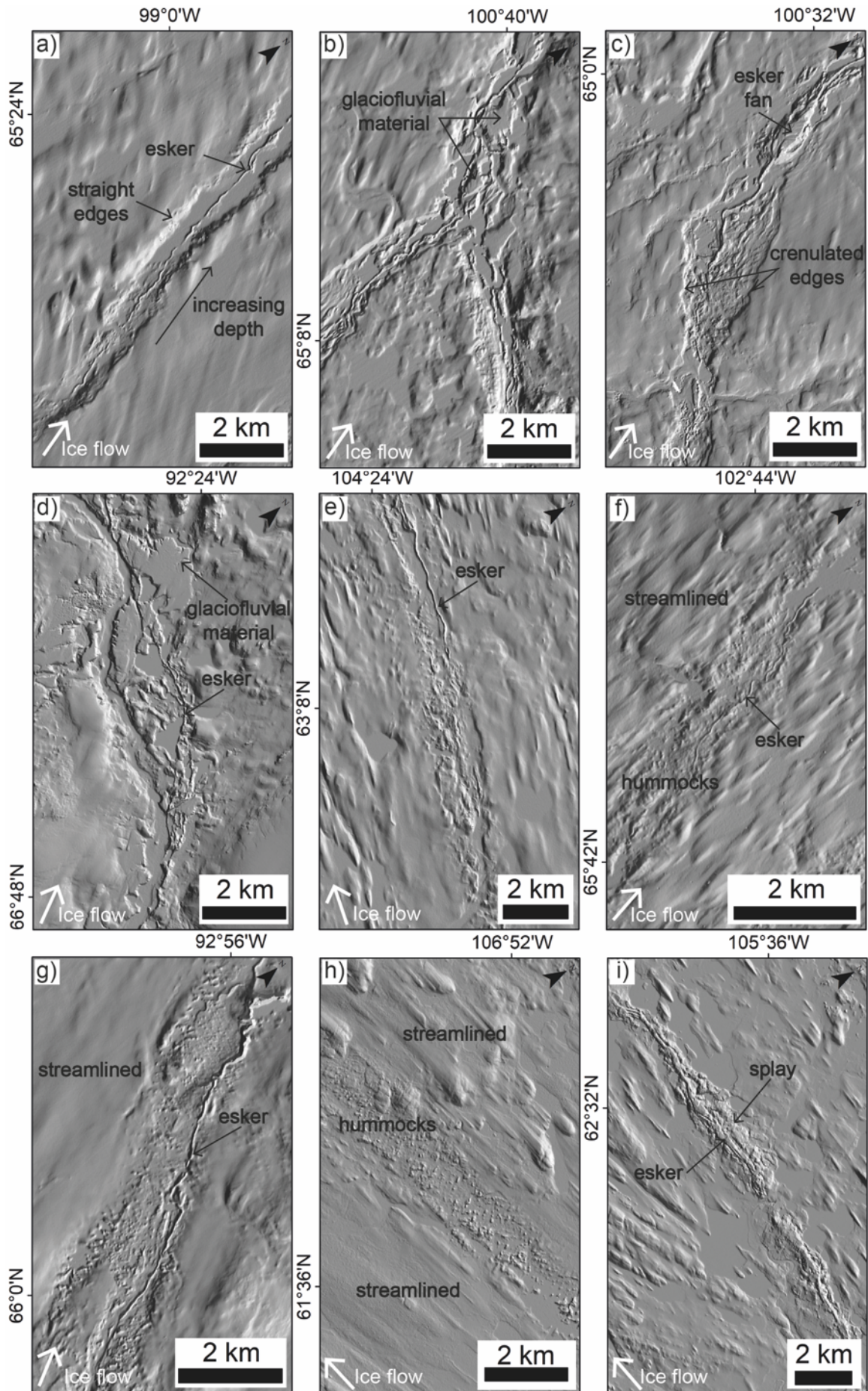
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Meltwater landforms are typically mapped and interpreted individually (e.g. Clark and Walder, 1994; Brennand, 2000; Storrar et al. 2013; Burke et al., 2015; Livingstone and Clark, 2016; Mäkinen et al., 2017) rather than as a holistic drainage signature (c.f. Storrar and Livingstone, 2017). As such, it is not yet clear whether or how differing expressions of subglacial drainage are interrelated and to what extent variations in drainage or background conditions (e.g. bed substrate, geology and local topography) control the preserved geomorphic signature we see today. This study aims to identify and map all discernible evidence of subglacial meltwater drainage across the Keewatin District of northern Canada from the ArcticDEM. We collectively refer to these as meltwater routes. Producing an integrated map of all visible subglacial meltwater evidence allows us to quantify the varying dimensions and geomorphological expressions of these features, to investigate associations between features traditionally treated separately and to explore potential controls on expression and formation. Importantly, we note this is a minimum map as some landforms – particularly tunnel valleys – may be fully or partially buried (e.g. Jørgensen and Sandersen, 2006).

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1170 Figure 2 (above). Varying geomorphic expressions of subglacial meltwater flow: (a) increasing depth hummock corridor transitioning into a tunnel valley; (b-d) hummock corridors with negative relief containing eskers, esker fans and glaciofluvial deposits. Corridor edges vary in straightness; (e-h) hummock corridors with more subdued relief, largely detectable by the elongated tracts of hummocks which stand out from the surrounding streamlined terrain and often surround an esker; (i) an esker surrounded by lateral fans i.e. esker splays.

1175 2. Study Area

1180 This study focusses on an area approximately 1 million km² to the west of Hudson Bay in northern Canada, surrounding the location of the former Keewatin Ice Divide of the Laurentide Ice Sheet (LIS) (Fig. 3) (Lee et al., 1957; McMartin et al., 2004). The area generally exhibits negligible local relief and is underlain by resistant Precambrian bedrock that is either exposed or covered by till ranging from thin and discontinuous (typically < 2 m) to thick and pervasive (typically > 2 m) (e.g. Clark and Walder, 1994).

1185 Traditionally, eskers have been identified as the predominant meltwater landform within the Keewatin area, although meltwater tracks (e.g. St-Onge, 1984; Aylsworth and Shilts, 1989; Rampton, 2000; Utting et al., 2009; Sharpe et al., 2017; Lewington et al., 2019) and meltwater channels (e.g. Storrar and Livingstone, 2017) have also been recorded. At a large scale, eskers radiate out from the ice divide, beneath which they are rare (Shilts et al., 1987; Aylsworth and Shilts, 1989; Storrar et al., 2013, 1190 2014a). At a local to regional scale, they exhibit a dendritic pattern and 12–15 km quasi-uniform spacing (e.g. Banerjee and McDonald, 1975; St-Onge, 1984; Shilts et al., 1987; Bolduc, 1992; Storrar et al., 2014a).

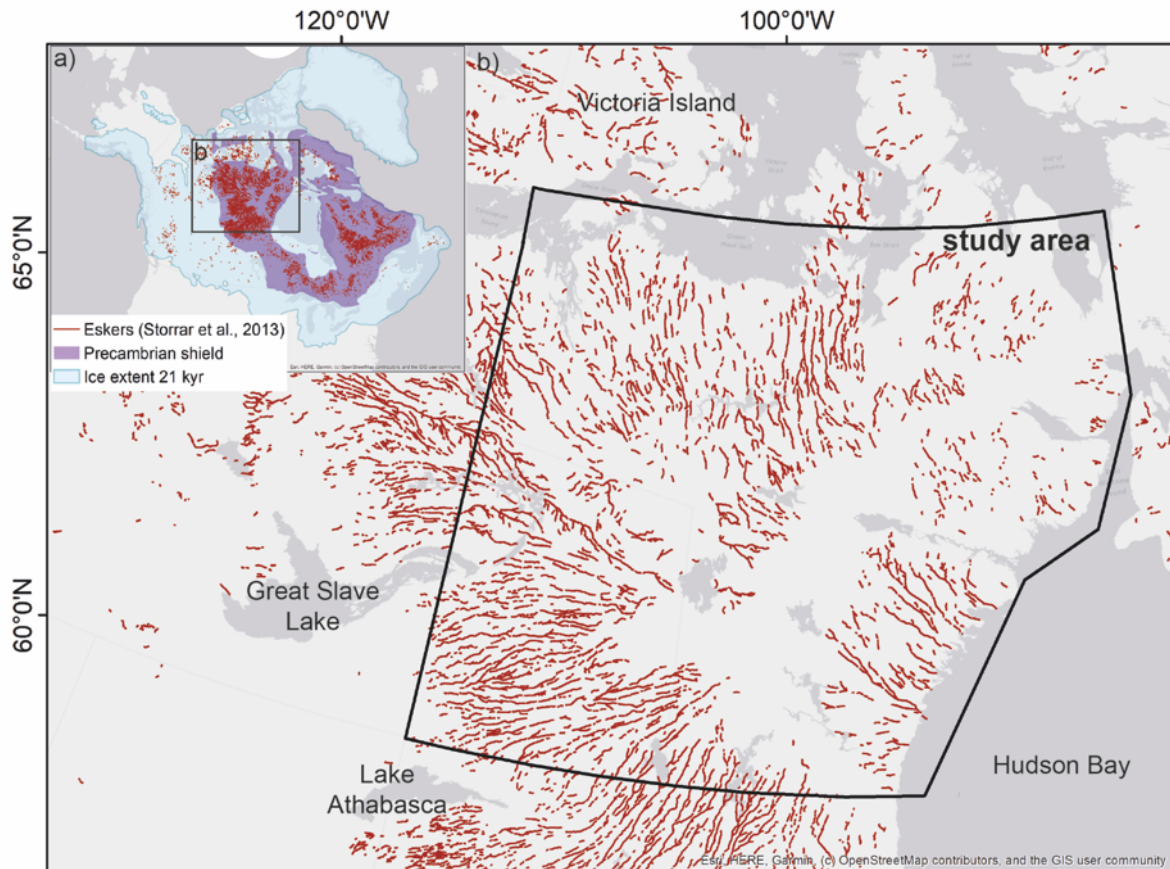


Figure 3. Large-scale distribution of eskers around Hudson Bay (Storrar et al., 2013) (a). The Laurentide Ice Sheet extent displayed in the inset is the Last Glacial Maximum (LGM) at 18 ¹⁴C ka BP (21.4 cal. ka BP) (Dyke et al., 2003) and the extent of the Precambrian shield is also mapped (Wheeler et al., 1996). Zoomed in location of the study area focussed on the area around the former Keewatin Ice Divide (b).

3. Methods

3.1 Data sources and mapping

High-resolution digital elevation data, made available through the ArcticDEM (10 m) (freely available at <https://www.pgc.umn.edu/data/arctidem>), and generated by applying stereo and auto-correlation techniques to overlapping pairs of high-resolution optical satellite images (Noh and Howat, 2015; Porter et al., 2018), were used in this study to identify and map meltwater landforms. In addition, eskers mapped by Storrar et al., (2013) from 30 m resolution Landsat ETM+ multispectral imagery

were used to inform further high-resolution esker mapping from the 10 m resolution [ArcticDEM](#). The automatic mapping approach developed in Lewington et al. (2019) was used to create a first pass map of hummock corridors – classified as meltwater tracks here (Appendices Fig. A1) – to augment the improved esker map. Together, these were used to create an integrated map of [meltwater routes](#) by manually mapping centrelines of all visible traces of subglacial meltwater drainage including meltwater tracks, meltwater channels and eskers. Multiple orthogonal hillshades were generated to avoid azimuth bias (Smith and Clark, 2005) and mapping was undertaken at a range of spatial scales to maximise the number of features captured (Chandler et al., 2018).

3.2. Classification and morphometry

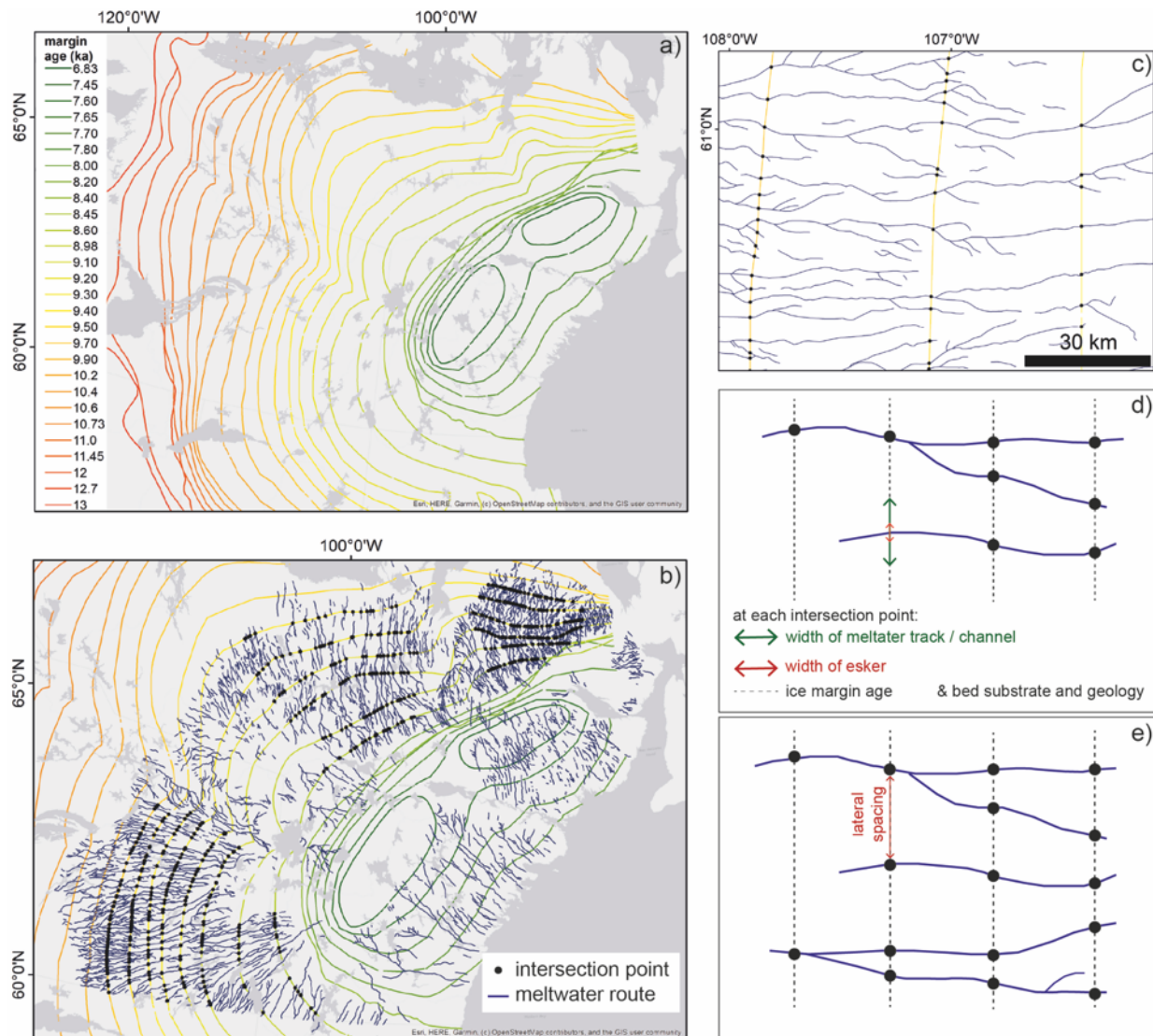
The [meltwater routes](#) were used to explore the occurrence and morphology of different types of meltwater landforms. Former ice-margin estimates from Dyke et al. (2003) were used as transects ([Fig. 4](#)). These transects are spaced approximately 30 – 40 km apart and in the study area, cover c. 1,000 years of deglaciation between 9.7 and 8.6 ka. This period encompasses the final stages of deglaciation when the ice sheet was experiencing a strongly negative surface mass balance with associated increasing rates of meltwater production (e.g. Carlson et al., 2008, 2009). Retreat rates were generally between 100 – 200 m yr⁻¹ from 13 to 9.5 ka, increasing rapidly between 9.5 and 9 ka to around 400 m yr⁻¹ after which retreat rate decreased briefly before another increase from ~8.5 ka (Dyke et al., 2003).

When a meltwater route intersected a transect, an intersection point was added, and the following information recorded:

- Landform type (i.e. esker ridge, esker with lateral splay, meltwater track or meltwater channel)
- Width of landform (or landforms if an esker ridge was present within a meltwater track, meltwater channel or surrounded by a lateral splay)
- Bed substrate and geology (Fulton, 1995; Wheeler et al., 1996).

Spacing between adjacent meltwater route centrelines was calculated along each transect with centrelines at the end of each transect and those separated by clear

breaks (e.g. due to the coincidence of a lake) discounted. The total length of meltwater route centrelines was calculated automatically in a GIS.



1250 Figure 4. (a) Ice margin estimates (Dyke et al., 2003) for the Keewatin sector of the LIS; (b)
Intersection points between mapped meltwater routes and ice margin estimates used for
sample locations; (c) A zoomed in example of meltwater routes, margin isochrones and
intersections from the SW of the study area; (d) Method for recording meltwater route
characteristics and; (e) lateral spacing.

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1260 3.3 Testing controls on meltwater routes width and expression

This study takes a large-scale approach to exploring controls on meltwater route width and expression. While this approach results in a compromise in terms of data resolution available for the surface substrate and geology maps, it also increases statistical confidence in the results due to the larger sample size. Before analysis was undertaken, three test sites were selected from the study area to allow for more detailed mapping and comparisons (Appendices Figs. A2 and A3).

To explore substrate and geological controls on meltwater route occurrence, distribution and properties, the overall length of meltwater routes overlying each substrate type (Fulton, 1995) and geology (Wheeler et al., 1996) within the three test sites was calculated. The total area of each basal unit within the test sites was also calculated and values converted to percentages. Following this, the percentage area was subtracted from the percentage of meltwater routes for each individual substrate and geology type, giving a positive (over-represented) or negative (under-represented) value. Next, meltwater routes were split and classified by feature type (i.e. esker, esker with lateral splay, meltwater channel and meltwater track). The above analysis was then repeated by feature type to explore whether geomorphological expression is controlled by surface substrate or geology. It is important to note that categorisations along meltwater routes were not always independent as the same section was sometimes coded as a meltwater track and an esker with splay as often 'positive' features are situated within wider erosional corridors.

It was noted that landform type varies both across adjacent meltwater routes and along individual meltwater route centrelines. To assess any potential relationship between landform type and background controls in more detail, individual centrelines were selected and sampled with a higher frequency (1 km intervals). At each sample location the width of the meltwater track or meltwater channel, the presence or absence of an esker (and its width if present), surface substrate, bed geology and elevation were recorded.

The transfer of surface meltwater to the bed via moulins is thought to be strongly controlled and largely fixed by bed topography; ice flow over bedrock ridges

1295 can cause elevated tensile stresses resulting in crevassing (Catania and Neumann,
2011), while the transfer of bed topography to the ice-surface preconditions where
surface lakes form (e.g. Gudmundsson, 2003; Karlstrom and Yang, 2016; Crozier et
al., 2018; Ignéczki et al., 2018). To investigate the spatial coincidence between
1300 subglacial meltwater pathway density and basal roughness, we initially applied a
circular median filter with a 2 km diameter to the bed topography (the 10 m resolution
resampled to 100 m). This was based on the understanding that bed perturbations
below 1 - 3 times the ice thickness are not transferred to the surface (Gudmundsson,
2003; Ignéczki et al., 2018) and that the LIS ice thickness was typically 500 – 2000 m
thick. Standard deviation was then calculated over a 20 km diameter window as per
1305 Ignéczki et al., (2018), who found this smoothing distance matched the requirements
that the smoothing window should not exceed 10 times the ice thickness
(Gudmundsson, 2003) while still capturing longer scale variations and dampening
rapid changes in local topography (Ng et al., 2018).

1310 Finally, ice stream locations (Margold et al., 2015) were quantitatively compared to
the distribution of meltwater routes. This allowed us to determine whether or not there
was a difference in expression of subglacial meltwater pathways between ice stream
and non-ice stream areas.

1315 **4. Results**

4.1 An integrated drainage signature

1320 _____ Mapping all traces of meltwater drainage reveals the ubiquity of former
subglacial drainage across the study area (Fig 5). A total of ~ 3000 meltwater routes
were mapped over a ~1 million km² area with a total length of almost 55,000 km. The
meltwater routes exhibit a similar overall pattern to earlier esker maps (e.g. Aylsworth
and Shilts, 1989; Storrar et al., 2013) radiating out from the former Keewatin Ice
Divide. Greater than 90 % of mapped esker ridges in this region are estimated to occur
along a meltwater route and therefore form part of the same network. In terms of the
1325 large-scale pattern, there are no obvious trends in meltwater route density, width or
feature type associated with margin retreat. However, the study area only covers

approximately 1,000 years, associated with a period of intense meltwater production and rapid retreat

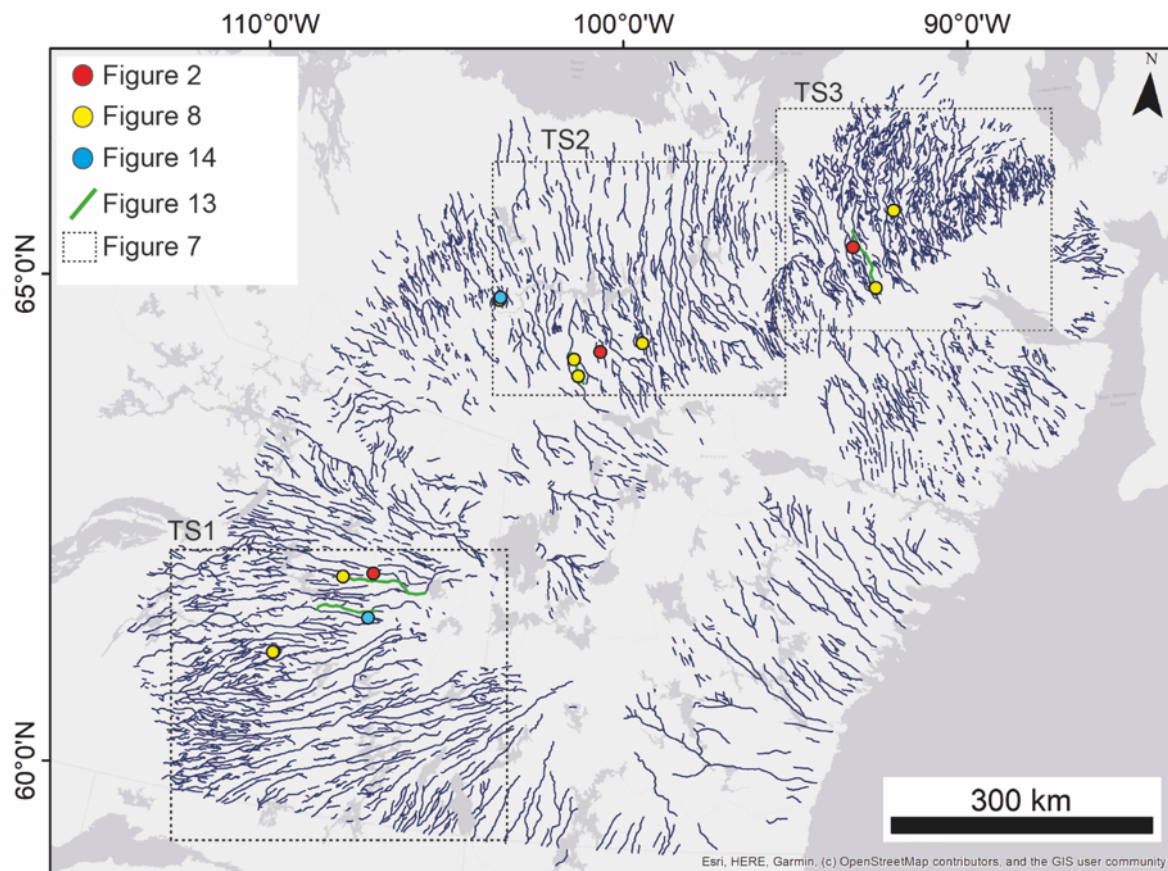


Figure 5. Integrated map of meltwater routes. Note how meltwater routes in this new map are less fragmented and denser than the existing esker map (Fig. 2b). Points and boxes represent locations of other figures.

Within the study area, 84 % of sample locations captured a meltwater track (65 %) or meltwater channel (19 %). The remaining samples captured an esker ridge alone (6 %), an esker ridge with a lateral splay (6 %) or were deemed unclassified (4 %). However, subglacial meltwater signatures were not always mutually exclusive and often esker ridges or sometimes even eskers with lateral splay, were recorded within the meltwater tracks and channels. Esker mapping by Storrar et al., (2013) was updated in the study area. Due to the higher resolution data available and the smaller spatial area covered, smaller features which may have been missed could be included. A comparison between the updated esker map and the new meltwater routes map confirms the large-scale association between eskers and wider meltwater features

1345 which often flank and connect intervening segments. Eskers were recorded at 43 % of all sample locations. Where they were recorded, 87 % of the time they were flanked by a meltwater track, channel or splay.

Table 1. Summary statistics for meltwater routes in the study area.

	Length (km)	Width (km)	<u>Centreline</u> spacing (km)
Min	0.7	0.05	0.4
<u>Lower</u> quartile	4.8	0.5	3.3
<u>Upper</u> quartile	20.1	1.1	10.1
Max	339.9	3.3	77.9
Mean	18.1	0.9	8.1
Std dev.	26.5	0.6	7.4

1350 Meltwater routes reach a maximum of 3.3 km in width and 340 km in length (Table 1), but are noted to reach up to 760 km when they extend beyond the limits of the study area (Storrar et al., 2014a). Meltwater channels and meltwater tracks are typically an order of magnitude wider (mean width: 900 m) than the eskers which they often contain (mean width: 97 m). Meltwater routes appear to vary in width across the study area and along individual centrelines but show no clear trend from the ice divide towards the margin. If these landforms are assumed to have formed time-transgressively, this would suggest no clear trend in width during deglaciation. Within the study area, adjacent centrelines are spaced on average 8 km apart (Table 1). This is at the lower end of the range reported in the literature (Fig. 6) (e.g. Banerjee and McDonald, 1975; St-Onge, 1984; Shilts et al., 1987; Hebrand and Amark, 1989; Bolduc, 1992; Boulton et al., 2009; Hewitt, 2011). This is not surprising given that we mapped all traces of subglacial meltwater flow including meltwater tracks not containing eskers. Like variations in width, there appears to be no coherent change in spacing during deglaciation (Fig. 4) if we assume time transgressive formation.

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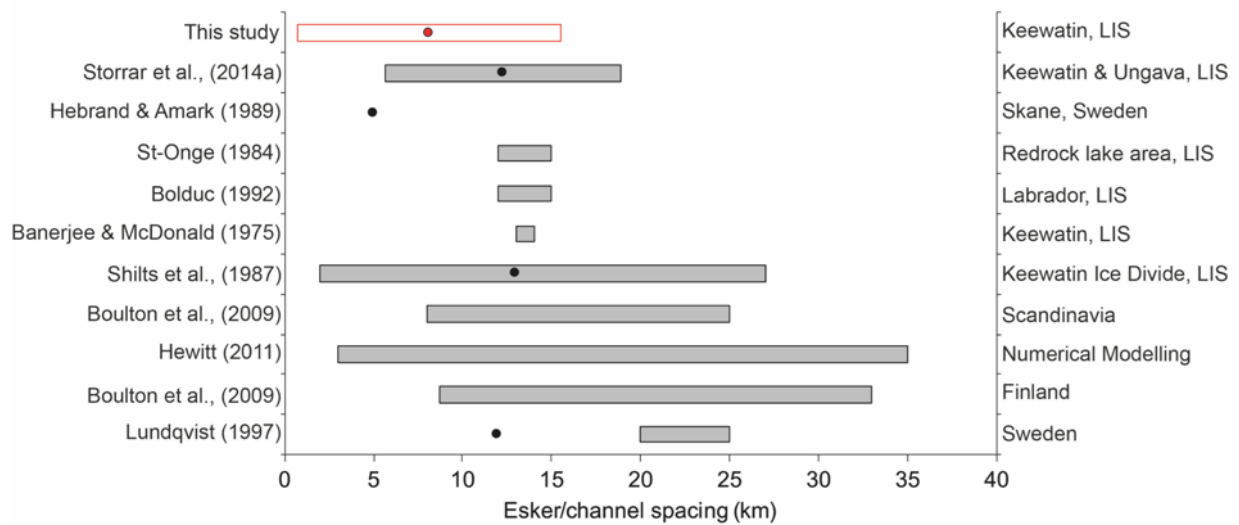


Figure 6. Examples of esker and subglacial channel spacing quoted in the literature with bars representing maximum and minimum and the points the mean (Storrar et al. 2014a). The top two bars represent a large-scale esker sample taken from an area which includes this study (Storrar et al., 2014a) and the spacing recorded by all visible traces of subglacial meltwater (i.e. eskers and meltwater corridors). For these two, the bars represent standard deviation and the points the mean. (Modified from Storrar et al., 2014a).

Eskers have been widely mapped in northern Canada. Initial mapping was largely undertaken by the Geological Survey of Canada using aerial photography and field observations (e.g. Aylsworth and Shilts, 1989). This included mapping of 'esker systems' – comprising a series of hummocks or short, flat-topped segments which phase downstream into relatively continuous esker ridges or occasionally beaded eskers – across 1.3 million km² of the Keewatin sector of the LIS (Aylsworth and Shilts, 1989; Aylsworth et al., 2012). Discontinuous esker ridges are connected to areas of outwash, meltwater channels or belts of bedrock stripped free of drift. More recently, increasing availability of remotely sensed data allowed Storrar et al., (2013) to digitise eskers at an ice sheet scale for the LIS (including the Keewatin sector) using Landsat 7 ETM+ imagery. From this, a secondary dataset was derived by interpolating a straight line between successive aligned esker ridges, creating a continuous pathway, which reflects the location of the major conduits in which the eskers formed (Storrar et al., 2014a). This paper extends earlier work, which recognises links between eskers and broader traces of subglacial meltwater flow but does not explicitly describe or

formally quantify them (e.g. Aylsworth and Shilts, 1989; Storrar et al., 2014a). It is encouraging that despite different datasets and mapping procedures, the overall patterns are similar (Fig. 7).

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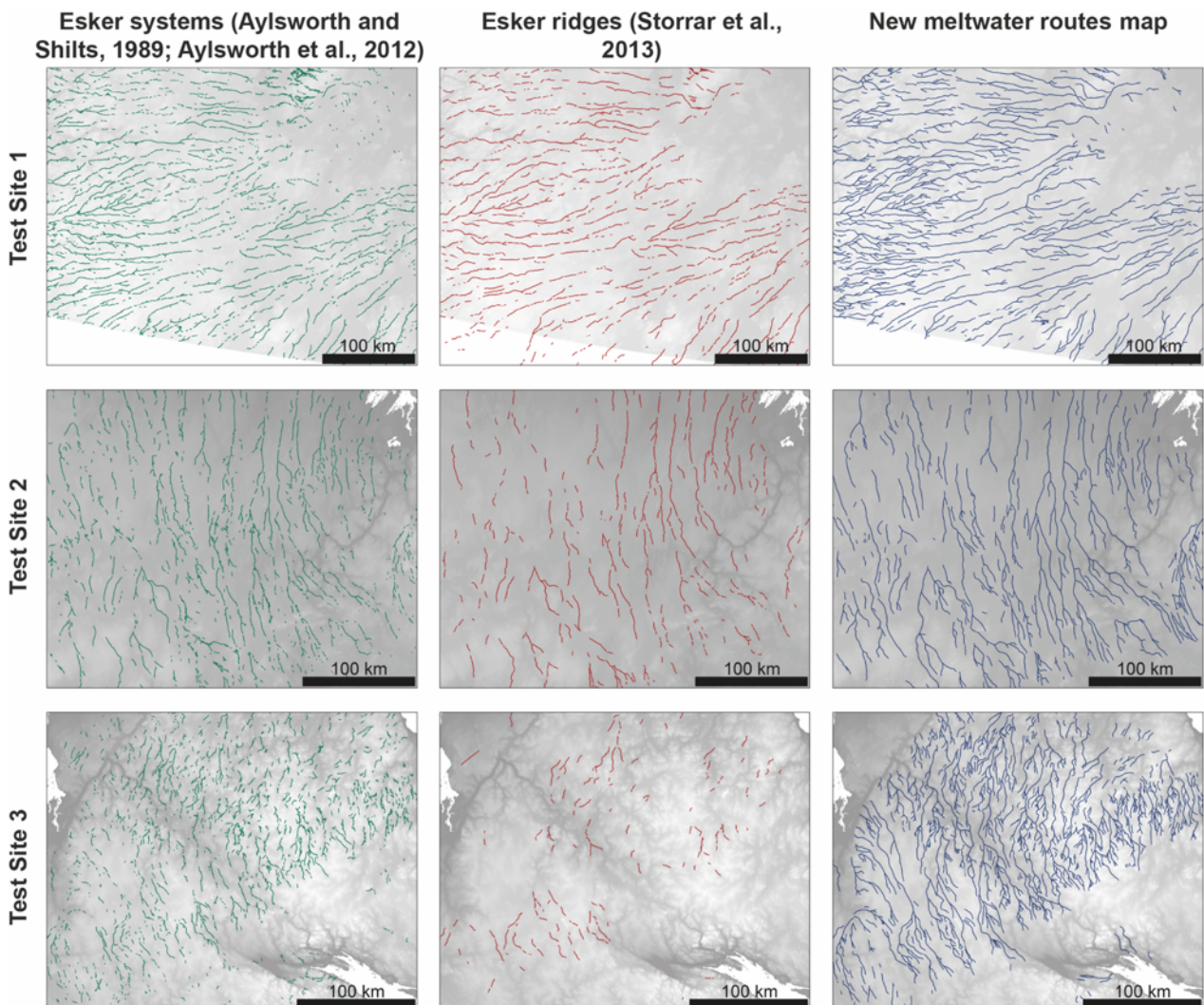


Figure 7. Comparison of existing maps of ‘esker systems’ (green) from air photo interpretation (Aylsworth and Shilts, 1989; Aylsworth et al., 2012), esker ridges (red) from Landsat imagery (Storrar et al., 2013) and the new meltwater routes from the ArcticDEM (blue). Mapping of meltwater routes includes all traces of subglacial meltwater flow (eskers, eskers with lateral splay_s, meltwater tracks and meltwater channels). The locations of test site 1, test site 2 and test site 3 are identified in Fig. 5. DEM(s) created from the Canadian Digital Elevation Model (CDEM). Ottawa, ON: Natural Resources Canada. [2015]

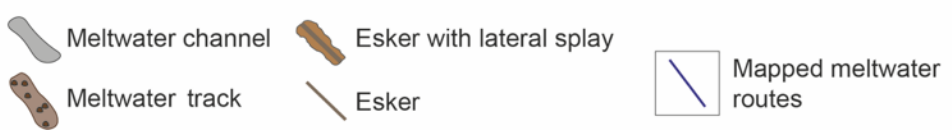
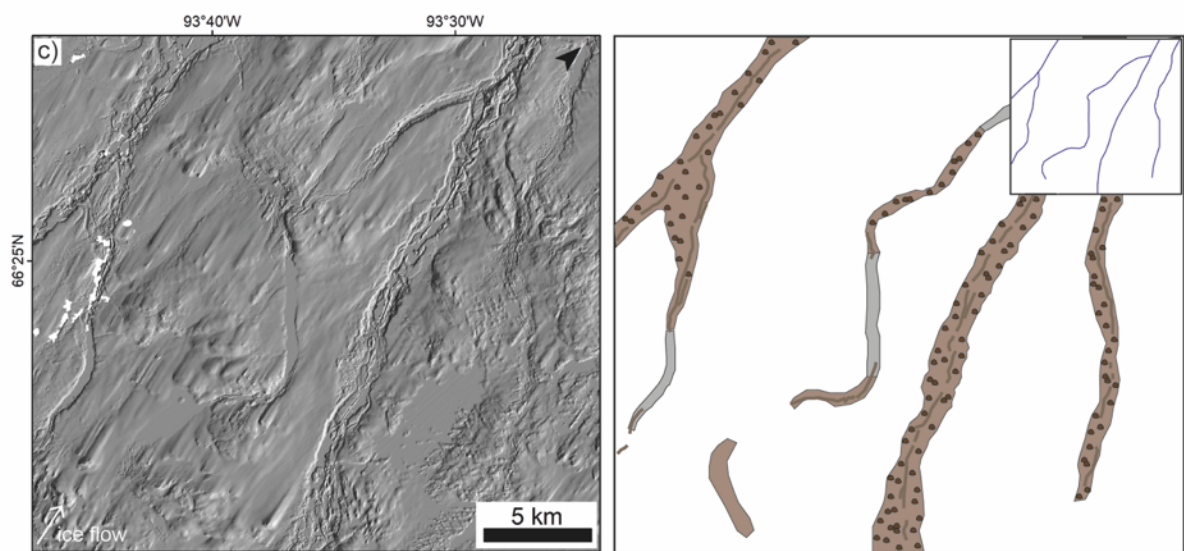
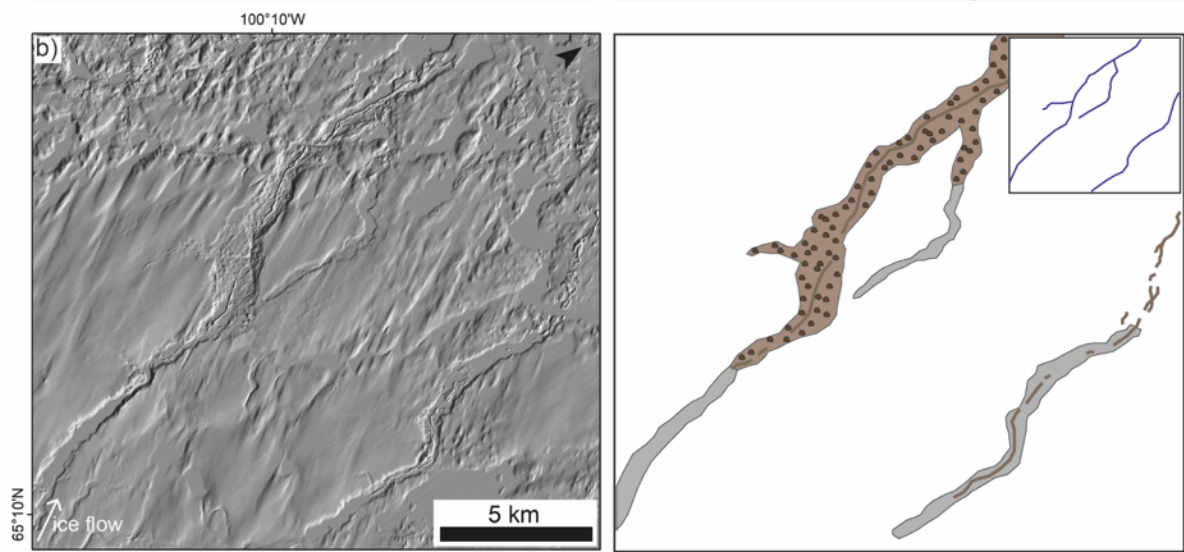
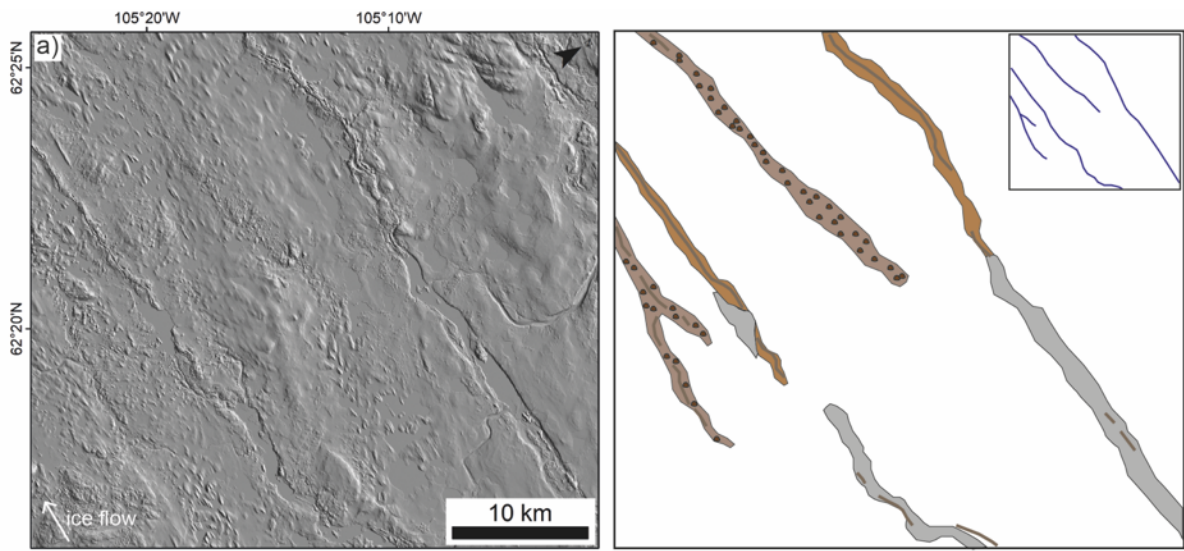
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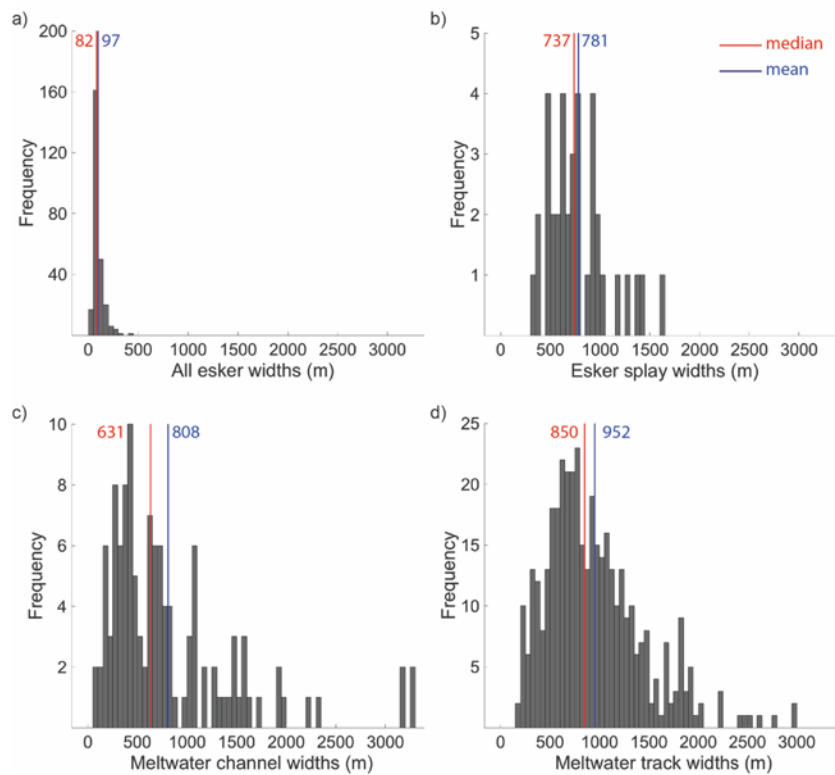
4.3 Geomorphological variations

Landforms along meltwater routes exhibit a high degree of geomorphic variability and each of the palaeo-meltwater landforms outlined in section 1.1 (meltwater channels, meltwater tracks and eskers) are identified in the study area. Meltwater channels exhibit negative relief down to ~ 30 m below their immediate surroundings (e.g. Fig. 2a). Meltwater tracks exhibit less pronounced (e.g. Fig. 2b - 2d) or even negligible relief (e.g. Fig. 2e - 2h), the latter being identified due to the presence of elongated tracts of hummocks. Meltwater route edges vary from straight (e.g. Fig 2a, 2e, 2h) to crenulated (e.g. Fig. 2c) and may be discontinuous along sections. A variety of landforms are found within the meltwater tracks and channels. These include hummocks of varying size, shape and relief (e.g. Fig 2e – 2h) and eskers and associated glaciofluvial material (e.g. Fig. 2a – 2d). In places, till may be entirely eroded, revealing patches of bedrock. Eskers display a high degree of variability along the meltwater routes with single, continuous ridges the exception rather than the norm. Meltwater routes vary in geomorphological expression both across flow, between adjacent routes, and along flow, with multiple transitions to and from 'different' feature types (Fig. 8).

Figure 8 (below). Examples of transitions and associations along meltwater routes. The left panel shows the DEM and the right panel shows an interpretation of the feature types with an inset (top right) showing how meltwater routes are mapped as single lines through all types. White patches in the DEM represent areas of missing data due to the presence of hydrological features (e.g. lakes and rivers) or in areas of cloud cover and shadow. DEM(s) created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.



1435 Despite variations in expression (e.g. relief, definition and the presence or
 1440 absence of hummocks, glaciofluvial material and eskers), meltwater tracks and
 meltwater channels are both associated with eskers (Fig. 2) and form an integrated
 and coherent large-scale spatial pattern (Fig. 5). Furthermore, both features have a
qualitatively similar width range of several hundred meters to ~3 kilometres (Fig. 9).
However, the null hypothesis that the data in each pairing are from the same
 continuous distribution using the two-sample Kolmogorov-Smirnov test could not be
 rejected for any pairings (esker, esker with splay, meltwater channel and meltwater
 track) at the 5 % significance level.



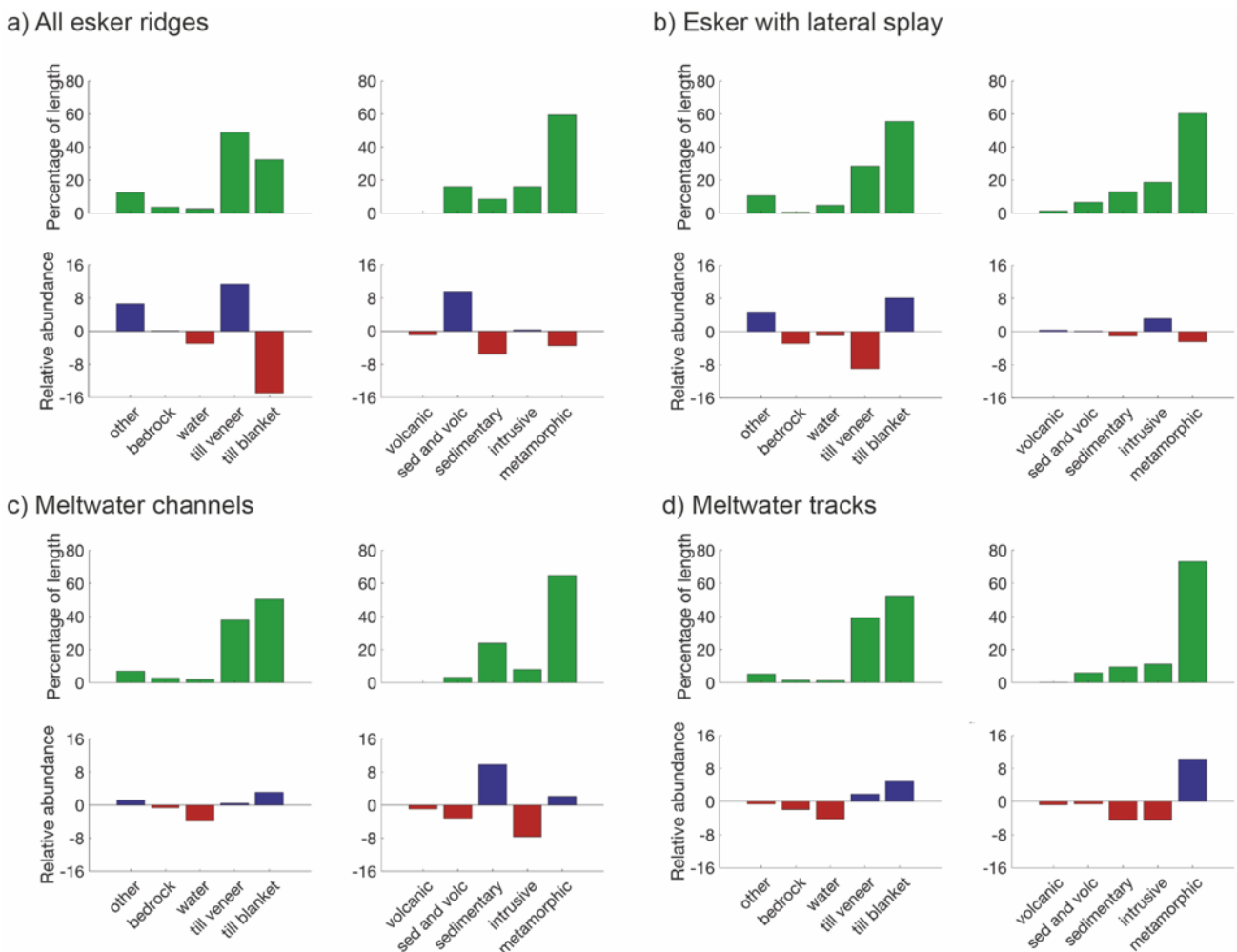
1445 **Figure 9.** Width distributions (in metres) of (a) all esker ridges (n = 259), (b) eskers with lateral
 1450 splays (n = 37), (c) meltwater channels (n = 118) and (d) meltwater tracks (n = 408) from the
whole study area. The median is marked on in red and the mean in blue.

4.4 Controls on the width and expression of meltwater landforms

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Most subglacial meltwater landforms occur within areas of till (Fig. 10). Meltwater tracks, meltwater channels and eskers with lateral splays are overrepresented in areas of till blanket, while esker ridges are strongly underrepresented. Meltwater features appear most commonly over areas of metamorphic bedrock, although meltwater channels (incisional features) are overrepresented on more erodible sedimentary rocks.

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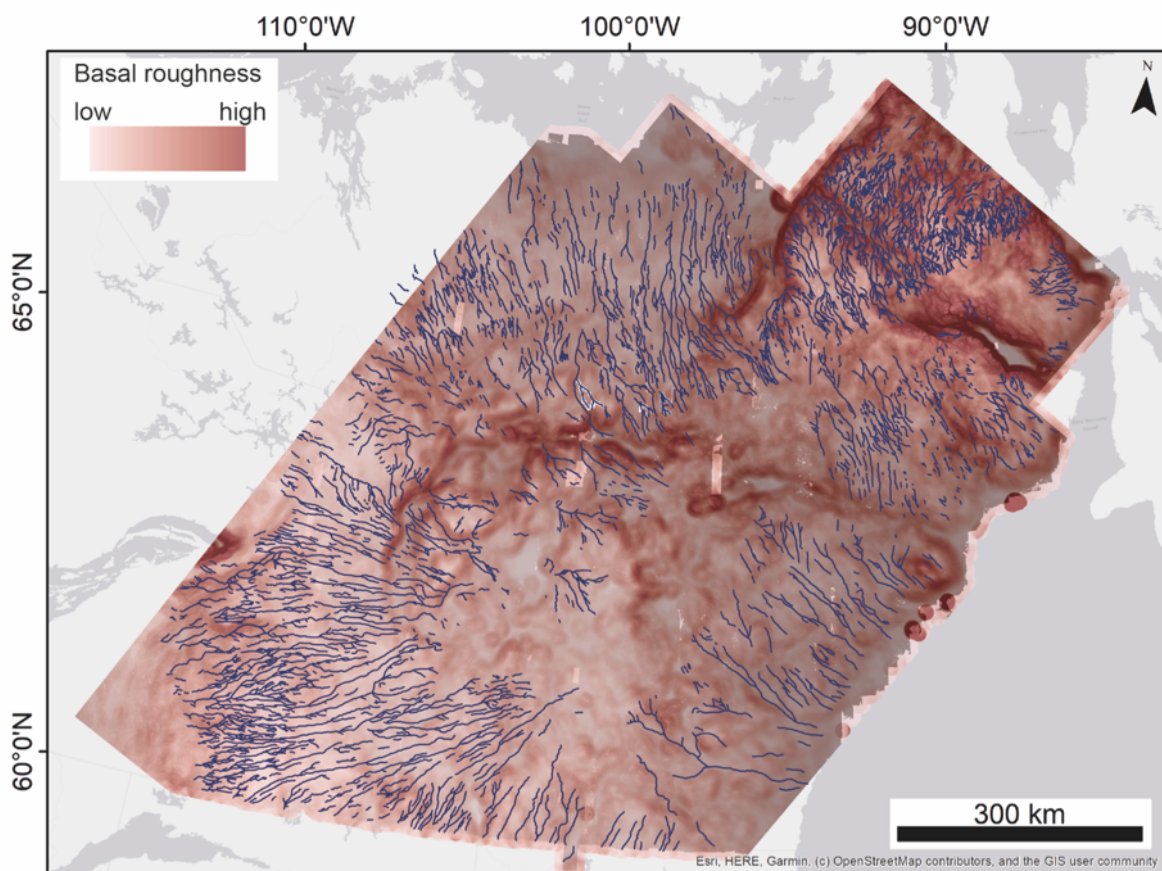
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Figure 10. Substrate control on geomorphological expression. Occurrence (percentage of length) and relative abundance of different meltwater features over varying surface substrates (Fulton, 1995) and background geology (Wheeler et al., 1996). ‘Other’ includes marine, lacustrine and glaciofluvial sediments. Blue represents over representation and red represents under representation.

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Figure 11 reveals high topographic variability in the NE of the study area. This coincides with the highest density of meltwater routes. Palaeo-ice streams are rare in the Keewatin District region (Stokes and Clark, 2003a, 2003b; Margold et al., 2018), but where they do occur, meltwater routes are noticeably sparser (Fig. 12). Comparing the spatial density of meltwater routes inside and outside of the ice streams (calculated simply as total length of meltwater routes per unit area) shows that the two datasets are statistically different ($p = 0.03$). On the bed of the Dubawnt Lake Ice Stream, meltwater routes also exhibit a more dendritic arrangement and extend further towards the ice divide.

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Figure 11. Meltwater routes overlain on local bed roughness calculated for the approximate wavelength expected to be relevant for the transfer of basal undulations to the ice surface). This is where the densest surface meltwater networks and ponding is likely to occur given sufficient melt conditions (Ignéczi et al., 2018). DEM created by the Polar Geospatial Center from DigitalGlobe, Inc. imagery.

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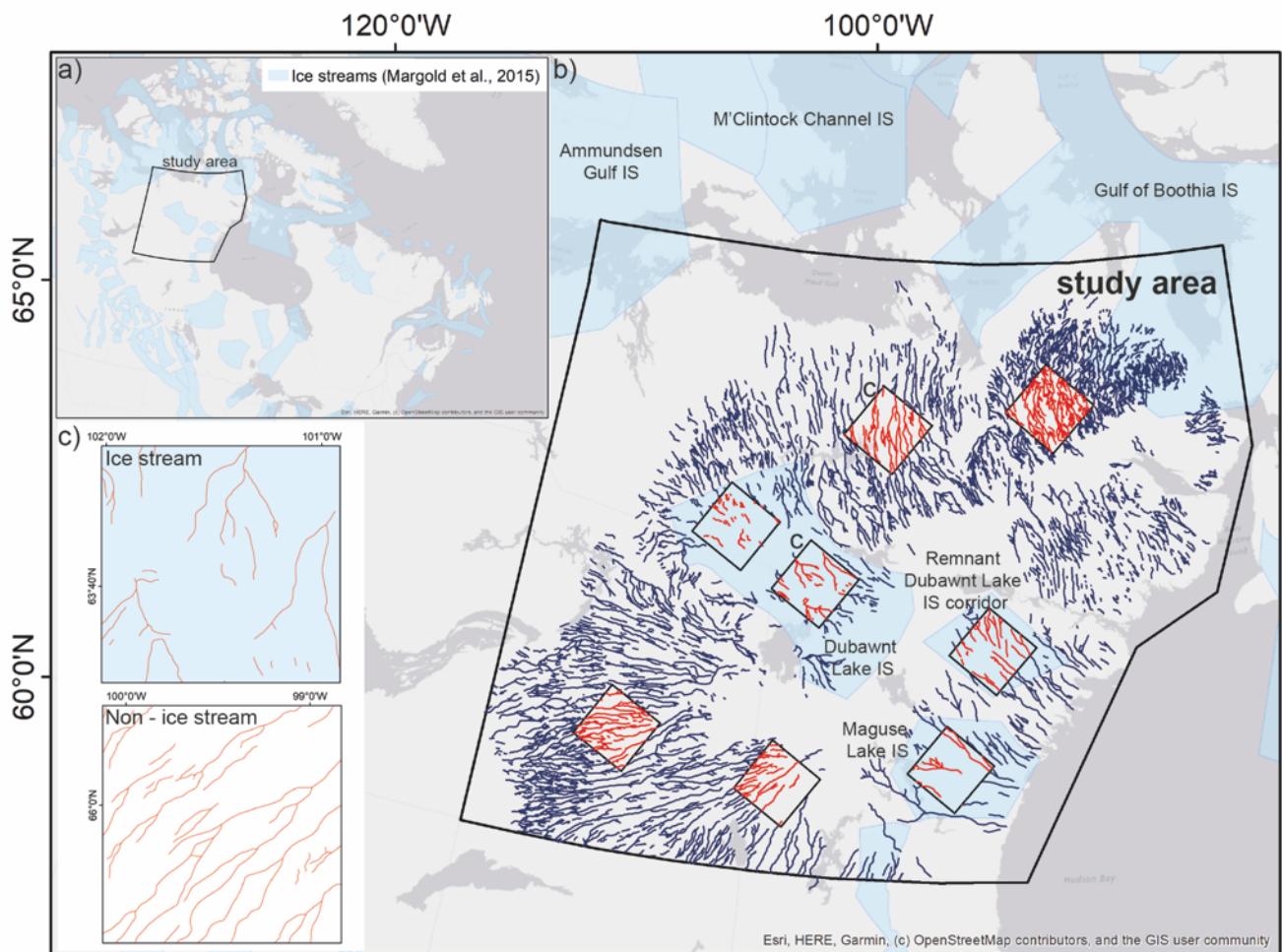


Figure 12. (a) Comparison of meltwater routes and palaeo-ice streams (Margold et al., 2015); (b) Spatial density was calculated for each of the randomly placed sample boxes (100 x 100 km). Ice stream density was compared to the non-ice stream density using a two sample t-test. The null hypothesis is rejected at the 5% significance level ($p = 0.03$); c) Visual comparison between meltwater routes in ice stream and non-ice stream areas.

To explore potential controls that govern how meltwater landform expression changes with variable background conditions (e.g. substrate, geology, topography), measurements of width, feature type and substrate were extracted along individual meltwater routes (Fig. 13). Although there is not a consistent ratio between esker width and the associated width of the meltwater track or meltwater channel when measured at the same location, there is a general positive relationship between the two, specifically when following topographic steps (e.g. Fig. 13a and 13d) and after the merging of tributaries (e.g. Fig. 13b and 13d). In Fig. 13a for example, a large increase in width (883 – 1550 m) is associated with an increase in elevation (~ 70 m over 6 km),

which also coincides with a transition from a strongly negative feature (a meltwater channel) to a positive relief depositional feature (esker with lateral splay). This sharp transition may be related to the emergence of the meltwater route out of the Thelon sedimentary basin.

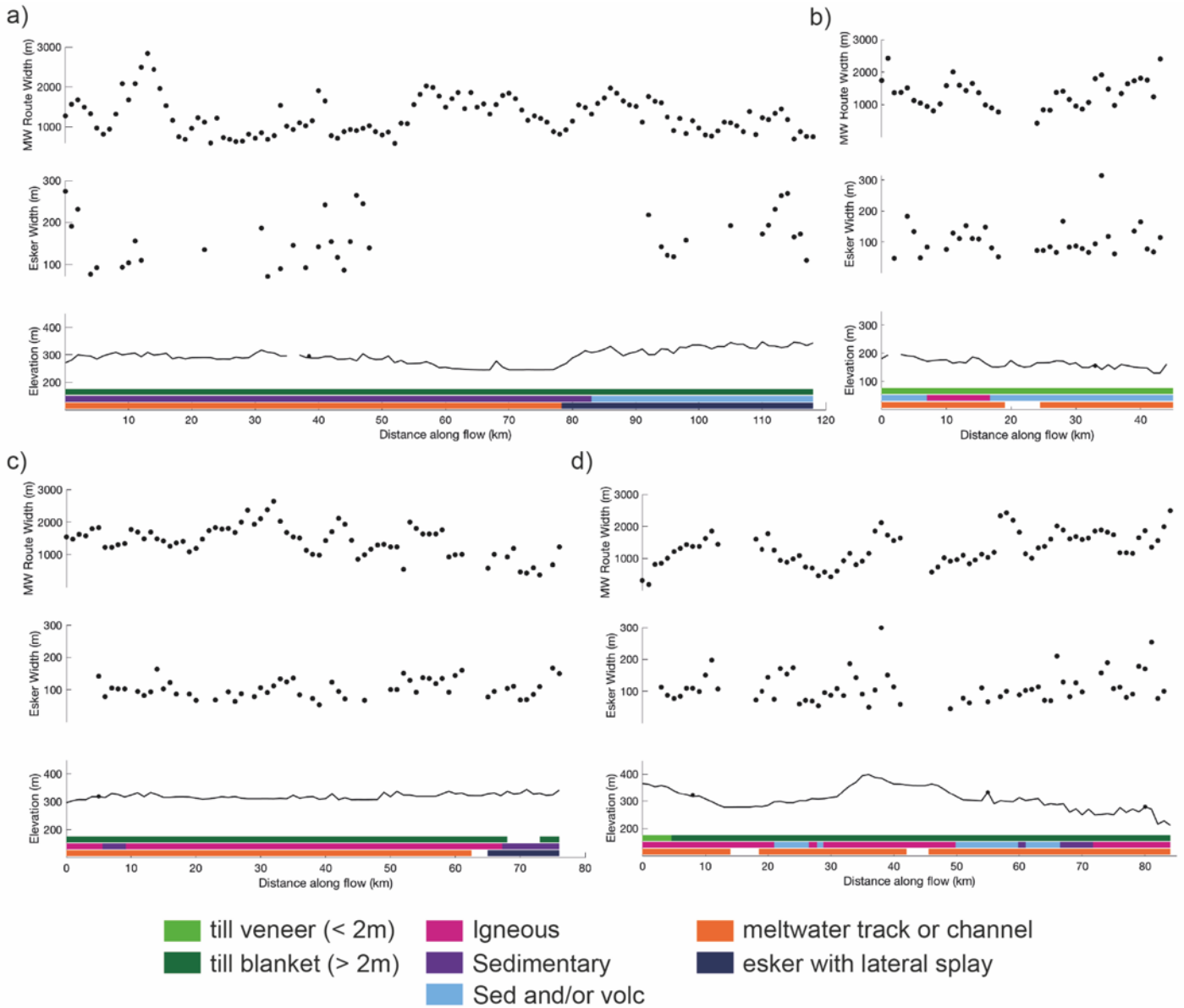


Figure 13. Exploring local-scale controls on meltwater route width and type. Detailed profiles (sampled at 1 km intervals along individual meltwater routes (location identified in green in fig. 5)) show how esker width, elevation, feature expression and surface substrate vary along flow from the interior (left) to the exterior (right). Black points on the elevation plot represent the location of joining tributaries.

1515 **5. Discussion**

Our new meltwater routes map shows that meltwater tracks and meltwater channels, which flank and connect (in an along-flow direction) esker ridges, are a dominant part of the landscape across the former Keewatin sector of the LIS. Mapping complete drainage pathways means we are better able to identify regional meltwater drainage patterns and unravel controls on feature expression.

The large-scale distribution and pattern of meltwater tracks and meltwater channels exhibit several key similarities, including width, spacing, association with eskers and occurrence within an integrated network characterised by transitions to and from different expressions along individual meltwater routes (Fig. 8). Together, this provides strong evidence that these meltwater landforms are varying expressions of the same phenomenon and we therefore group these features with widths in the order of 100s to 1000s of meters and term them meltwater corridors (Table 2). This is consistent with previous conceptual work linking meltwater landforms. For example, Sjogren et al., (2002) identify various tunnel valley (meltwater channel) expressions that they attribute to different developmental stages, from discontinuous through to fully developed valleys. Peterson and Johnson (2018) suggest that negative relief hummock corridors (meltwater tracks) are a type of tunnel valley and positive relief hummock corridors are equivalent to 'glaciofluvial corridors' in Canada (e.g. Utting et al., 2009).

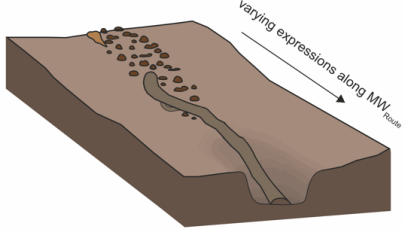
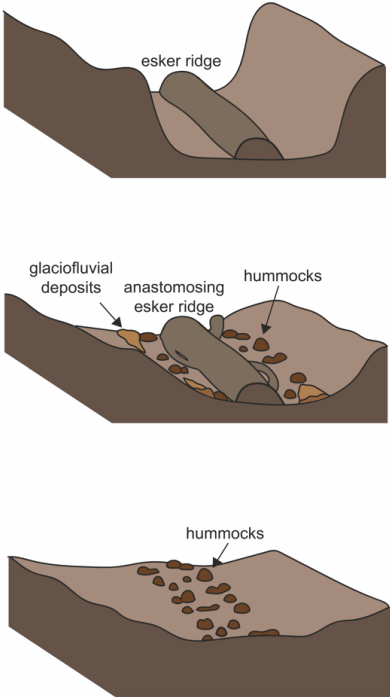
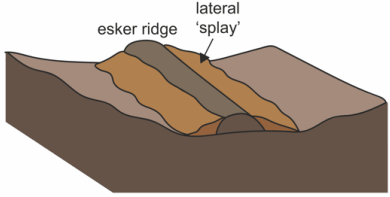
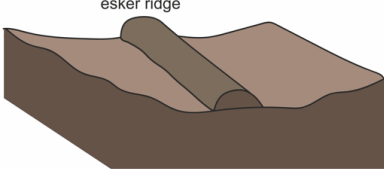
Esker splays also have similar widths and a close spatial association with meltwater corridors (e.g. transitions along flow or occurring within meltwater corridors). However, it is possible that some or even all of these features were deposited marginally (e.g. Hebrand and Amark, 1989) rather than in subglacial cavities. In fact, marginal deposition is supported by the fact that some of the esker splays align across flow in line with estimated ice sheet isochrones (Dyke et al., 2003). Nonetheless, it is difficult to constrain their formation from geomorphology alone.

While recognised previously in local case studies (e.g. St-Onge, 1984; Rampton, 2000; Utting et al., 2009), we confirm that across this 1 million km² area of the former LIS, meltwater corridors of varying geomorphic expression are widespread

1550 (captured at 84 % of all sample points) rather than an isolated phenomenon. Esker
ridges are captured at just 43 % of sample locations, however, we do note that the
presence or absence of an esker at the sample point may not be indicative of the entire
length of the meltwater route as in many cases the esker ridges within a meltwater
corridor are fragmented. Nonetheless, we suggest that the model of R-channels
1555 across the Canadian Shield (e.g. Clark and Walder, 1994) is an oversimplification and
may under-represent the modes and thus coverage of drainage in this sector and fail
to capture important processes recorded on the bed.

Holistic mapping of meltwater routes including features cut up into the ice (i.e.
eskers) and features cut down into the bed (i.e. meltwater corridors) creates a more
1560 complete and less fragmented drainage map than mapping individual features (Fig.
7). The broad scale pattern of palaeo-drainage radiating out from the former Keewatin
Ice Divide, which remains noticeably absent of meltwater evidence (Fig. 5), is
consistent with previous studies (Shilts et al., 1987; Aylsworth and Shilts, 1989; Storrar
et al., 2013, 2014a), but our mapping results in a greater density, narrower spacing
1565 (Fig. 6) and higher number of tributaries.

Table 2. Proposed classification for subglacial meltwater traces observed on palaeo-ice sheet beds. Meltwater routes encompass all visible evidence and consists of negative and negligible relief meltwater corridors with widths in the order 100's of meters and esker ridges with widths in the order of 10's of meters.

Proposed Classification	Description	Example
Meltwater route	All visible traces of subglacial meltwater drainage (i.e. all of below)	 <p>Diagram illustrating a meltwater route, showing a channel with varying expressions along its length.</p>
Meltwater corridor	<ul style="list-style-type: none"> - Meltwater channel - Tunnel channel - Tunnel valley - Hummock corridor (negative) (e.g. Peterson and Johnson, 2018; Lewington et al., 2019) - Erosional corridor (e.g. Burke et al., 2011) - Esker corridor (e.g. Sharpe et al., 2017) - Meltwater corridor (e.g. Rampton, 2000) - Washed zone (e.g. Ward et al., 1997) - Hummock corridor (positive) (e.g. Peterson and Johnson) 	 <p>Diagram illustrating various meltwater corridor types: esker ridge, anastomosing esker ridge with glaciofluvial deposits and hummocks, and hummocks. A red arrow indicates increasing erosion.</p>
Esker with lateral splay	Esker ridge flanked by lateral splay (e.g. Cummings et al., 2011)	 <p>Diagram illustrating an esker ridge flanked by lateral splay.</p>
Esker ridge	Single, multiple or anastomosing esker ridges	 <p>Diagram illustrating a single esker ridge.</p>

5.1 Proposed model for meltwater corridor formation

1575 To interpret palaeo-landforms and reconstruct subglacial meltwater behaviour
an understanding of the processes that formed the landforms is needed. This is the
'glacial inversion' problem (e.g. Kleman and Borgström, 1996). One approach to
understanding glacial processes is through contemporary observations. In this
1580 hydraulically connected distributed drainage system (e.g. Hubbard et al., 1995;
Bartholomaeus et al., 2008; Andrews et al., 2014; Hoffman et al., 2016) is consistent
with the form and distribution of mapped meltwater corridors and can explain the range
of depositional to erosional signatures observed in the study area.

1585 Although hydrological theory dictates that a conduit in steady state will operate
at lower pressure than the surrounding distributed system, large or relatively rapid
fluctuations in surface meltwater inputs (compared to the rate at which conduits
expand from melting caused by turbulent heat dissipation) during the melt season
mean the system is rarely in steady-state (Bartholomew et al., 2012). Once a conduit
1590 system has evolved gradually to accommodate high meltwater fluxes (Cowton et al.,
2013), it is likely to operate at lower pressure than the surrounding high-pressure
weakly connected system during periods of low meltwater input (e.g. at night and later
in the melt season), thus drawing water in (Fig. 14a and 14c). During this phase, the
geomorphic work in the hydraulically connected distributed drainage system is likely
1595 limited by the small cross-sectional area of passage and slow water movement (Willis
et al., 1990; Alley et al., 1997). However, there could be migration of finer sediments
into the central conduit contributing to gradual lateral channel growth over time; this
has been invoked to explain steady state growth of tunnel valleys for example, (e.g.
Boulton and Hindmarsh, 1987).

1600 Variations in borehole water pressure measurements observed at glaciers in
the Alps (e.g. Hubbard et al., 1995; Gordon et al., 1996), Canada (e.g. Rada and
Schoof, 2018) and Alaska (e.g. Bartholomaeus et al., 2008), ice velocity measurements
taken from the Greenland Ice Sheet (e.g. Tedstone et al., 2014) and numerical
1605 modelling (e.g. Werder et al., 2013), suggest that large or rapid meltwater inputs can
cause spikes in conduit water pressure (Cowton et al., 2013). This temporarily

reverses the hydraulic potential gradient and causes water to flow out of the conduit and into the surrounding hydraulically connected distributed drainage system (Fig. 14b).

The width of the hydraulically connected distributed drainage system affected and the form the drainage takes likely depends on the magnitude of the pressure perturbation, determined by the volume and rate of meltwater input, basal substrate and antecedent conduit conditions (e.g. Iken and Bindshadler, 1986; Andrews et al., 2014; Rada and Schoof, 2018; Nanni et al., 2020). For example, the hydraulically connected distributed drainage system is widest during the early melt season when the hydrological system is less developed and the system can be easily over pressurised. Later during the summer, the same magnitude meltwater input does not cause the same degree of over pressurisation as conduits have increased their capacity to accommodate fluctuations in surface meltwater inputs (e.g. Rada and Schoof). The magnitude of the pressure perturbation is also likely to result in different forms of drainage through the hydraulically connected distributed drainage system. This may range from expansion of linked cavities during smaller magnitude events (Fig. 14b1), to drainage re-organisation into braided canals (e.g. Catania and Paola, 2001) or anastomosing conduits (e.g. Gulley et al., 2012) (Fig. 14b2), and finally to narrow sheet floods (e.g. Russell et al., 2007) (Fig. 14b3). While water flows laterally out of the conduit down the pressure gradient during these high-pressure events, the dominant flow direction is still parallel to the main conduit (i.e. down-flow). Fluctuations in pressure within the subglacial conduits may therefore be key to understanding how sediment is accessed and eroded and for explaining variations in sediment flux.

The hydrological system is responsible for transporting the majority of subglacial sediment (e.g. Walder and Fowler, 1994; Richards and Moore, 2003). This is influenced by access to sediment (e.g. Willis et al., 1996; Burke et al., 2015) and subglacial water velocity (e.g. Walder and Fowler, 1994; Ng, 2000). Water flow through the distributed system is slow and inefficient with limited sediment mobilisation and restricted transport (e.g. Willis et al., 1990; Alley et al., 1997). Faster and more turbulent water flow within conduits is more efficient at eroding and transporting sediment and this capability increases rapidly with increased discharge (Alley et al., 1997). However, conduits cover only a small fraction of the bed, which restricts their

1645 ability to erode and transport sediment across large areas (Alley et al., 2019). Thus, there is a need for an additional mechanism(s) to access surrounding sediments. While deformation of till into channels (e.g. Boulton and Hindmarsh, 1987) and lateral conduit migration (e.g. Beaud et al., 2018b) have been proposed, our model focusses on the connection of the hydraulically connected distributed drainage system to the conduit in a range of forms (Fig. 14b). This idea is grounded in the wider glacio-fluvial literature, which suggests that rapid increases in water input create high water pressures that overwhelm the conduit and surrounding drainage system, causing both increased access to and high enough water velocities to carry sediment (e.g. Swift et al., 2002, 2005b; Gimbert et al., 2016; Delaney et al., 2018). This enhanced sediment transport typically occurs at the start of the melt season (e.g. Liestol, 1967; Hooke et al., 1985; Collins, 1989; 1990), but also during large meltwater events (e.g. precipitation (Delaney et al., 2018)). An extreme example is during the 1996 Icelandic jökulhlaup, when a subglacial flood evacuated sediment creating a large tunnel valley (Russell et al., 2007). Thus, fluctuations in subglacial conduit pressure within the ablation zone of ice sheets are likely to be a key mechanism by which sediment either side of the conduit is accessed and mobilised.

1660 In our proposed model, meltwater corridor relief is caused by localised turbulent flow enhancing erosion (e.g. Rampton, 2000). Sedimentological evidence suggests that hummocks within the corridors occur as a result of both erosional and depositional processes. Our proposed model can account for either process, with hummocks forming as a result of: (i) erosion by high energy turbulent water flow along conduits and across the hydraulically connected distributed system (e.g. Rampton, 2000; Peterson et al., 2018); or (ii) deposition during waning stages of the flood within cavities either melted up into the overlying ice by turbulent floods (e.g. Utting et al., 2009), or minor conduits and linked cavities alongside the conduit (e.g. Brennand, 1994). Hummocks may also form as a combination of processes akin to the interpretation of triangular shaped landforms ('murtoos'), which are attributed to subglacial till transported by creep and subsequently eroded and shaped by subglacial meltwater (Mäkinen et al., 2017; Ojala et al., 2019).

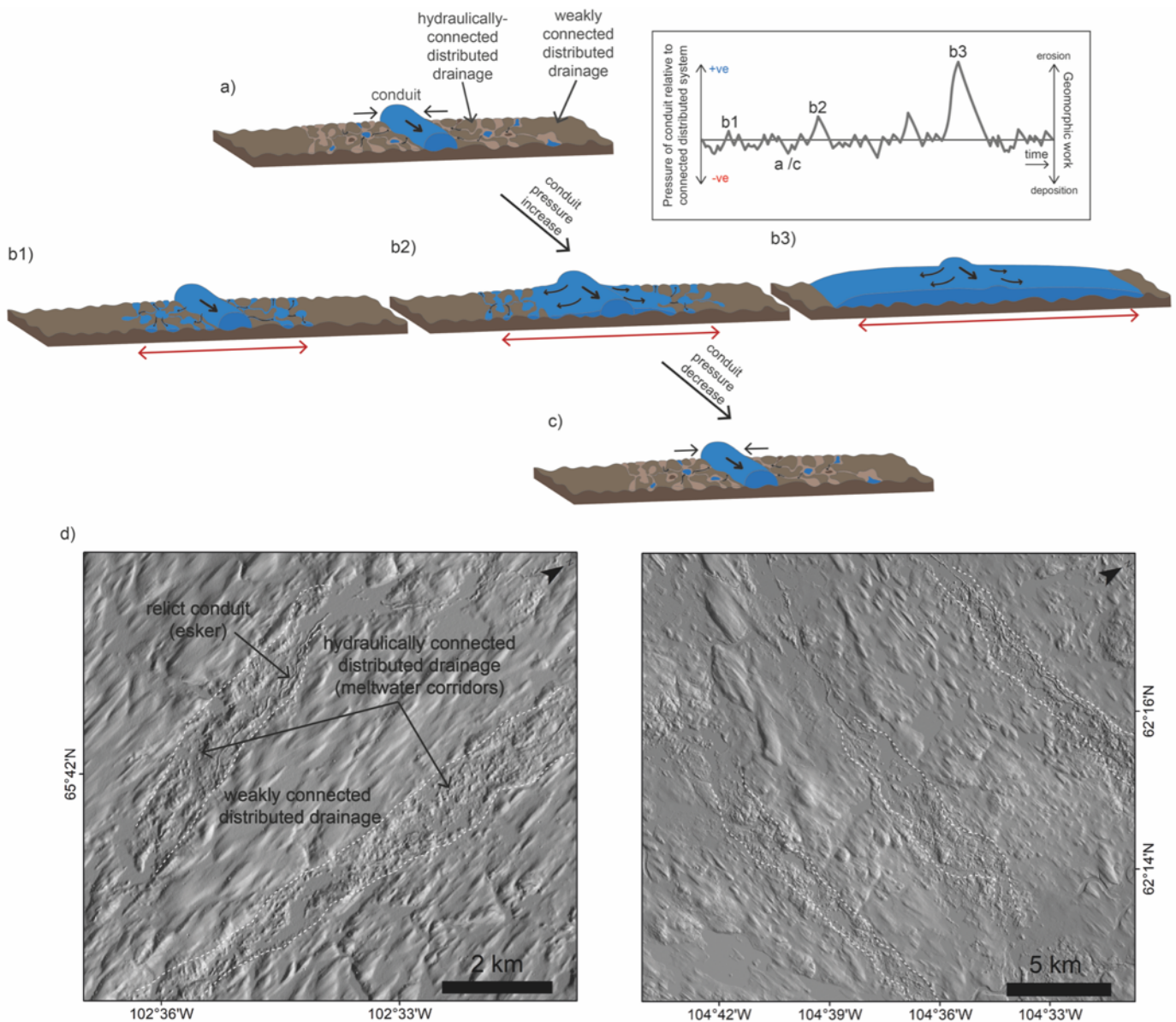


Figure 14. Effects of pressure perturbations on the hydraulic conductivity within the conduit connected distributed subsystem: (a) steady state – water is drawn in from across the connected distributed system into the conduit (low pressure) down the pressure gradient, geomorphic work is limited to the conduit, although there may be some lateral sapping (e.g. Boulton and Hindmarsh, 1987); (b) During over-pressurisation events water is forced out of the conduit across and into the surrounding hydraulically connected distributed drainage system. The width and form (i.e. flood or cavity expansion) this takes likely depends on the magnitude of the pressure perturbation. Geomorphic work (erosion and deposition) likely occurs during this phase; (c) Return to steady state as meltwater input decreases or the conduit expands to accommodate a sustained increase in input; (d) Proposed cumulative geomorphic imprint of the process over time, creating the meltwater corridors (white dashed lines) preserved on the landscape today. The inset in the upper right corner demonstrates that

pressure perturbations within the conduit fluctuate throughout the melt season and vary in size from regular diurnal fluctuations (e.g. b1) to irregular larger 'events' (e.g. b2 and b3), which may represent precipitation or supra/sub-glacial lake drainages.

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In areas of thicker sediment, pressure-driven drainage reorganisation, which takes the form of cavity expansion or sheet floods in other areas, may result in braiding across the hydraulically connected distributed system (e.g. Catania and Paola, 2001). This is consistent with braided meltwater channels identified within tunnel valleys in the North Sea (Kirkham et al., 2020), while the spacing and shape of the hummocky topography observed along meltwater corridors has been interpreted as remnants of braided conduits and intervening bars (e.g. Dahlgren, 2013; Peterson et al., 2018). Likewise water driven from the conduit into the hydraulically connected distributed system during discrete recharge from moulins has been recognised to form anastomosing conduits (Gulley et al., 2012). Thus, anastomosing or braided conduits moving around at the bed and formed during conduit over pressurisation may produce an erosional signature wider than the individual conduit.

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While we fully expect to see transient conduit migration and reconfiguration during conduit over pressurisation, we also do not rule out the possibility that individual conduits could migrate laterally across the bed over longer periods of time, for instance due to changes in ice thickness, subglacial topography, and regional and local basal water pressure. This theory has been invoked to explain the formation of some tunnel valleys by the lateral merging of a series of smaller discrete drainage events over time (e.g. Jørgensen and Sandersen, 2006; Kehew et al., 2012; Beaud et al., 2018b). Indeed, seismic tremor observations suggest that areas with low hydraulic gradients (i.e. flatter parts of the bed, higher up the ice sheet) are characterised by quasi-stable conduit configurations where water is less restricted and can flow through multiple conduits, which alternate and migrate on multiday timescales (Vore et al., 2019). In contrast, the same research suggests that nearer the margin where the hydraulic gradient is steeper, conduits are relatively stable in space (Vore et al., 2019). This fits with esker sinuosity studies which demonstrate that eskers are often very straight (median sinuosity 1.04 on the Canadian Shield) with esker segments aligning over distances of 10s of km's (Storrar et al., 2014a). If the conduit migrated extensively in

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1720 the marginal zone, we would expect to find more sinuous eskers or esker sections
which are offset. Our work and earlier studies indicate that esker ridges can be
superimposed on hummocks within meltwater corridors, but to date, there are no
examples of hummocks overlying eskers (e.g. Peterson et al., 2018). Together, this
1725 suggests that the formation of eskers are separated in time from the meltwater
corridors in which they often occur (e.g. Beaud et al., 2018a; Hewitt and Creyts, 2019;
Livingstone et al., 2020). This supports the notion that palaeo-ice sheet beds are a
composite picture of geomorphic effects, combining different stages and potentially
different subglacial drainage regimes (Greenwood et al., 2016).

1730 Using an inland limit of 60 km for subglacial channelisation (e.g. Chandler et
al., 2013), and minimum and maximum retreat rates in the study area ($\sim 230 \text{ m yr}^{-1}$ -
 $\sim 540 \text{ m yr}^{-1}$), we estimate the time likely spent beneath the channelised zone
influenced by surface meltwater inputs at between ~ 110 and ~ 260 years. We
1735 therefore suggest that meltwater corridors reflect the geomorphic work arising from
repeated pressure perturbations in the ablation zone over 10s – 100s years. The most
significant erosion likely occurred where fluctuating surface meltwater inputs were
clustered (e.g. Alley et al., 2019) or where cumulative upstream drainage produced
the threshold shear stresses required to erode and transport the substrate, which may
have occurred upstream of the peak local meltwater input. While the location of
1740 surface meltwater drainage and discrete water input points (crevasses and moulins)
are important controls on the distribution of subglacial drainage at the bed (e.g.
Decaux et al., 2019), observations suggest that both supraglacial networks (e.g. Koziol
et al., 2017) and moulin locations (e.g. Catania and Neumann, 2010) are relatively
stable, at least over decadal timescales. Where changes in surface meltwater input
1745 areas are observed, this occurs over relatively short distances ($\sim 300 \text{ m}^2$) with the new
routes likely occurring along the same drainage axes and thus not resulting in
significant subglacial drainage system reorganisation (Decaux et al., 2019). This is
consistent with geomorphological evidence, which reveals a coherent drainage
network (Fig. 5) with individual meltwater corridors extending 100s km (Table 1).

1750 The variable extent to which the hydraulically connected drainage system (and
thus the meltwater corridors width) is affected by conduit over pressurisation may be
influenced by ambient variations in the conduits lateral hydropotential gradient (e.g.

1755 narrower meltwater corridors within a steep 'hydropotential valley'). However, we
1760 suggest the key control will be the magnitude of the pressure perturbation, which will
vary depending on meltwater input and antecedent subglacial drainage conditions. If
a corridor represents a single maximum flow, meltwater corridor widths in this study
(0.05 – 3.3 km (mean 0.9 km)) are comparable to measurements in alpine settings (~
140 m (Hubbard et al., 1995; Gordon et al., 1998)) and modelled ice sheet settings (~
2 km (Werder et al., 2013)).

5.3 Exploring potential controls on network patterns and variations in expression of meltwater routes

1765 In this section, we explore spatial controls governing the overall pattern of the
subglacial hydrologic network, as well as variations in meltwater landform expression
(i.e. the patterns of and balance between erosion and deposition and the resulting
geomorphic expression) along individual meltwater routes. Erosional and depositional
features are frequently observed along the same meltwater route and even at the
1770 same location, for example eskers with lateral splays occurring within meltwater
corridors.

1775 There is a high degree of channelisation across the Keewatin sector of the ice
sheet bed, but channelisation is not uniform and the densest areas of meltwater routes
coincide with the 'roughest' basal topography (Fig. 11). This may be the result of
subglacial drainage route fragmentation around bed obstacles, with a greater number
of tributaries and broken patterns common in regions of high bed roughness (e.g. Test
Site 3). Basal topography also preconditions the large-scale spatial structure of
surface drainage (Ignéczi et al., 2018) and the association between rough areas and
1780 dense clusters of meltwater routes could be a response to more surface water
penetrating to the bed as the result of extensive crevassing. For a typical melt season
in west Greenland, crevasses capture a significant amount of surface water – more
than moulins or the hydrofracture of surface lakes (Koziol et al., 2017). Surface
meltwater inputs are thought to be an important control on the distribution of drainage
1785 across the bed (e.g. Gulley et al., 2012; Banwell et al., 2016) and the formation and
evolution of subglacial meltwater landforms (e.g. Banerjee and McDonald, 1975; St-

Onge, 1984; Hooke and Fastook, 2007; Storrar et al., 2014b; Livingstone et al., 2015; Peterson and Johnson, 2017).

1790 There are significantly fewer meltwater routes coinciding with palaeo-ice stream
locations – particularly the Dubawnt Lake Ice Stream (Fig. 12). In addition, the network
pattern of meltwater routes corresponding with the location of the Dubawnt Lake Ice
Stream are more dendritic and extend further towards the ice divide. These
1795 observations are consistent with Livingstone et al., (2015), who find fewer eskers on
palaeo-ice stream beds where modelled subglacial meltwater drainage is greatest. We
suggest the scarcity of meltwater routes beneath palaeo-ice streams could be the
result of (i) lower ice-surface slopes and hydraulic potential gradients, which favour
distributed rather than channelised drainage (e.g. Kamb, 1987; Bell, 2008) or (ii) lack
of preservation beneath fast flowing ice (Boulton, 1996). Where channelised drainage
1800 does occur beneath palaeo-ice streams, networks are typically more dendritic, which
may also be the result of shallower hydraulic gradients and lower relief bed topography
enabling greater lateral water flow.

Dynamic ice mass loss via streaming or surging (and subsequent melting and
1805 iceberg calving) has implications for ice sheet stability (e.g. Bell, 2008; Christianson et
al., 2014; Christoffersen et al., 2014). The Keewatin sector of the LIS had a relatively
low spatial density of ice streams compared to the western and southern margins
(Margold et al., 2015; Stokes et al., 2016). This may be partially attributed to the low
relief, resistant bed of the shield which was unable to provide the fine grained
1810 sediments required to lubricate ice flow and the fact that the margin reached this
position later during deglaciation when the remaining ice sheet was much smaller (e.g.
Margold et al., 2015; Stokes et al., 2016). Nonetheless, we also suggest that efficient
evacuation of meltwater through the dense channelised network, which developed in
this region during the final stages of deglaciation, as the climate warmed (Storrar et
1815 al., 2014b), could have inhibited the development of fast flow and potentially
contributed to the shut-down of existing ice streams. This is consistent with recent
physical modelling (Lelandais et al., 2018) and modern temporal observations that link
decadal-scale ice-flow decelerations with more pervasive and efficient drainage
channelisation driven by increased surface meltwater inputs to the bed (Sole et al.,
1820 2013; Tedstone et al., 2014; van de Wal et al., 2015; Davison et al., 2019) and vice

1825 versa (Williams et al., 2020). If this hypothesis is correct we would expect to see this large-scale inverse spatial relationship between channelisation and ice streaming in other palaeo-ice sheet settings. This potential drainage control on ice-sheet velocity and stability may also influence the pace of deglaciation; we note slower retreat rates ($\sim 230 \text{ m yr}^{-1}$) in the northwest of the study area, which coincide with the highest density of meltwater routes, compared to much faster retreat rates ($\sim 540 \text{ m yr}^{-1}$) associated with the sparsest meltwater routes. This conclusion is tentative given uncertainty in the regions deglacial chronology (Dyke et al., 2003) and the many other factors that can influence retreat rate, and thus requires further testing.

1830 At a large-scale, there is a general tendency for meltwater routes to preferentially form on till, which is more easily eroded than bedrock and where geomorphic evidence is likely to be better developed. Eskers are over-represented on harder, more resistant rock (Fig. 10d) where R-channels are more likely to form (Clark and Walder, 1994; Storrar, 2014a), while there is a slight tendency for meltwater channels (i.e. incisional features) to form on the softer, more erodible sedimentary rock (Fig. 10b). Eskers with lateral splays (i.e. depositional features) appear preferentially on till blankets (Fig. 10c) where there is an abundance of sediment that may overwhelm and clog up the conduit (e.g. Burke et al., 2015), while isolated esker ridges favour thin till and are under-represented on thick till. Though detailed long-profiles (Fig. 13) hint at local relationships between bed substrate changes and the resultant landform expression, we caution against the assumption that this is a widespread occurrence rather than an isolated coincidence.

1845 5.3 Implications

1850 Western sectors of the contemporary Greenland Ice Sheet are broadly analogous to our study area: both are underlain by resistant Precambrian Shield rocks and both experience(d) rapid retreat and high meltwater production rates. This is also similar to southern Sweden, which lay beneath the palaeo Scandinavian Ice Sheet, where similar geomorphic features to those described here, occur extensively (e.g. Peterson et al., 2017; Peterson and Johnson, 2017). This study therefore has potential implications for our understanding of the impact of subglacial hydrology on overlying ice dynamics and ice flow regulation of past, current and future ice sheets.

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The interaction between a subglacial conduit and the surrounding hydraulically connected distributed drainage system is believed to be widespread in contemporary glaciological settings (e.g. Hubbard et al., 1995; Gordon et al., 1996; Bartholomaeus et al., 2008; Werder et al., 2013; Tedstone et al., 2014) and has been identified as key to understanding ice velocity variations and predicting future ice sheet mass loss (Davison et al., 2019). However, the true extent and influence of the hydraulically connected distributed drainage system beneath the Greenland Ice Sheet is unknown due to the challenge of observing contemporary subglacial environments. Palaeo-studies, such as this one, offer the potential to reveal new insights into the nature and configuration of the subglacial hydrological system at an ice sheet scale and potential quantification of how much of the bed and ice surface dynamics were affected by subglacial meltwater.

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Based on our proposed model, we estimate the coverage of each drainage element across the bed of the Keewatin Ice Sheet. Conduits (i.e. eskers) cover ~ 0.5 % of the bed based on an average esker width of 100 m and spacing of 18.8 km (Storrar et al., 2014a). The coverage of conduits and the surrounding hydraulically connected distributed drainage system (i.e. meltwater corridors) increases to an average of ~ 13 % using the average width and spacing of meltwater routes in this study, but could realistically vary between 5 % (lower quartile width and upper quartile spacing) and 36 % (upper quartile width and lower quartile spacing). This represents an area 25 times greater than the conduits (eskers) alone, but assumes that all meltwater routes were active at the same time.

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Based on the above and while we propose a significant increase in the area of the bed influenced by surface meltwater inputs, these findings also fit with the hypothesis that the weakly-connected distributed system covers a large percentage of the subglacial bed (Hoffman et al., 2016). Our results suggest that somewhere between 64 – 95 % of the bed existed within the weakly-connected distributed system where there are no visible traces of subglacial meltwater flow. This finding is similar to Hodge (1979) who suggested that 90 % of the bed at the South Cascade Glacier in Washington was hydraulically isolated. Quantifying the relative coverage of the inactive hydraulically isolated regions of the bed and better understanding how they

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1890 regulate the active drainage regions and modulate basal traction is likely to be important for understanding ice sheet dynamics (Hoffman et al., 2016).

1895 In contemporary settings, the hydraulically connected distributed drainage system is strongly linked to surface meltwater inputs and conduit over pressurisation. The LIS is expected to have exhibited strong surface melting during the period of retreat over this area (estimated at -0.85 m yr^{-1} for 9 ka) with surface ablation accounting for much of this (Carlson et al., 2009). The widespread presence of meltwater corridors across Keewatin thus complements their interpretation and reveals a geomorphic signature of this interaction.

1900 Finally, there are large uncertainties as to how sediment is accessed by subglacial meltwater and transported to conduits (Alley et al., 2019). We suggest that the over pressurisation of conduits and their interaction with the surrounding hydraulically connected distributed drainage is a key driver of sediment erosion and entrainment within the ablation zone and may help address this question. As a result, conduits may be less sediment limited than previously thought and, much like the evolution of the subglacial drainage system (e.g. Schoof, 2010), rates of subglacial fluvial erosion may be strongly controlled by melt supply variability rather than the overall input of meltwater into the system.

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1910 6. Conclusions

1915 We used the ArcticDEM to identify and map all visible traces of subglacial meltwater drainage in the Keewatin sector of the former LIS. We found that wider meltwater features (meltwater tracks and meltwater channels) on the order of 100's to 1000's m flanking or joining up intervening segments of esker ridges were common. These have previously been termed and described as different features. However, as they form part of the same integrated network and display similarities in spacing and morphometry, we propose collectively grouping these features under the term meltwater corridor (Table 2). Combing esker ridges and all varying geomorphic expressions of meltwater corridors within a single meltwater routes map, we have created the first large-scale holistic map of subglacial meltwater drainage for this area.

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1925 Based on our observations and modern analogues, we propose a new model, which accounts for the formation and geomorphic variations of meltwater corridors. In this model, we propose that a principal conduit (i.e. the esker) interacts with the surrounding hydraulically connected distributed drainage network (i.e. the meltwater corridor) with the extent and intensity of this interaction, determined by the magnitude of water pressure fluctuations within the conduit. The geomorphic expression (i.e. net erosion or deposition), is likely governed by a combination of glaciological (i.e. relative water pressure fluctuation) and background controls (i.e. topography, basal substrate and geology). Eskers likely represent the final depositional imprint of channelised drainage within the large-scale meltwater routes network close to the ice margin, while meltwater corridors represent a composite imprint of drainage formed over 10s - 100s years. If our model is correct, the drainage footprint of the hydraulically connected distributed drainage system in this sector is 25 times greater than previously assumed from eskers s alone, which only account for the central conduit.

1940 Our results suggest that the overall distribution and pattern of drainage is influenced by background topography, with greater relief resulting in denser channelised networks, possibly due to fragmentation of subglacial drainage around basal obstacles and the result of more spatially distributed meltwater delivery to the bed. Channelised drainage is relatively rare beneath palaeo ice streams, which instead favour distributed drainage configurations due to the lower ice surface slopes and subglacial hydraulic gradients, and likely also exhibit reduced landform preservation potential. The style of meltwater drainage may influence ice dynamics, with the high degree of channelisation observed in the region able to efficiently dewater the bed leading to slower ice-flow and limited ice stream activity.

1950 Finally, our results suggest that conduit over pressurisation events and the subsequent connection between conduits and the surrounding hydraulically connected distributed drainage system may be important for understanding how sediment is accessed and entrained at the bed. While conduits (eskers) alone cover ~ 0.5 % of the bed, the connected distributed drainage system (meltwater corridors), cover 5 – 36 % of the bed, providing a greater area for sediment erosion and likely the high velocity flows required to do so.

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Further research should focus on determining how common the proposed interaction between conduits and the surrounding distributed drainage system is beneath other palaeo and contemporary ice sheets and the controls governing its variability. We hypothesise that where less surface meltwater is delivered to the bed or ice-surface slopes are shallower for instance when the LIS was larger and the climate colder, the geomorphic expression will be less extensive and subtler. This is because conduits are less likely to evolve due to lower hydraulic gradients, and their interaction with the surrounding distributed system is limited because of invariant melt supply. Understanding where this interaction and signature occurs will help confirm or refute our proposed model, and develop understanding of how meltwater drainage evolves and influences ice dynamics and mass balance over long time-scales.

Data Availability

The mapping of meltwater routes is archived at xxxx.

Author Contributions

ELML carried out the mapping and analysis with input and interpretation from co-authors. ELML prepared the manuscript with contributions from all co-authors.

Competing Interests

The authors declare that they have no conflicts of interest.

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8. References

2000

Alley, R.B. Cuffey, K.M. Evenseon, E.B. Strasser, J.C. Lawson, D.E. Larson, G.J. How glaciers entrain and transport basal sediment : physical constraints. *Quarternary Science Reviews*. 16 : 1017-38. 1997.

Alley, R.B. Cuffey, K.M. Zoet, L.K. Glacial erosion : status and outlook. *Annals of Glaciology*. 60(80) : 1-13. 2019.

2005

Andrews, L.C. Catania, G.A. Hoffman, M.J. Gulley, J.D. Lüthi, M.P. Ryser, C. et al., Direct observations of evolving subglacial drainage beneath the Greenland Ice Sheet. *Nature*, 514(7520). 80–83. 2014

2010

Aylsworth, J. M. and Shilts, W. W. Glacial features around the Keewatin Ice Divide: Districts of Mackenzie and Keewatin. Geological Survey of Canada, Map 24-1987. 1:1,000,000. 1989.

Aylsworth, J.M. Shilts, W.W. Russel, H.A.J. Pyne, D.M. Eskers around the Keewatin Ice Divide: Northwest Territories and Nunavut. Geological Survey of Canada, Open File, 7047. 2012.

2015

Banerjee, I. McDonald, B.C. Nature of esker sedimentation. In: Jopling, A.V. McDonald, B.C. (Eds.), *Glaciofluvial and Glaciolacustrine Sedimentation*, vol 23. Society of Economic Palaeontologists and Mineralogists. Special Publication. 304-20. 1975.

2020

Banwell, A.D. Arnold, N.S. Willis, I.C. Tedesco, M. Ahlstrøm, A.P. Modelling supraglacial water routing and lake filling on the Greenland Ice Sheet. *J. Geophys. Res.* 117. 2012.

Banwell, A. Hewitt, I. Willis, I. Arnold, A. Moulin density controls drainage development beneath the Greenland ice sheet. *Journal of Geophysical Research: Earth Surface*. 121: 2248-69. 2016.

2025

Bartholomaeus, T.C., Anderson, R.S. Anderson, S.P. Response of glacier basal motion to transient water storage. *Nature Geoscience*, 1. 33–37. 2008.

2030

Beaud, F. Flowers, G. Venditti, J.G. Efficacy of bedrock erosion by subglacial water flow. *Earth Surface Dynamics*. 4: 125-45. 2016.

Beaud, F. Flowers, G. Venditti, J.G. Modeling sediment transport in ice-walled subglacial channels and its implications for esker formation and proglacial sediment yields. *Journal of Geophysical Research: Earth Surface*. 123: 3206-27. 2018a.

2035

Beaud, F. Venditti, J.G. Flowers, G.E. Koppes, M. Excavation of subglacial bedrock channels by seasonal meltwater flow. *Earth Surface Processes and Landforms*. 2018b.

- 2040 Bell, R.E. The role of subglacial water in ice-sheet mass balance. *Nat. Geosci.* 1(5): 297-304. 2008.
- Bindscahlder, R.A. The importance of pressurized subglacial water in separation and sliding at the glacier bed. *Journal of Glaciology.* 57: 929-41. 1983.
- 2045 Bingham, R.G. Hubbard, A.L. Nienow, P.W. Sharp, M.J. An investigation into the mechanisms controlling seasonal speedup events at a High Arctic glacier. *Journal of Geophysical Research.* 113. 2008.
- 2050 Bolduc, A.M. The formation of eskers based on their morphology, stratigraphy and lithologic composition, Labrador, Canada (Unpublished Ph.D thesis). Lehigh University. 1992.
- [Bougamont, M. Christoffersen, P. Hubbard, A.L. Fitzpatrick, A.A. Doyle, S.H. Carter, S.P. Sensitive response of the Greenland Ice Sheet to surface meltwater drainage over a soft bed. *Nature Communications.* 5\(5052\). 2014.](#)
- 2055 Boulton, G. S., Caban, P. E. and Van Gijssel, K. Groundwater flow beneath ice sheets: part I - large scale patterns. *Quaternary Science Reviews*, 14, 545-562. 1995.
- 2060 Boulton, G.S. Lunn, R. Vidstrand, P. Zatzpein, S. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part I – Glaciological observations. *Quaternary Science Reviews.* 26(7–8). 1067-90. 2007a.
- Boulton, G.S. Lunn, R. Vidstrand, P. Zatzpein, S. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part II - Theory and simulation of a modern system. *Quaternary Science Reviews.* 26(7–8). 1091–105. 2007b.
- 2065 Boulton, G. S., Hagdorn, M., Maillot, P. B. and Zatzepin, S. Drainage beneath ice sheets: groundwater-channel coupling, and the origin of esker systems from former ice sheets. *Quaternary Science Reviews*, 28, 621-638. 2009.
- 2070 Boulton, G.S. Hindmarsh, R.C.A. Sediment deformation beneath glaciers: rheology and geological consequences. *Journal of Geophysical Research.* 92. 9059-82. 1987.
- 2075 [Brennand, T.A. Macroforms, large bedforms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario: implications for esker genesis and meltwater regime. *Sedimentary Geology.* 91\(1\). 9-55.](#)
- Brennand, T.A. Deglacial meltwater drainage and glaciodynamics: Inferences from Laurentide eskers, Canada. *Geomorphology.* 32(3–4). 263–93. 2000.
- 2080 Brennand, T.A. Shaw, J. Tunnel channels and associated landforms, south-central Ontario: their implication for ice-sheet hydrology. *Canadian Journal of Earth Sciences.* 31. 505-22. 1994.
- 2085 Burke, M.J. Brennand, T.A. Perkins, A.J. Evolution of the subglacial hydrologic system beneath the rapidly decaying Cordilleran Ice Sheet by ice-dammed lake drainage: implications for meltwater-induced ice acceleration. *Quaternary Science Reviews.* 50: 125-40. 2012.
- Burke, M.J. Brennand, T.A. Sjogren, D.B. The role of sediment supply in esker formation and ice tunnel evolution. *Quaternary Science Reviews.* 115: 50-77. 2015.

- 2090 Carlson, A.E. Legrande, A.N. Oppo, D.W. Came, R.E. Schmidt, G.A. Anslow, F.S. Licciardi, J.M. Obbink, E.A. Rapid early Holocene deglaciation of the Laurentide ice sheet. *Nature Geoscience*. 1(9): 620-24. 2008.
- 2095 Carlson, A.E. Anslow, F.S. Obbink, E.A. LeGrande, A.N. Ullman, D.J. Licciardi, J.M. Surface melt driven Laurentide Ice Sheet retreat during the early Holocene. *Geophysical Research Letters*. 36. 2009.
- [Catania, G. Paola, C. Braiding under glass. *Geology*. 29\(3\): 259-62. 2001.](#)
- 2100 Chandler, B. M. P., Lovell, H., Boston, C. M., Lukas, S., Barr, I. D., Benn, D. I., Clark, C. D., Darvill, C. M., Evans, D. J. A., Ewertowski, M., Loibl, D., Margold, M., Otto, J., Roberts, D. H., Stokes, C. R., Storrar, R. D. and Stroeven, A. Glacial geomorphological mapping: a review of approaches and frameworks for best practice. *Earth-Science Reviews*, 185, 806-846. 2018.
- 2105 [Chandler, D.M. Wadham, J.L. Lis, G.P. Cowton, T. Sole, A. Bartholomew, I. Telling, J. Nienow, P. Bagshaw, E.B. Mair, D. Vinen, S. Hubbard, A. Evolution of the subglacial drainage system beneath the Greenland Ice Sheet revealed by tracers. *Nature Geoscience*. 6: 195-98. 2013.](#)
- 2110 Christianson, K. Peters, L.W. Alley, R.B. Anandakrishnan, S. Jacobel, R.W. Riversman, K.W. Muto, A. Keisling, B.A. Dilatant till facilitates ice-stream flow in northeast Greenland. *Earth Planet. Sci. Lett.* 401: 57-69. 2014.
- 2115 Christoffersen, P. Bougamont, M. Carter, S.P. Fricker, H.A. Tulaczyk, S. Significant groundwater contribution to Antarctic streams hydrologic budget. *Geophysical Research Letters*. 41. 2003-10. 2014.
- 2120 Clark, P.U. Walder, J.S. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. *Geol. Soc. Am. Bull.* 106: 304 – 14. 1994.
- Clayton, L. Teller, J.T. Attig, J.W. Surging of the southwestern part of the Laurentide ice sheet. *Boreas*. 14: 235-41. 1985.
- 2125 [Collins, D.N. Seasonal development of subglacial drainage and suspended sediment delivery to meltwater beneath an Alpine glacier. *Annals of Glaciology*. 13: 45-50. 1989.](#)
- 2130 [Collins, D.N. Seasonal and annual variations of suspended sediment transport in meltwaters draining from an Alpine glacier. *International Association of Hydrological Sciences Publication*. 193: 439-46. 1990.](#)
- [Collins, D.N. A conceptually based model of the interaction between flowing meltwater and subglacial sediment. *Annals of Glaciology*. 22\(1\). 224-32. 1996.](#)
- 2135 Cowton, T. Nienow, P. Sole, A. Wadham, J. Lis, G. Bartholomew, I. et al., Evolution of drainage system morphology at a land-terminating Greenlandic outlet glacier. *Journal of Geophysical Research. Earth Surface Processes*. 118. 29-41. 2013.

- 2140 [Cowton, T. Nienow, P. Sole, A. Bartholomew, I. Mair, D. Variability in ice motion at a land-terminating Greenlandic outlet glacier: the role of channelized and distributed drainage systems. *Journal of Glaciology*. 62\(233\): 451-66. 2016.](#)
- 2145 Cowton, T. Nienow, P. Bartholomew, I. Sole, A. Mair, D. Rapid erosion beneath the Greenland ice sheet. *Geology*. 40: 343-46. 2012.
- [Crozier, J. Karlstrom, L. Yang, K. Basal control of supraglacial meltwater catchments on the Greenland Ice Sheet. *Cryosphere*. 12: 3383-407. 2018.](#)
- 2150 Cummings, D.I. Kjarsgaard, B.A. Russell, H.A.J. Sharpe, D.R. Eskers as mineral exploration tools. *Earth Science Reviews*. 109: 32-43. 2011a.
- 2155 Cummings, D.I. Gorrell, G. Guillbault, J-P. Hunter, J.A. Logan, C. Ponomarenko, D. Pugin. A. J-M. Pullan, S.E. Russell, H.A.J. Sharpe, D.R. Sequence stratigraphy of a glaciated basin fill, with a focus on esker sedimentation. *Geological Society of American Bulletin*. 2011b.
- Cutler, P.M. Colgan, P.M. Mickelson, D.M. Sedimentological evidence for outburst floods from the Laurentide Ice Sheet margin in Wisconsin, USA: implications for tunnel-channel formation. *Quaternary International*. 90. 23-40. 2002.
- 2160 [Dahlgren, S. Subglacially meltwater eroded hummocks. MSc Thesis. Department of Earth Sciences, University of Gothenburg. 2013.](#)
- 2165 Das, S.B. Joughin, I. Behn, M.D. Howat, I.M. King, M.A. Lizarralde, D. Bhatia, M.P. Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage. *Science*. 320 (5877). 963-64. 2008.
- 2170 Davison, B.J. Sole, A.J. Livingstone, S.J. Cowton, T.W. Nienow, P.W. The influence of hydrology on the dynamics of land-terminating sectors of the Greenland Ice Sheet. *Front. Earth Sci*. 7:10. 2019.
- [Decaux, L. Grabiec, M. Ignatiuk, D. Jania, J. Role of discrete water recharge from supraglacial drainage systems in modelling patterns of subglacial conduits in Svalbard glaciers. *The Cryosphere*. 13: 735-52. 2019.](#)
- 2175 [Delaney, I. Bauder, A. Werder, M.A. Farinotti, D. Regional and annual variability in subglacial sediment transport by water for two glaciers in the Swiss Alps. *Frontiers in Earth Science*. 6: 175. 2018.](#)
- 2180 [Downs, J.Z. Johnsson, J.V. Harper, J.T. Meierbachtol, T. Werder, M.A. Dynamic hydraulic conductivity reconciles mismatch between modeled and observed winter subglacial water pressure. *Journal of Geophysical Research: Earth Surface*. 123: 818-36. 2018.](#)
- 2185 Doyle, S.H. Hubbard, A. Fitzpatrick, A.A.W. van As, D. Mikkelsen, A.B. Pettersson, R. et al., Persistent flow acceleration within the interior of the Greenland ice sheet. *Geophysical Research Letters*. 41: 899-905. 2014.

- 2190 Doyle, S.H. Hubbard, A. Van De Wal, R.S. van As, D. Scharrer, K. Meierbachtol, T.W. et al., Amplified melt and flow of the Greenland ice sheet driven by late-summer cyclonic rainfall. *Nature Geoscience*. 8: 647-53. 2015.
- Dredge, L. Nixon, F. Richardson, R. Surficial Geology, Northwestern Manitoba: Geological Survey of Canada, 'A' Series Map 1608A, 1: 500 000. 1985.
- 2195 Dyke, A.S. Moore, A. Robertson, I. Deglaciation of North America. Geological Survey of Canada. Open File, 1574. 2003.
- Englehardt, H. Harrison, W. Kamb, B. Basal sliding and conditions at the glacier bed as revealed by bore-hole photography. *Journal of Glaciology*. 20: 469-508. 1978.
- 2200 Fitzpatrick, A.A. Hubbard, A. Joughin, I. Quincey, D.J. Van As, D. Mikkelsen, A.P. et al., Ice flow dynamics and surface meltwater flux at a land-terminating sector of the Greenland ice sheet. *Journal of Glaciology*. 59: 687-96. 2013.
- 2205 Fowler, A. Sliding with cavity formation. *Journal of Glaciology*. 33: 131-41. 1987.
- Fulton, R.J. Surficial materials of Canada. Geological Survey of Canada, 'A' Series Map 1880A. 1:5,000,000. 1995.
- 2210 [Gimbert, F. Tsai, V.C. Amundson, J.M. Bartholomaeus, T.C. Walter, J.I. Subseasonal changes observed in subglacial channel pressure, size and sediment transport. *Geophysical Research Letters*. 43: 3786-94. 2016.](#)
- 2215 Gordon, S. Sharp, M. Hubbard, B. Smart, C. Ketterling, B. Willis, I. Seasonal reorganization of subglacial drainage inferred from measurements in boreholes. *Hydrological Processes*. 12. 105-33. 1998.
- Gorrell, G. Shaw, J. Deposition in an esker, bead and fan complex, Lanark, Ontario, Canada. *Sedimentary Geology*. 72(3-4): 285-314. 1991.
- 2220 Greenwood, S.L. Clark, C.D. The sensitivity of subglacial bedform size and distribution to substrate lithological control. *Sedimentary Geology*. 232: 130-44. 2010.
- 2225 [Greenwood, S.L. Clason, C.C. Helanow, C. Margold, M. Theoretical, contemporary observational and palaeo-perspectives on ice sheet hydrology: Processes and products. *Earth Science Reviews*. 155: 1-27. 2016.](#)
- 2230 Glasser, N.F. Sambrook Smith, G.H. Glacial meltwater erosion of the Mid-Cheshire Ridge: implications for ice dynamics during the Late Devensian glaciation of northwest England. *Journal of Quaternary Science*. 14: 703-10. 1999.
- Gudmundsson, G.H. Transmission of basal variability to a glacier surface. *Journal of Geophysical Research: Solid Earth*. 108(B5). 2003.
- 2235 Gulley, J.D. Grabiec, M. Martin, J.B. Jania, J. Catania, G. Glowacki, P. The effect of discrete recharge by moulins and heterogeneity in flow-path efficiency at glacier beds on subglacial hydrology. *Journal of Glaciology*. 58(211). 2012.

- 2240 Hebrand, M. Amark, M. Esker formation and glacier dynamics in eastern Skane and adjacent areas, southern Sweden. *Boreas*. 18(1): 67-81. 1989.
- Hewitt, I.J. Modelling distributed and channelized subglacial drainage: the spacing of channels. *Journal of Glaciology*. 57(202). 2011.
- 2245 Hewitt, I.H. Creyts, T.T. A model for the formation of eskers. *Geophysical Research Letters*. 46. 2019.
- Hodge, S.M. Direct measurements of basal water pressures: progress and problems. *Journal of Glaciology*. 23, 309-19. 1979.
- 2250 Hoffman, M.J. Andrews, L.C. Price, S.A. Catania, G.A. Neumann, T.A. Luthi, M.P. et al., Greenland subglacial drainage evolution regulated by weakly connected regions of the bed. *Nature Communications*. 7: 13903. 2016.
- 2255 Hooke, R.L. Fastook, J. Thermal conditions at the bed of the Laurentide ice sheet during deglaciation: implications for esker formation. *Journal of Glaciology*. 53(183). 2006.
- Hooke, R.L. Jennings, C.E. On the formation of the tunnel valleys of the southern Laurentide ice sheet. *Quaternary Science Reviews*. 25(11–12). 1364–72. 2006.
- 2260 Hooke, R. LeB. Laumann, T. Kohler, J. Subglacial water pressures and the shape of subglacial conduits. *Journal of Glaciology*. 36 (122). 67-71. 1990.
- 2265 [Hooke, R.L. Wold, B. Hagen, J.O. Subglacial hydrology and sediment transport at Bondhusbreen, southwest Norway. *Geological Society of American Bulletin*. 96: 388-97. 1985.](#)
- Hoyal, D.C.J.D. Van Wagoner, J.C. Adair, N.L. Deffenbaugh, M. Li, D. Sun, T. Huh, C. Griffin, D.E. Sedimentation from jets: A depositional model for clastic deposits of all scales and environments: Salt Lake City, Utah, Search and Discovery Article No. 40082, American Association of Petroleum Geologists Annual Meeting, May 14, 2003, 10.
- 2270 Hubbard, B.P. Sharp, M.J. Willis, I.C. Nielsen, M.K. Smart, C.C. Borehole water-level variation and the structure of the subglacial hydrological system of Haut Glacier d’Arolla, Valais, Switzerland. *Journal of Glaciology*. 41(139). 572–83. 1995.
- 2275 Ignéczi, A. Sole, A.J. Livingstone, S.J. Ng, F.S.L. Yang, K. Greenland ice sheet surface topography and drainage structure controlled by transfer of basal variability. *Frontiers in Earth Science*. 6: 101. 2018.
- 2280 Iken, A. Bindschadler, R.A. Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: conclusions about drainage system and sliding mechanisms. *Journal of Glaciology*. 32: 101-19. 1986.
- 2285 Iken, A. Rothlisberger, H. Flotron, A. Harberli, W. The uplift of Unteraargletscher at the beginning of the melt season – a consequence of water storage at the bed? *Journal of Glaciology*. 29: 28-47. 1983.

- 2290 Iverson, N.R. Baker, R.W. Hooke, R.L. Hanson, B. Jansson, P. Coupling between a glacier and a soft bed: I. A relation between effective pressure and local shear stress determined from till elasticity. *Journal of Glaciology*. 45: 31-40. 1999.
- Jørgensen, F. Sandersen, P.B.E. Buried and open tunnel valleys in Denmark – erosion beneath multiple ice sheets. *Quaternary Science Reviews*. 25(11-12): 1339-63. 2006.
- 2295 Joughin, I. Das, S.B. King, M. Smith, B.E. Howat, I.M. Moon, T. Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science*. 320: 781-83. 2008.
- Kamb, B. Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *Journal of Geophysical Research, Solid Earth*. 92(B9). 9038-100. 1987.
- 2300 Kamb, B. Raymond, C. Harrison, W. Engelhardt, H. Echelmeyer, K. Humphrey, N. et al., Glacier surge mechanism: 1982-1983 surge of Variegated Glacier, Alaska. *Science*. 227: 469-79. 1985.
- 2305 [Karlstrom, L. Yang, K. Fluvial supraglacial landscape evolution on the Greenland Ice Sheet. *Geophysical Research Letters*. 43: 2638-92. 2016.](#)
- Kehew, A.E. Nicks, L.P. Straw, W.T. Palimpsest tunnel valleys: evidence for relative timing of advances in an interlobate area of the Laurentide ice sheet. *Ann. Glaciol.* 28: 47 – 52. 1999.
- 2310 Kehew, A.E., Piotrowski, J.A. and Jørgensen, F. Tunnel valleys: Concepts and controversies - A review. *Earth-Science Reviews*. 113(1–2). 33–58. 2012.
- 2315 [Kirkham, J. Hogan, K. Larter, R. Self, E. Games, K. Huuse, M. Stewart, M. Ottesen, D. Arnold, N. Dowdeswell, J. New insights into North Sea tunnel valley infill and genesis from high-resolution 3D seismic data. EGU General Assembly 2020, Online 2020, Online 4-8 May, 2020. EGU2020-118.](#)
- 2320 Kleman, J. Borgström, I. Reconstruction of palaeo-ice sheets: the use of geomorphological data. *Earth Surface Processes and Landforms*. 21(10): 893-909. 1996.
- 2325 Koziol, C. Arbold, A. Pope, A. Colgan, W. Unifying supraglacial meltwater pathways in the Paakitsoq region, West Greenland. *Journal of Glaciology*. 63(239): 464-76. 2017.
- Kerr, D. Knight, R. Sharpe, D. Cummings, D. Reconnaissance surficial geology, Lynx Lake, Northwest Territories, NTS 75-J: Geological Survey of Canada, 1: 125 000. 2014a.
- 2330 Kerr, D. Knight, R. Sharpe, D. Cummings, D. Reconnaissance surficial geology, Walmsley Lake, Northwest Territories, NTS 75-N, Canadian Geoscience Map-140: Geological Survey of Canada, 1:125 000. 2014b.
- Lee, H.A. Craig, B.G. Fyles, J.G. Keewatin ice divide. *Geol. Soc. Am. Bull.* 68: 1760-61. 1957.
- 2335 Lelandais, T. Ravier, E. Pochat, S. Bourgeois, O. Clark, C. Mourgues, R. Strzeczynski, P. Modelled subglacial floods and tunnel valleys control the life cycle of transitory ice streams. *The Cryosphere*. 12: 2759-72. 2018.

- 2340 Lewington, E.L.M. Livingstone, S. Sole, A.J. Clark, C.D. Ng, F. An automated method for mapping geomorphological expressions of former subglacial meltwater pathways (hummock corridors) from high resolution digital elevation data. *Geomorphology*. 339: 70-86. 2019.
- [Liestøl, O. Storbreen Glacier in Jotunheimen, Norway. Norsk Polarinstitutt Skrifter. 141. 1967.](#)
- 2345 Livingstone, S.J. and Clark, C.D. Morphological properties of tunnel valleys of the southern sector of the Laurentide ice sheet and implications for their formation. *Earth Surface Dynamics*. 4. 567–89. 2016.
- 2350 Livingstone, S.J. Storrar, R.D. Hillier, J.K. Stokes, C.R. Tarasov, L. An ice-sheet scale comparison of eskers with modelled subglacial drainage routes. *Geomorphology*. 246. 104–12. 2015.
- 2355 Livingstone, S.J. Lewington, E.L.M. Clark, C.D. Storrar, R.D. Sole, A.J. McMartin, I. Dewald, N. Ng, F.. A quasi-annual record of time-transgressive esker formation: implications for ice sheet reconstruction and subglacial hydrology. *The Cryosphere*. [14: 1989-2004. 2020.](#)
- Lliboutry, L. General theory of subglacial cavitation and sliding of temperate glaciers. *Journal of Glaciology*. 7. 21-58. 1968.
- 2360 Mäkinen, J. Time-transgressive deposits of repeated depositional sequences within interlobate glaciofluvial (esker) sediments in Köyliö, SW Finland. *Sedimentology* 50. (2): 337-60. 2003.
- Mäkinen, J. Kajutti, K. Palmu, J-P. Ojala, A. Ahokangas, E. Triangular-shaped landforms reveal subglacial drainage routes in SW Finland. *Quaternary Science Reviews*. 164. 37–53. 2017.
- 2365 Margold, M. Stokes, C.R. Clark, C.D. Ice streams in the Laurentide Ice Sheet: Identification, characteristics and comparison to modern ice sheets. *Earth Science Reviews*. 143. 117-46. 2015.
- 2370 Margold, M. Stokes, C.R. Clark, C.D. Reconciling records of ice streaming and ice margin retreat to produce a palaeographic reconstruction of the deglaciation of the Laurentide Ice Sheet. *Quaternary Science Reviews*. 189: 1-30. 2018.
- 2375 McMartin, I. Henderson, P. J. Evidence from Keewatin (central Nunavut) for paleo-ice divide migration. *Géographie physique et Quaternaire*, 58, 163-186. 2004.
- Mooers, H.D. On the formation of the tunnel valleys of the Superior Lobe, Central Minnesota. *Quaternary Research*. 32: 24 – 35. 1989.
- 2380 [Nanni, U. Gimbert, F. Vincent, C. Graff, D. Walter, F. Piard, L. Moreau, L. Quantification of seasonal and diurnal dynamics of subglacial channels using seismic observations on an Alpine glacier. *The Cryosphere*. 14: 1475-96. 2020.](#)
- 2385 Ng, F. Ignéczi, A. Sole, A.J. Livingstone, S.J. Response of surface topography to basal variability along glacial flowlines. *Journal of Geophysical Research: Earth Surface*. 123: 2319-40. 2018.

- Nienow, P. Sharp, M. Willis, I. Seasonal changes in the morphology of the subglacial drainage system, Haut Glacier d'Arolla, Switzerland. *Earth Surface Processes and Landforms*. 23: 825-84. 1998.
- 2390
- Noh, M.J. Howat, I.M. Automated stereo-photogrammetric DEM generation at high latitudes: Surface Extraction with TIN-based Search-space Minimisation (SETSM) validation and demonstration over glaciated regions. *GISci. Remote Sens.* 52(2), 198-217. 2015.
- 2395
- Nye, J. Water at the bed of a glacier. IASH Publications 95. (Symposium at Cambridge 1969 – Hydrology of Glaciers). Pp. 189-194. 1973.
- Ó Cofaigh, C. Tunnel valley genesis. *Progress in Physical Geography*. 20. 1-19. 1996.
- 2400
- Ojala, A.E.K. Peterson, G. Mäkinen, J. Johnson, M.D. Kajutti, K. Palmu, J-P. Ahokangas, E. Öhrling, C. Ice-sheet scale distribution and morphometry of triangular shaped hummocks (murtoos): a subglacial landform produced during rapid retreat of the Scandinavian Ice Sheet. *Anal. of Glaciology*. 1-12. 2019.
- 2405
- Palmer, S. Shepherd, A. Nienow, P. Joughin, I. Seasonal speed-up of the Greenland ice sheet linked to routing of surface water. *Earth Planet Science Letters*. 302: 423-28. 2011.
- Perkins, A.J., Brennand, T.A. Burke, M.J. Towards a morphogenetic classification of eskers: Implications for modelling ice sheet hydrology. *Quaternary Science Reviews*. 134. 19–38. 2016.
- 2410
- Peterson, G. Johnson, M.D. Hummock corridors in the south-central sector of the Fennoscandian ice sheet, morphometry and pattern. *Earth Surface Processes and Landforms*. 43: 919-29. 2018.
- 2415
- Peterson, G. Johnson, M.D. Smith, C.A. Glacial geomorphology of the south swedish uplands – focus on the spatial distribution of hummock tracts. *Journal of Maps*. 13(2): 534 – 44. 2017.
- 2420
- Peterson, G. Johnson, M.D. Dahlgren, S. Pässe, T. Alexanderson, H. Genesis of hummocks found in tunnel valleys: an example from Horda, southern Sweden. *GFF*. 140(2): 189 – 544. 2018.
- Piotrowski, J.A. Tunnel-valley formation in north west Germany – geology, mechanisms of formation and subglacial bed conditions for the Bornhöved tunnel valley. *Sedimentary Geology*. 89. 107-41. 1994.
- 2425
- Piotrowski, J.A. Channelized subglacial drainage under soft-bedded ice sheets: evidence from small N-channels in Central European lowland. *Geol. Q.* 43(2): 153-62. 1999.
- 2430
- Porter, C., Morin, P., Howat, I., Noh, M.J., Bates, B., Peterman, K., Keeseey, S., Schlenk, M., Gardiner, J., Tomko, K. Willis, M., et al., ArcticDEM. Harvard Dataverse, V1. 2018.
- Powell, R.D. Glacimarine processes at grounding-line fans and their growth to ice-contact deltas. Geological Society, London, Special Publications, 53(1): 53-73. 1990.
- 2435

- Praeg, D. Seismic imaging of mid-Pleistocene tunnel valleys in the North Sea Basin – high resolution from low frequencies. *Journal of Applied Geophysics*. 53 273-298. 2003.
- 2440 Prowse, N.D. Morphology and Sedimentology of Eskers in the Lac de Gras Area, Northwest Territories, Canada. PhD Thesis. Carleton University. Ottawa, Canada. 2017.
- Price, S.F. Payne, A.J. Catania, G.A. Neumann, T.A. Seasonal acceleration of inland ice via longitudinal coupling to marginal ice. *Journal of Glaciology*. 54: 213-19. 2008.
- 2445 Punkari, M. Glacial and glaciofluvial deposits in the interlobate areas of the Scandinavian Ice Sheet. *Quaternary Science Reviews*, 16, 741-753. 1997.
- [Rada, C. Schoof, C. Channelized, distributed, and disconnected: subglacial drainage under a valley glacier in the Yukon. *The Cryosphere*. 12: 2609-36. 2018.](#)
- 2450 Rampton, V.N. Large-scale effects of subglacial meltwater flow in the southern Slave Province, Northwest Territories, Canada. *Canadian Journal of Earth Sciences*. 37(1). 81–93. 2000.
- [Richards, G. Moore, R.D. Suspended sediment dynamics in a steep, glacier-fed mountain stream, Place Creek, Canada. *Hydrological Processes*. 17: 1733-53. 2003.](#)
- 2455 Rothlisberger, H. Water pressure in Intra-and Subglacial Channels. *Journal of Glaciology*. 11: 177-203. 1972.
- 2460 Russell, A.J., Gregory, A.R., Large, A.R., Fleisher, P.J. and Harris, T.D. Tunnel channel formation during the November 1996 jökulhlaup, Skeiðarárjökull, Iceland. *Annals of Glaciology*, 45, 95-103. 2007.
- 2465 Russell, A.J. Roberts, M.J. Fay, H. Marren, P.M. Cassidy, N.J. Tweed, F.S. Harris, T. Icelandic jökulhlaups impacts: Implications for ice-sheet hydrology, sediment transfer and geomorphology. *Geomorphology*. 75: 33-64. 2006.
- Rust, B.R. Romanelli, R. Late quaternary subaqueous outwash deposits near Ottawa, Canada. A.V. Jopling, B.C. McDonald (Eds.), *Glaciofluvial and Glaciolacustrine Sedimentation*, Soc. Econ. Paleontol. Mineral., Spec. Publ. 177-92. 1975.
- 2470 [Schoof, C. Ice sheet acceleration driven by melt supply variability. *Nature*. 468: 803-806. 2010.](#)
- 2475 Sergienko, O. V. Glaciological twins: Basally controlled subglacial and supraglacial lakes. *Journal of Glaciology*. 59(213). 3–8. 2013.
- Sharpe, D., Kjarsgaard, B. Knight, R.D. Russell, H.A.J. Kerr, D.E. Glacial dispersal and flow history, East Arm area of Great Slave Lake, NWT, Canada. *Quaternary Science Review*. 165: 49 – 72. 2017.
- 2480 Shepherd, A. Hubbard, A. Nienow, P. King, M. McMillan, M. Joughin, I. Greenland ice sheet motion coupled with daily melting in late summer. *Geophysical Research Letters*. 36: 2-5. 2009.

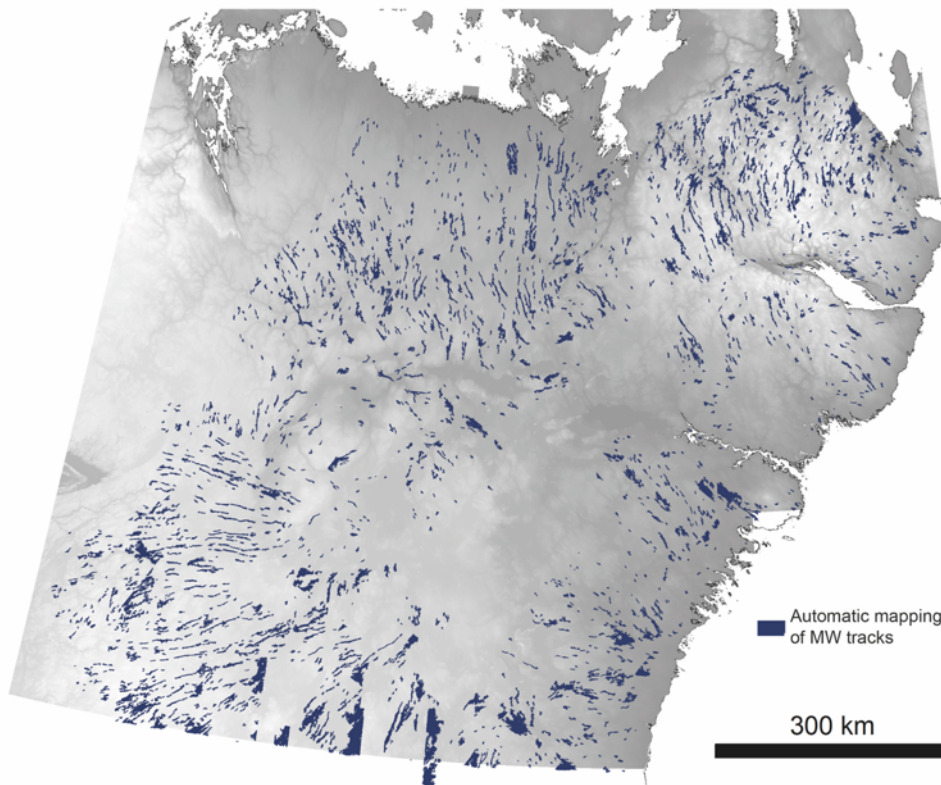
- 2485 Shilts, W.W. Aylsworth, J.M. Kaszycki, C.A. Klasson, R.A. Canadian Shield. In: Graf, W.L. (Ed.), *Geomorphi Systems of North America*. Geological Society of America, Boulder, Colorado. pp. 119-61. Centennial Special Volume 2. 1987.
- Shreve, R.L. Movement of water in glaciers. *Journal of Glaciology*. 11(62). 205–14. 1972.
- 2490 Shreve, R.L. Esker characteristics in terms of glacial physics, Katahdin esker system, Maine. *Geol. Soc. Am. Bull.* 96, 639 – 46. 1985.
- Sissons, J.B. A subglacail drainage system by the Tinto Hills, Lankashire. *Trans Edinb. Geol. Soc.* 18: 175 – 92. 1961.
- 2495 Sjogren, D.B. Fisher, T.G. Taylor, L.D. Jol, H.M. Munro-Stasiuk, M.J. Incipient tunnel channels. *Quaternary International*. 90. 41–56. 2002.
- 2500 Smith, M.J. Clark, C.D. Methods for the cisualisation of digital elevation models for landform mapping. *Earth Surface Processes and Landforms*. 30(7) : 885-900. 2005.
- 2505 Sole, A. Nienow, P. Bartholomew, I. Mair, D. Cowton, T. Tedstone, A. et al., Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers. *Geophysical Research Letters*. 40(15). 3940–44. 2013.
- Stevens, L.A. Behn, M.D. Das, S.B. Joughin, I. Noel, B.P. Broeke, M.R. et al., Greenland Ice Sheet flow response to runoff variability. *Geophys. Res. Lett.* 43: 11295-303. 2016.
- 2510 Stokes, C.R. Clark, C.D. TheDubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behaviour on the Canadian Shield and insights regarding the controls on ice-stream location and vigour. *Boreas*. 32(1): 263-79. 2003a.
- Stokes, C.R. Clark, C.D. Laurentide ice streaming on the Canadian Shield: A conflict with the soft-bedded ice stream paradigm? *Geology*. 31(4): 347-50. 2003b.
- 2515 Stokes, C. R., Margold, M., Clark, C. D. Tarasov, L. Ice stream activity scaled to ice sheet volume during Laurentide Ice Sheet deglaciation. *Nature*, 530: 322-326. 2016.
- 2520 St-Onge, D.A. Surficial deposits of the Redrock Lake area, District of Mackenzie; in *Current Research, Part A, Geological Survey of Canada, Paper 84 (1A)*. 271-78. 1984.
- Storrar, R.D. Reconstructing subglacail meltwater dynamics from the spatial and temporal variation in the form and pattern of eskers. Doctoral thesis, Durham University. 2014.
- 2525 Storrar, R. D., Ewertowski, M., Tomczyk, A., Barr, I. D., Livingstone, S. J., Ruffell, A., Stoker, B. Evans, D. J. A. Equifinality and preservation potential of complex eskers. *Boreas*. 2019.
- Storrar, R.D. Livingstone, S.J. Glacial geomorphology of the northern Kivalliq region, Nunavut, Canada, with an emphasis on meltwater drainage systems. *J. Maps*. 13: 153-64. 2017.
- 2530 Storrar, R.D. Stokes, C.R. Evans, D.J.A. A map of large Canadian eskers from Landsat imagery. *Journal of Maps*. 3: 456-73. 2013.

- 2535 Storrar, R.D. Stokes, C.R. Evans, D.J.A. Morphometry and pattern of a large sample (> 20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. *Quaternary Science Reviews*. 105: 1 – 25. 2014a.
- 2540 Storrar, R.D., Stokes, C.R. Evans, D.J.A. Increased channelization of subglacial drainage during deglaciation of the Laurentide Ice Sheet. *Geology*. 42(3). 239–42. 2014b.
- 2545 Stroeven, A. P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B. W., Harbor, J. M., Jansen, J. D., Olsen, L., Caffee, M. W., Fink, D., Lundqvist, J., Rosqvist, G. C., Strömberg, B. Jansson, K. N. Deglaciation of Fennoscandia. *Quaternary Science Reviews*, 147, 91-121. 2016.
- 2550 [Swift, D.A. Nienow, P.W. Spedding, N. Hoey, T.B. Geomorphic implications of subglacial drainage configuration: rates of basal sediment evacuation controlled by seasonal drainage system evolution. *Sedimentary Geology*. 149. 5-19. 2002.](#)
- 2555 [Swift, D.A. Nienow, P.W. Hoey, T.B. Basal sediment evacuation by subglacial meltwater: suspended sediment transport from Haut Glacier d’Arolla, Switzerland. *Earth Surface Processes and Landforms*. 30: 867-83. 2005a.](#)
- [Swift, D.A. Nienow, P.W. Hoey, T.B. Mair, D.W.F. Seasonal evolution of runoff from Haut Glacier d’Arolla, Switzerland and implications for glacial geomorphic processes. *Journal of Hydrology*. 309: 133-48. 2005b.](#)
- 2560 Tedstone, A.J. Nienow, P.W. Gourmelen, N. Dehecq, A. Goldberg, D. Hanna, E. Decadal slow-down of a land-terminating sector of the Greenland Ice Sheet despite warming. *Nature*. 526: 692 – 95. 2015.
- 2565 Tedstone, A.J. Nienow, P.W. Gourmelen, N. Sole, A.J. Greenland ice sheet annual motion insensitive to spatial variations in subglacial hydraulic structure. *Geophysical Research Letters*. 41: 8910-17. 2014.
- 2570 Tedstone, A.J. Nienow, P.W. Sole, A.J. Mair, D.W. Cowton, T.R. Bartholomew, I.D. et al., Greenland ice sheet motion insensitive to exceptional meltwater forcing. *Proceedings of the National Academy of Sciences of the United States of America*. 110(49). 19719–24. 2013.
- 2575 Utting, D.J., Ward, B.C. Little, E.C. Genesis of hummocks in glaciofluvial corridors near the Keewatin Ice Divide, Canada. *Boreas*. 38(3). 471–481. 2009.
- 2580 Van der Vegt, P., Janszen, A. Moscariello, A. Tunnel valleys: current knowledge and future perspectives. Geological Society, London, Special Publications. 368(1). 75–97. 2012.
- van de Wal, R.S.W. Boot, W. Van den Broeke, M.R. Smeets, C.J.P.P. Reijmer, C.H. Donker, J.J.A. et al., Large and rapid melt-induced velocity changes in the ablation zone of the Greenland Ice Sheet. *Science*. 321. 111-13. 2008.
- van de Wal, R.S.W. Smeets, C.J.P.P. Boot, W. Stoffelen, M. van Kampen, R. Doyle, S.H. et al., Self-regulation of ice flow varies across the ablation area in south-west Greenland. *Cryosphere*. 9: 603-11. 2015.

- 2585 [Vore, M.E. Bartholomaeus, T.C. Winberry, J.P. Walter, J.I. Amundson, J.M. Seismic tremor reveals spatial organisation and temporal changes of subglacial water system. Journal of Geophysical Research. 124: 427-46. 2019.](#)
- 2590 Walder, J.S. Hydraulics of subglacial cavities. *Journal of Glaciology*. 32(112). 439-445. 1986.
- Walder, J.S. Fowler, A. Channelized subglacial drainage over a deformable bed. *Journal of Glaciology*. 40(134). 1994.
- 2595 Ward, B.C. Dredge, L.A. Kerr, D.E. Surficial geology, Lac de Gras, District of Mackenzie, Northwest Territories (NTS 76-D): Geological Survey of Canada, 1:125 000. 1997.
- Warren, W.P. Ashley, G.M. Origins of the ice-contact stratified ridges (eskers) of Ireland. *Journal of Sedimentary Research*. 64(3a). 433-49. 1994.
- 2600 Weertman, J. General theory of water flow at the base of a glacier or ice sheet. *Reviews of Geophysics and Space Physics*. 10. 287-333. 1972.
- 2605 Werder, M.A. Hewitt, I.J. Schoof, C.G. Flowers, G.E. Modeling channelized and distributed subglacial drainage in two dimensions. *Journal of Geophysical Research: Earth Surface*. 118(4). .2140–58. 2013.
- Wheeler, J.O. Hoffman, P.F. Card, K.D. Davidson, A. Sanford, B.V. Okulitch, A.V. Roest, W.R. Geological Map of Canada. Geological Survey of Canada, map 1860A. 1996.
- 2610 [Williams, J.J. Gourmelen, N. Nienow, P. Dynamic response of the Greenland ice sheet to recent cooling. Scientific Reports. 10: 1647. 2020.](#)
- 2615 [Willis, I.C. Richards, K.S. Sharp, M.J. Links between proglacial stream suspended sediment dynamics, glacier hydrology and glacier motion at Midtdalsbreen, Norway. Hydrological Processes. 10: 629-48. 1996.](#)
- 2620 [Willis, I.C. Sharp, M.J. Richards, K.S. Configuration of the drainage system of Midtdalsbreen, Norway, as indicated by dye-tracing experiments. Journal of Glaciology. 36\(122\): 89-101. 1990.](#)
- Zwally, H.J. Abdalati, W. Herring, T. Larson, K. Saba, J. Steffen, K. Surface melt induced acceleration of the Greenland Ice Sheet flow. *Science*. 297. 218-22. 2002.
- 2625

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9. Appendices



2645 **Figure A1.** Automatic mapping output (cleaned up) for test site using code associated with
Lewington et al., 2019.

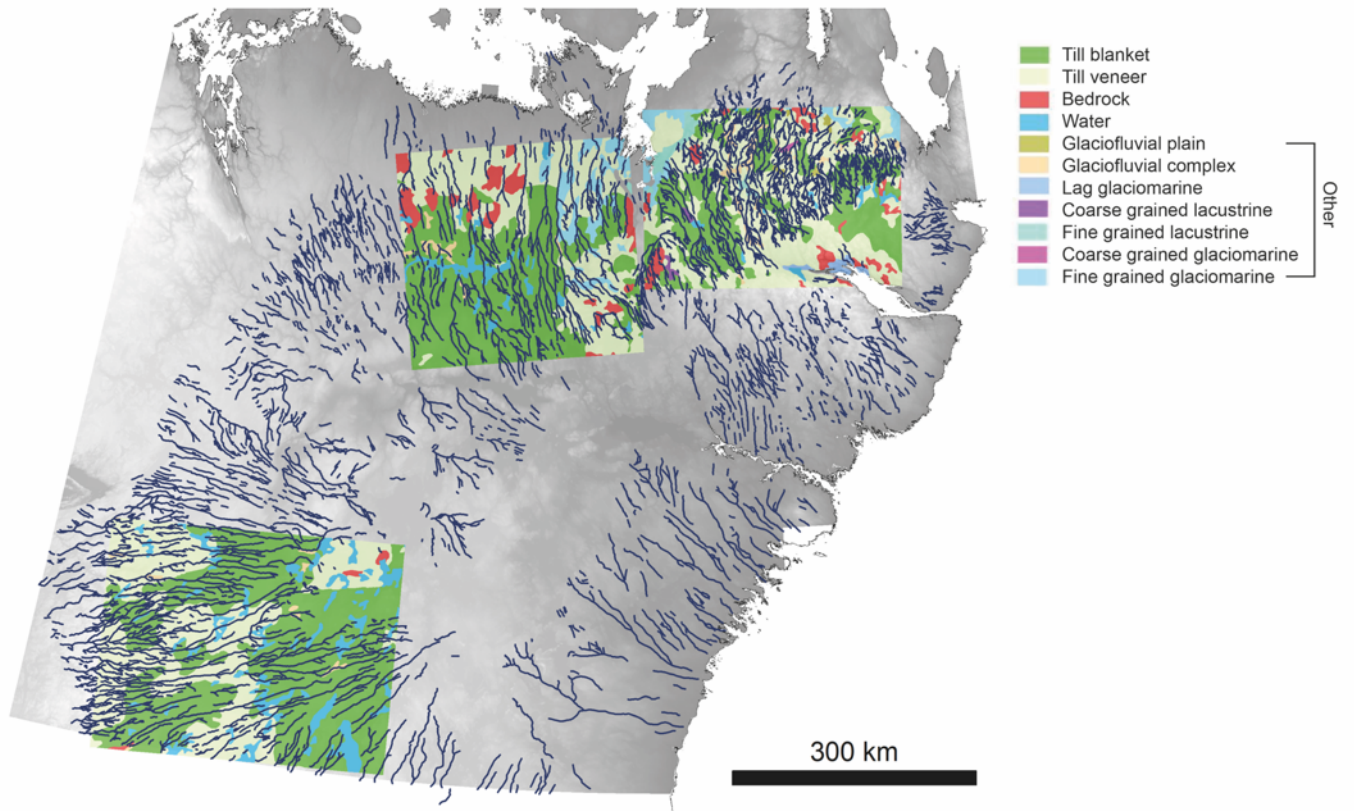


Figure A2. Surface substrate across the three test sites (left – right) used for analysis in section 3.3

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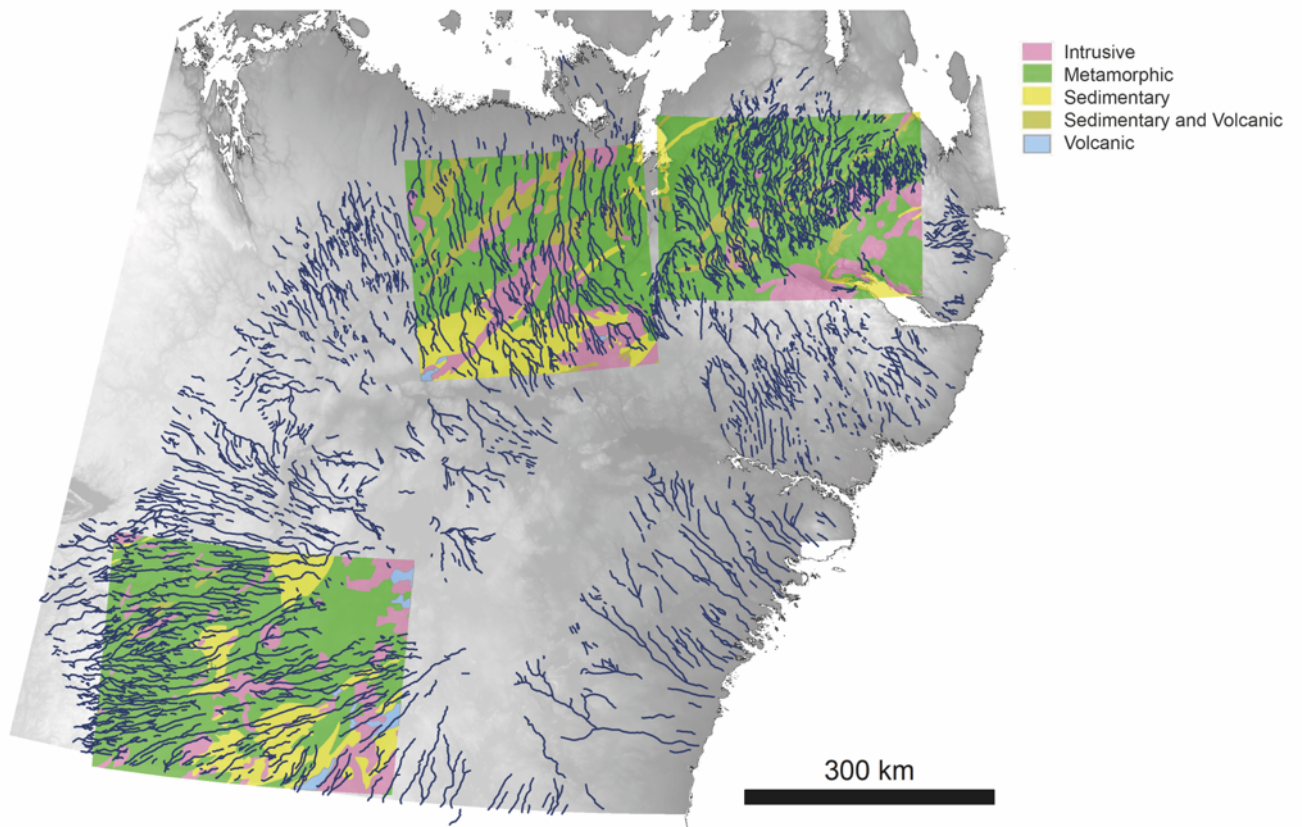


Figure A3. Bed geology across the three test sites (left to right) used for analysis in section 3.3