Response to the Reviewer's Comments

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We would like to thank the editor for considering the revised version of this manuscript, and the two reviewers (Stephen Livingstone and Martin Margold) for the very detailed and thorough reviews, as well as constructive criticism. The comments of the reviewers made us particularly aware of the lack of detailed geomorphological characterization of the subglacial channels described, as well as the missing literature relevant to the topic, which hindered the interpretation and purpose of the paper. In response to the comments, we added a detailed geomorphological description of the subglacial channels, together with a discussion of lateral meltwater drainage vs. subglacial drainage in the channels in consideration. The most significant changes in order of their appearance in the paper are:

1.- Following S. Livingstone's suggestion regarding the use of the term " tunnel valleys". We agree that the drainage systems described in this manuscript are considerably smaller and therefore should be referred to as subglacial channels. Consequently, we substituted " tunnel valleys" by " subglacial channels" throughout the manuscript, removed most of the references to [7] and other tunnel valley studies, and built the discussion around literature relevant to subglacial channels [e.g., 6, 8, 13, 14]. We also added a table (table 1) that summarizes the main characteristics of subglacial channels and puts our study in the context of the existing literature.

2.- Regarding our lack of consideration of lateral meltwater channels, we added a short subsection and a figure (subsection 4.2 and figure 7) where we discuss the relationship between the direction of the studied channel networks and the topographic gradients and regional slopes. Their direction perpendicular to canyon rims, roughly following topographic gradients, and radial to the ice sheet margins agrees with subglacial incision mechanisms. We also quantified the angle between channel direction and regional slope in table 2, and removed panel (d) in figure 2, as we acknowledge the possibility that this particular example is indeed a lateral meltwater channel.

3.- We added a new section, additional figures, and a table (section 5: Detailed morphology of subglacial channels in Devon Island, figures 8 and 9, table 3) where we present detailed field observations, including additional field photographies, and provide a much more elaborate description of subglacial channel morphology. Table 3 now includes a summary of observations for each subglacial network observed in the field as suggested by S. Livingstone.

We list the main comments of each reviewer and our corresponding response below. We would like to thank the reviewers again for their thorough comments, which were helpful to improve this manuscript.

Sincerely,

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S. Livingstone (in order of appearance, reviewer's comments in bold for easy referencing)

Major comments:

1.- Use of the term tunnel valley : The term tunnel valley is traditional used to refer to much larger features of the order of several kilometers wide and tens of kilometers long, that may be cut into sediment or bedrock. The features described here seem to be an order of magnitude smaller and I therefore suggest sticking to the term subglacial meltwater channel or N-channel throughout.

We addressed Stephen Livignstone's comment by substituting the term "tunnel valley" with the term "subglacial channel" throughout the manuscript. We agree with his correction regarding the length scales of the features here described (see also major comments)

2.1.- Missing literature: A large body of work on subglacial meltwater channels, including how to identify them in the geological record (e.g. Greenwood et al., 2007 and references therein) and their morphological properties and spatial distribution (e.g. Brennand and Shaw, 1994; Kristensen et al., 2007; Livingstone and Clark, 2016 to name but a few) seem to have been missed, with a lot of emphasis instead given to the Kehew et al. (2012) paper. In the discussion at least I was expecting the authors to refer back to previous work to put into context how these features are similar or different.

We addressed this issue throughout the paper. We added a whole section of subglacial channel morphological properties (see the list of major changes above) where we relate the field observations of channel characteristics with the work by [1, 3, 6, 8, 14, 16]. Acknowledging the first major comment, we also removed the emphasis on Kehew's work and support instead our categorization of subglacial channels on Greenwood's work (in particular table 1) and references therein.

2.2.-Indeed, in the discussion, the text on the hydraulic potential equation is presented as original work, whilst it is actually well known (see Shreve, 1972), and their new metric for tunnel valley identification on channel directionality is not really new (e.g. see Greenwood et al., 2007).

We corrected this part, which was indeed a badly worded section. We clarified this mistake by giving emphasis to the theoretical work done supporting the oblique direction of subglacial channels [e.g., 10, 12, 17] and also the observational evidence [e.g., 6, 13, 14, 16]. We highlight, however, the little attention that quantifying this metric has received, which allows for its use on morphometric channel comparisons. We added the numerical measure of this metric in table 2.

2.3.-The authors may also want to look at and compare their work to some of the recent modeling work that has tried to incorporate fluvial erosion into numerical ice models to investigate the formation of N-channels.

This is a very good suggestion, and it is in fact explored in detail in another manuscript in preparation. We believe that the work presented here is already extensive.

3.1.- Morphology of the subglacial meltwater features : I believe this paper really undersells what is a fantastically high resolution study of the morphology of bedrock carved channels. I am not aware of such detailed work in such well preserved landforms and yet the results seem rather hidden away after the comparison of the different techniques. I would like to see more made (and example figures shown) of the channel morphologies, including further discussion of the headwalls, anabranching pattern, spacing, cross-sectional profiles and association with other bedforms, while

a summary statistics table would also really help the reader. As currently written, it is the use of the different techniques which really comes out from this, not the morphology of the features.

To address this comment, we present an additional section (section 5) meant to cover in more depth the morphological characteristics of subglacial channels. We largely base our description of the channel morphology in the work by [14], and complement the field observations with additional data drawn from the elevation maps we produced. Spacing, however, will be addressed in detail in a follow-up study in preparation.

3.2.-To broaden this work out it would have been nice to see how their dimensions compare with other studies of similar sized features (and then also the larger tunnel valleys) and to discuss what this means in terms of their formation (e.g. slow and steady vs catastrophic drainage).

We added a comparison of our observations to other studies in table 1 [e.g., 1, 6, 13, 14], but we will not include an interpretation of channel formation mechanisms here as it will be a focus of a follow-up manuscript in preparation.

Minor comments:

P1L1: Tunnel valleys can also be cut into sediment.
We adopted the correction.

P1L6: should be extent
We fixed the typo.

P2L28: I think there needs to be some recognition of the different scales here. N-channels are typically associated with much smaller channels cut specifically into bedrock. Tunnel valleys/channels may also be cut into sediment and are much large. In terms of the effect on ice dynamics most of the work is associated with the evolution to channelized drainage and these channels are again envisaged to be an order of magnitude smaller than tunnel valleys/channels.
We added a sentence referring to the distinct scales of tunnel valleys and subglacial channels.

P2L10: from instead of only with.
We incorporated this suggestion.

P2L26: e.g. in wrong position in brackets beginning Denton
We fixed the typo.

P2L27: See also for a comprehensive mapping along a large portion of the southern sector of the Laurentide Ice Sheet: Livingstone, S.J. and Clark, C.D., 2016. Morphological properties of tunnel valleys of the southern sector of the Laurentide Ice Sheet and implications for their formation. Earth Surface Dynamics, 4(3), p.567. Indeed, there is a large body of work in this area, and also in the North Sea: see older papers in review by Kehew et al. (2012) for completeness it would be good to reference some of the key work.
We added this reference and a reference to an earlier review by [4] for completeness. However, we do not go in further detail about tunnel valleys in this revised manuscript, other than to compare their length scales to those of the channels on Devon Island.

P2L34: This is conjecture where is the evidence for temporal variability and large inputs?

We removed this sentence as it was written referring to tunnel valley identification. See however [11] for a mathematical analysis of channelization driven by melt supply variability.

P3L2: Although there has been a large body of work on the morphology of tunnel valleys (e.g. Livingstone and Clark, 2016).
We removed this comment. See the comment above, and major comment 1.

P3L15: ice sheet began retreating towards the current
We adopted this suggestion.

P3L17: Capitalise Ice Sheet.
We incorporated this suggestion.

P5L11: This is not obvious from Fig. 1.
We fixed the wording to remove the reference to fluvial vs. subglacial drainage here, to be discussed in the next section with the longitudinal profile results.

P5L25: What about figures 2 and 3?
Here we would refer to figure 1 and 3 or only to figure 3. We fixed this.

P9L1-5: It would be useful for the reader if you included a schematic, perhaps on one of the profiles in Fig. 3 as it is not clear to me.
We adopted the suggestion in figure 10, (previous figure 6) which now shows a cartoon with a representation of the metrics introduced in the text.

P9L19: to have originated in a subglacial regime.
We fixed the wording.

P9L8: tributaries have widths of
We believe there is a typo in the page/ line reference provided, it actually refers to P11L8. We fixed the typo suggested here.

P9L8-10: I also found that apparent anabranching of the channels an interesting feature worth observing. In particular, can you tell from the DEM whether the channels were formed synchronously (same depth of channel bottom), or time-transgressively (which might manifest as different depths of anabranching channels).
We added a subsection (subsection 5.3) about the anastomosing characteristics of some of these networks, and took a cross section profile across an anabranching section to include the point suggested by the reviewer.

P13L1-2: More details are needed here. How does the cross-sectional shape and depth change between recognised tunnel valleys and river channels? This is a key distinction that has been glossed over here.
We agree with the reviewer. We added a characterization of subglacial channel and river cross section (see Fig. 6), including their scales and downstream evolution, context drawn from the fluvial literature [9] for the fluvial channel cross sectional evolution in terms of the discharge in gravel streams.

P13L3: This is not clear to me as only a small portion of the image corresponds to tributaries that you pick out as having similar widths. Is there a better example?
We reworded the description of this figure (see comment about Fig. 5), in the context of three zones: tributary origin, tributary development, and merging into a meltwater seasonal stream.

P13L10: Braiding is the wrong term here I believe as this would refer to temporary

islands as part of a dynamic sedimentary system. Anabranching is a more appropriate term
We adopted the reviewer's comment.

P13L8-11: Again, this seems very short on details. You state that you can pick out the key characteristics of tunnel valley networks but then seem to restrict this to a few choice observations.
We eliminated this paragraph in the rewording of the description of this figure. In the new manuscript, section 5 offers more details on channel morphology.

P13L13: criteria exposed before is an odd phrase. Re-write.
We reworded this sentence.

P13L19: delete targeted
We deleted this word.

P13L21: and approximately constant downstream from the origin until
We rephrased this subsection to add more details. In particular, we added a figure describing the evolution of fluvial and subglacial cross sections, which adds more context to the following comparative discussion.

P13L17: tunnel valley widths are up to tens
We fixed the typo.

Do these channels merge into the surrounding topography at their origin or do they have a clear amphitheater-headed canyons? (e.g. see Lamb et al., 2006, 2014). This might give you some clues as to their origin.
They merge in the surrounding topography. We state this in more detail in section 5 and in the description of figure 5, as we realize it is an important aspect of the channel network morphology. In particular, in figure 5 panel (a) (photogrammetry), we show the region where all tributaries grade smoothly into the surrounding plateaus, with no topographic sign of clear heads within the resolution of the DSM (40 cm).

P13L34: Examples of this pattern are shown in
We fixed the typo.

P14L1: tree-like network typical of
We reworded this sentence to offer a more detailed description of the anabranching/ anastomosing patterns observed in the subglacial networks.

P14L3: tunnel valleys also have very few.
We reworded this sentence to offer a more detailed description of the anabranching/ anastomosing patterns observed in the subglacial networks. In particular, section 5.2.2 describes the number of tributaries and shape of the networks.

P14L8-21: This is nicely summarized, but not new. The hydraulic potential gradient has been widely used to infer channel direction and we know that the ice surface slope can drive water over topographic undulations.
We rephrased this section, and put this metric in the context of both theoretical descriptions [e.g., 10, 12, 17] and observational evidences [e.g., 8, 13, 14, 16] showing oblique subglacial channel direction to topographic gradients. We then highlight our addition, which is the quantification of this deviation (table2, column 5, figure 10) in a numerical metric.

P15L4: And critically, their morphology and association with other subglacial fea-

tures like eskers, moraines, outwash fans.
We added the list of subglacial features suggested (P20L11 in this version).

P15L5: What is the example and how does that help? The text below does not mention other subglacial bedforms.
We reworded this section in the context of an improved, more detailed characterization of subglacial channel morphology. The text in the first version of the manuscript was referring to other subglacial features as in other subglacial channels. Indeed, if two individual channels within one same network display undulations in their profile, according to criteria (4) (association with other subglacial features) we could expect the other tributaries to have formed subglacially.

P15L10-12: I am not convinced this is a new metric for tunnel valley identification (e.g. see Greenwood et al., 2007; Livingstone and Clark, 2016 section 3.1).
We agree with the referee. This is not a new metric, but we did suggest its quantification to improve objective and remote sensing characterization of subglacial channels.

P15L11-12: I do not understand this final sentence. If the ice is cold based surely large meltwater channels are unlikely to form?
Our affirmation is wrong, indeed. We removed it from the text in the revised manuscript, although in the first version we were referring to cold based ice sheets with water accumulation at the ice margin, or in a more general context where ice moves (and erodes) very slowly relative to channel formation, to avoid channel destruction.

P16L5: How can you be so precise in stating the timing of these features?
This affirmation was based on the assumption that the networks formed close to the ice margins, given how short the networks are (up to 2 km). However, and given the fact that we do not discuss channel formation mechanisms in the text, we removed this sentence from the conclusions.

Figures

Figure 1: Can you distinguish, maybe with different colour arrows, between the river valleys and tunnel valleys. This would help the reader.
We highlighted each network by surrounding it with a coloured box: black for fluvial and white for subglacial. We also changed the identification scheme used to refer to channel groups, an refer now to specific networks as opposed to ”groups of channels”, in response to a comment by M. Margold, which are also indicated in this figure.

Figure 2: In the caption you refer to distinct groups but these are not clear from the figure. It would be useful to include these headings so the reader can easily distinguish. It is not that obvious from the profiles why some have been termed tunnel valleys and some rivers. For instance, most of group 4 and 5 tunnel valleys are relatively smooth with little in the way of reverse bed slops, and are therefore comparable to groups 2 and 3. What allowed you to distinguish these as tunnel valleys rather than river channels?
We believe the reviewer is referring to Fig. 3 here. We changed Fig. 3 by referring directly to the channel networks introduced in the text (see comment above), and adding a title to each of these networks in the figure. We also discuss the longitudinal profiles of fluvial and subglacial systems in more detail in the text, particularly in section 5. Distinguishing subglacial channels in the basis of remote sensing data (in particular longitudinal profiles) is challenging, and it is indeed one of the objectives of this paper. Notice how we added two additional metrics that were only qualitatively discussed in the previous manuscript: a shape factor (top width to depth) and a measure of deviation from topographic gradients. The quantification of these metrics makes the distinction between both systems easier.

Figure 4: Missing a colour legend for panels (c) and (d).
We added the colour legend, and also a better scale for panels (a) and (b).

Figure 5: What do the arrows refer to? More details on what is actually picked up in these images would be helpful to the reader.
We clarified the description of figure 5, and now use this figure to describe the different stages of network evolution, from the formation of the tributaries to their merging into meltwater fed seasonal streams.

M. Margold

Major comments

The motivation for the study and its setting within the context of existing knowledge in the field is not articulated enough. The authors might attempt to spell out more clearly what the study brings that older studies were lacking this is a point where to refer to the existing literature on glacial meltwater channels.
In response to M. Margold's comment, we now clearly state in the introduction how the primary motivation for this study is to provide a remote sensing based identification scheme for subglacial channels, together with the highest resolution topographic study presented regarding these drainage systems. We come back to these objectives in the discussion and conclusions.

The methods section is lengthy and at places self-serving. Why is there a need to reproduce the surface topography at cm resolution? The authors might attempt to better align the methods used with the stated objectives.
One of the objectives of the expedition to Devon Island (although not necessarily the primary focus of this paper) was to test the capabilities of portable LiDAR systems at analyzing channel geometries, which is the reason behind the high detail provided in the methods section. In addition, LiDAR resolution (cm scale) of the channels provides a very reliable data set for (1) analyzing the presence of inner channels in the subglacial channels, (2) providing ways to constrain the angle of channel walls (close to the angle of repose), and (3) ground truthing the GPS filtered longitudinal profile data in figure 3. We acknowledge, however, the disproportionately large methods section compared to results in the previous version of the manuscript, and we have addressed this issue by adding section 5 with a much more detailed geomorphological analysis of subglacial channels. This section includes cross sectional characteristics and evolution, network directionality with respect to regional slopes, characteristics of the channel heads, etc. , and addresses the need to better align methods, objectives, and results.

The distinction between tunnel valley erosional regime and river valley erosional regime is vague. Ideally, the authors might qualify the main characteristics of subglacial and fluvial drainage (based on literature) and look for the characteristic features in their data. The manuscript is overly relying on Kehew et al. (2012).
We acknowledge our mistake in identifying our features as tunnel valleys. Indeed, as M. Margold and S. Livingstone point out, these channels are better described as subglacial channels in terms of their spatial scales. To fix this issue, we removed most of the references to the work by [7] as it does not apply to subglacial channels, and added relevant literature [e.g., 1, 6, 8, 14, 16]. Addressing the first part of the comment, in this revised version we give further references to fluvial erosion regimes: i.e., the description of bankfull width in gravel rivers by [9] or the introduction of a shape factor (width over depth, widely used in the fluvial literature), which helps to quantify the characteristics of fluvial vs. subglacial cross sections.

Portions of the text that refer to the figures read very much like figure captions.
We agree with the reviewer, particularly regarding the photogrammetry and LiDAR figures (Fig.

4 and Fig. 5). We fixed this issue by avoiding repetition with figure captions, by adding further descriptions and implications of the figures, and by removing the text that did not add any additional information from the caption.

Broader, v-shaped cross profile of the river valleys vs. narrower, flat-bottom, steep-walled cross profile of the meltwater channels could something be inferred about the discharge and the length of formation/operation of the feature(s)? While this goes beyond the scope of the manuscript, a few references could be provided where this topic might be followed.
This is indeed a topic of interest and will be analysed in further detail in a second manuscript in preparation, particularly regarding the relationship between spacing and discharge [e.g., 2, 17]. In this study we introduced the shape factor to capture quantitatively some of these differences, in particular the top width evolution of fluvial vs. subglacial channels. To our knowledge, however, hydraulic relationships evaluating discharge vs. bankfull width for subglacial channel cross sections have not been derived, and in fact there is little work addressing the mechanics of erosion in N channels (see i.e., [2, 5, 17]). Erosion efficiency is often calculated per unit channel width, which makes the estimation of such relationship difficult (algebraically, it is possible to derive one from the work by [15] for canals, but it does not apply to the channels here described).

Minor comments:

P1 L8 Kinematic mobile LiDAR. I am not an expert on this instrumentation but from checking briefly online, either one or the other adjective is usually used. Pairing the two adjectives seems to make little sense to me since they mean largely the same, just one having a Greek root and the other a Latin one.
We fixed this mistake and refer to it as Kinematic LiDAR Scan (KLS) as in other sections of the text. Our intention is to refer to its portability (hence mobile), which is the asset of this new technique.

P2 L23 Younger Dryas
We fixed the typo.

P2 L33 Criteria is plural, write criterion where it is a singular.
We fixed this issue throughout the manuscript.

P2 L34 Warm-based is a more common term than wet-based
We adopted the reviewer's suggestion.

P3 L14-17 Ages in Dyke (1999) are in radiocarbon years, however, the notation ka BP is now commonly used for calendar years. Either state that it is C-14 years or calibrate.
We adopted the reviewer's suggestion.

P3 L20 remove the full stop before the reference
We fixed the typo.

P3 L34 deposition landforms is a more common term
We adopted the reviewer's suggestion.

P5 L12-13 Downstream of. . . I dont understand what do you mean with this sentence.
We reworded this sentence by referring to stream orders: once the network develops a stream order of 2 or more.

P8 L24-25 Check the wording, represent appears two times
We fixed the typo.

P8 L32-33 requires quantitative field longitudinal profile observations reword to requires measuring longitudinal profiles in the field.
We adopted the reviewer's suggestion.

P9 L24 agreement
We fixed the typo.

P13 L3 replace in panel (b) with in Fig. 5b
We adopted the reviewer's suggestion.

P13 L4 replace packs with accumulations
We adopted the reviewer's suggestion.

P13 L13 criteria exposed before exposed does not work here very well, search for a more fitting verb (stated, listed).
We reworded this sentence to make it specific to the longitudinal profile analysis.

P13 L31 shallow
We fixed the typo

P13 L33-34 This is something that should be discussed further with references to older literature.
We reworded this whole section when we added the more detailed characterization of subglacial channel morphology. We do provide a description of channel and network shape in section 5 that includes references to older literature, in particular the observations by [1, 14].

P14 L8-10 We argue here that differences among channel direction and local topographic gradients are also indicative of subglacial erosion in areas where the ice erosion rate by sliding is lower than the meltwater erosion rate (Weertman, 1972; Paterson,1994). These can be submarginal meltwater channels that record the ice surface slope direction but do not necessarily bear any evidence with regard to ice erosion rate.
The previous draft was missing any reference to or discussion about lateral meltwater channels, and therefore it was impossible for the reader to make this distinction. Following a comment by M. Margold (see above in Major Comments) we incorporated a full subsection describing the differences between lateral and subglacial channels, and showed how the networks analysed are subglacial. The reference about fast/ slow sliding rates, and the destruction of N-channels that do not follow ice flow lines in fast-moving glaciers and ice sheets is old [17]. Given our distinction between lateral and subglacial meltwater channels, we believe we have addressed this comment with no further changes needed.

P15 L1-4 Here the fact that you have been ignoring all the types of meltwater channels other than subglacial really becomes problematic because you might be dealing with lateral or submarginal channels in this case.
We fixed this issue (see above in Major Comments).

15 L10-12 Again, there is a possibility that these might be submarginal or lateral meltwater channels. It might well be that most or all the channels that you classify as subglacial indeed are subglacial and not submarginal or lateral. But you need to be provide argumentation for this.
see comment above.

Figures

Fig. 3 Add group numbers or panel letters so that the groups can be easily identified.
We adopted the reviewer's suggestion

The figure would be more informative if one could see the topographic settings of the pictured groups of channels. Could the photographs possibly be draped on a DEM derived hillshade?
We adopted the reviewer's suggestion in an additional figure (Fig. 6), which we also use to identify lateral meltwater channels from subglacial channels.

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Subglacial drainage patterns of Devon Island, Canada: Detailed comparison of river rivers and tunnel valleyssubglacial meltwater channels

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Abstract. Tunnel valleys are bedrock incised Subglacial meltwater channels (N-channels) are attributed to erosion by meltwater in subglacial conduits. They exert a major control on meltwater accumulation at the base of ice sheets, serving as drainage pathways and modifying ice flow rates. Exposed relict tunnel valleys offer The study of exposed relict subglacial channels offers a unique opportunity to study characterize the geomorphologic fingerprint of subglacial erosion and characterize the geometry of individual channelsas well as study the structure and characteristics of ice sheet drainage systems. In this study we present detailed field and remote sensing observations of exposed tunnel valleys subglacial meltwater channels in excellent preservation state on Devon Island (Canadian Arctic Archipelago), including descriptions of tunnel valley cross sections and . We characterize channel cross section, longitudinal profiles, as well as network morphology, to describe the spatial extend and network morphologies and establish the spatial extent and distinctive characteristics of subglacial drainage systems. We use field-based GPS measurements of tunnel valley subglacial channel longitudinal profiles, along with stereo imagery derived Digital Surface Models (DSM), and novel kinematic mobile portable LiDAR data to establish a quantitative comparison of tunnel and river valleys detailed characterization of subglacial channels in our field study area. Tunnel valleys , including their distinction from rivers and other meltwater drainage systems. Subglacial channels typically cluster in groups of 5-10 channels throughout the island, oriented radially with respect ∼ 10 channels and are oriented perpendicular to active or former ice margins. We identify departures in tunnel valley direction from local topographic gradientsand undulations in the Although their overall direction generally follows topographic gradients, channels can be oblique to topographic gradients and have undulating longitudinal profiles. We also observe that the width of first order tributaries is one to two orders of magnitude larger than in Devon Island river systems, and remarkably constantdownstream. These distinctive aspects of tunnel valley morphology are similar among the different locations characterized in the study. approximately constant. Furthermore, our findings are consistent with expectations theoretical expectations drawn from analyses of flow driven by gradients in effective water pressure related to variations in ice thickness. Our field and remote sensing observations provide a rigorous way to distinguish tunnel and river valleys in local and regional topography data that revisits represent the first high resolution study of the subglacial geomorphology of the high Arctic, and provide quantitative and qualitative descriptions of subglacial channels that revisit

well-established field identification guidelines. Distinguishing ~~river and tunnel valleys~~ subglacial channels in topographic data is critical for understanding the emergence, geometry and extent of channelized ~~subglacial drainage systems~~ meltwater systems and their role in ice sheet drainage. The final aim of this study is to facilitate the identification of ~~tunnel valley~~ subglacial channel networks throughout the globe by using remote sensing techniques, which will improve the detection of these systems and help to build understanding of the underlying mechanics of subglacial channelized drainage.

1 Introduction

~~Tunnel valleys~~Subglacial meltwater channels, often referred to as ~~tunnel channels,~~ N-channels, ~~and snake coils in the literature,~~ are the erosional expression of turbulent flows in pressurized subglacial channels. Together with subglacial channels incised in ~~the~~ overlying ice (R-channels), they modulate meltwater accumulation at the base of ice sheets and serve as highly efficient drainage pathways carrying meltwater to the ice terminus ~~(e.g., Röthlisberger, 1972; Weertman, 1972; Nye, 1976; Kehew et al., 2012). Indeed~~(e.g., Röthlisberger, 1972; Weertman, 1972; Nye, 1976; Sugden et al., 1991; Greenwood et al., 2007; Kehew et al., 2012). In particular, the transition from distributed to channelized drainage ~~, and the characteristics of the resulting subglacial channel network~~ leads to a reduction in ice flow rates, ~~affecting ice loss and ice~~ modifying ice loss rates and enhancing surging (e.g., Schoof, 2010). Subglacial channelized drainage plays a key role in deglaciation, and so their spatial characteristics, density, and distribution can help understand the patterns of glacial retreat (e.g., Sugden et al., 1991; Greenwood et al., 2007).

In spite of their importance, some outstanding questions remain: What are the typical lengthscales that characterize subglacial drainage systems (i.e., what is the drainage area, how many individual valleys form, how many tributaries do they have, etc.)? ~~How do tunnel valleys differ geometrically from river valleys? How can~~ Can we reliably identify ~~tunnel valleys only with~~ subglacial channels from rivers and other meltwater channels by using remote sensing techniques, including imagery and topographic data? ~~We use~~ And how do the characteristics of remarkably well preserved channels compare with channels elsewhere? To answer these questions, here we perform a detailed geomorphological study of exposed ~~tunnel valleys~~ subglacial channels on Devon Island (Canadian Arctic Archipelago)~~to build understanding of these questions. Our study of exposed tunnel valleys represents a complementary approach to in situ and modelling studies of active subglacial drainage, allowing for a network wide~~. This work represents the first field and high resolution remote sensing characterization of subglacial ~~drainage which adds context to point measures of discharge or effective pressure, and ground truths models of subglacial channel formation~~channels in the high Arctic, one of the areas with the best exposures of such features worldwide.

~~Exposures of tunnel valleys~~ Well preserved exposed subglacial channels are rare. During glacial recession, meltwater released from the ice sheet accumulates at the ice marginal area and erodes the channel, with post-glacial sediment accumulation causing burial or partial burial (Le Heron et al., 2009). Vegetation overprint and fluvial incision makes the detailed study of channel geometry and morphology difficult (e.g., Walder and Hallet, 1979). Exceptions include areas with polar desert climate in the Antarctica Dry Valleys (e.g., Sugden et al., 1991) and the Canadian High Arctic ~~(e.g., Dyke, 1999)~~(e.g., Dyke, 1993, 1999). The reduced rainfall conditions of these sites, recent ice retreat, and null or minimal vegetation cover are key for the preservation of ~~tunnel valleys~~these features. The morphology of ~~tunnel valleys~~ subglacial channels at our field study area on Devon

Island (Fig. 1), the second-largest of the Queen Elizabeth Islands in the Canadian Arctic Archipelago, is consequently well-preserved~~, and the~~ . The retreat of the Devon Island ice cap, in addition, offers a unique opportunity to compare recently exposed ~~tunnel valleys with tunnel valleys~~ subglacial channels with systems incised during the Younger ~~Drias~~ Dryas Innuitian de-glaciation.

The ~~main goal of this study is to characterize tunnel valley morphology using remote sensing data. Although tunnel valleys~~ systems identified by Dyke (1999) as subglacial meltwater channels on Devon Island are ∼10-20m wide and 3 – 6m deep, which is consistent with subglacial channels observed elsewhere, and one to two orders of magnitude smaller than tunnel valleys (e.g., Cofaigh, 1996; Kehew et al., 2012; Livingstone and Clark, 2016). Although subglacial channels have been described in ~~northern Europe (e.g., Piotrowski et al., 2006; Jørgensen and Sandersen, 2006), the Dry Valleys in Antarctica (Denton et al., 1984; Sugden et al., 1991, e.g.,), northern Canada (e.g., Shaw, 2002)~~detail in the field in northern Europe (e.g., Kleman, 1992; Clark et al., 2004; Piotrowski et al., 2006), the Antarctica Dry Valleys (e.g., Denton et al., 1984; Sugden et al., 1991), Canada (e.g., Kor et al., 1991; Beaney and Shaw, 2000; Shaw, 2002), and the ~~north-west of the United States (e.g. Walder and Hallet, 1979)~~United States (e.g., Walder and Hallet, 1979; Booth and Hallet, 1993), their rigorous distinction from ~~river drainage systems in satellite~~ other drainage systems from remote sensing imagery and topographic data ~~remains challenging. A well-established guideline for tunnel valley identification is reviewed by Kehew et al. (2012) and includes four criteria:~~ is limited (Greenwood et al., 2007). Field identification of subglacial channels consists on (1) ~~orientation parallel to former ice flow lines; (2) undulations in the longitudinal profiles; (3) location at or near active or former ice margins; and (4) presence of other features characteristic of subglacial processes such as eskers. Flows in subglacial meltwater channels are driven by large lateral pressure gradients resulting from variations in ice overburden thickness, which allows for water to flow largely independently from ground topography. Thus criteria (1) and (2) are useful indicators of erosion by subglacial flows. Criteria (3) refers to the onset of channelized flow in areas with high input and temporal variability of meltwater, i. e., close to ice margins and wet-based areas underneath the ice sheet. Criteria (4) is self-explanatory.~~ identification from fluvial runoff (proglacial channels or river systems) and (2) distinction from other melwater features, primarily lateral meltwater channels (e.g., Beaney and Shaw, 2000; Greenwood et al., 2007; Syverson and Mickelson, 2009; Margold et al., 2013). A set of subglacial channel identification criteria is presented by Greenwood et al. (2007) and summarized in table 1. These guidelines are qualitative, and ~~a topographic and imagery based approach to tunnel valley identification is yet to be developed. (e.g., Kehew et al., 2012).~~ the characteristics listed here may or may not be all present in a set of subglacial channels (e.g., Sugden et al., 1991; Beaney and Shaw, 2000).

To ~~address this objective~~ categorize and characterize the features presented as subglacial meltwater channels in Dyke (1999), we conducted fieldwork on central Devon Island~~, and complemented it with airborne imagery data of central to eastern Devon Island acquired in a helicopter campaign~~. In section 2 we provide a detailed description of ~~the~~ our field data acquisition and processing~~for river and tunnel valleys~~. We acquired GPS borne channel longitudinal profiles ~~, stereo imagery ,~~ along with stereo imagery and derived photogrammetry digital elevation models. We also used ~~, for the first time, a kinematic mobile LiDAR scanning~~ a Kinematic LiDAR Scanning (KLS) portable system, a novel method of measuring ultra-high resolution topography (<2cm/pixel Digital Elevation Models (DEMs)), which is described in more detail in Section 2.1.2. ~~Section~~ In section

3 ~~includes the results from field observations regarding channel longitudinal profiles, the Digital Surface Models produced with photogrammetric and KLS datasets, and a comparison of rivers and tunnel valleys within the same geological units. The compiled data allows us to discuss and revisit the guidelines reviewed by Kehew et al. (2012) in the context of remote sensing of previously glaciated areas~~we present a quantitative characterization of the observed channel networks, which we apply to distinguish subglacial channels from lateral meltwater channels and rivers in section 4. In section 5 we present a detailed qualitative description of subglacial channel morphology and the shape of subglacial drainage networks, which serves to further characterize and distinguish subglacial channel networks.

1.1 Field site: Devon Island

Devon Island was covered by an extensive Innuitian ~~ice sheet~~ Ice Sheet that reached its maximum extent during the last glacial maximum (e.g., England, 1987; Dyke, 1999; England et al., 2006). Shortly after the Younger Dryas, around 10 ~~ka~~ radiocarbon years BP, the margin of this ice sheet ~~was under recession to~~ began retreating towards the current coast line, and the final remnants in central Devon Island vanished around 8.8 ~~ka~~ radiocarbon years BP (Dyke, 1999), leaving a landscape of plateaus, fiords and deeply incised canyons. We refer to the work by Dyke (1999) and England et al. (2006) for a detailed discussion on the glacial history of the island during and since the Innuitian ice sheet. Since deglaciation, the landscape evolution is mainly the result of periglacial processes and erosion by ephemeral seasonal streams (e.g., McCann et al., 1972; Dyke, 1999). Fluvial incision represents only a small and highly localized contribution to the overall landscape evolution as a consequence of the island's polar desert climate conditions ~~.~~ (e.g., French, 2013). Aerial photography obtained from the National Air Photo Library (National Resources Canada) of Devon Island reveals ~~exposed tunnel valleys (Dyke, 1999)~~ highly directional channel networks, which Dyke (1999) described as meltwater channels. These systems are incised into the otherwise flat plateaus that comprise the majority of the topography ~~on the island (typical~~ (regional slopes are 1 to ~~3~~6°)~~. These channels~~ , and typically drain into deeply incised canyon systems that are believed to pre-date Innuitian glaciation (Dyke, 1999).

~~The study site~~ To categorize and study these meltwater channels in detail, we selected a study site that comprises an area of approximately 15 km^2 to the E-SE of the Haughton impact structure in central northern Devon Island (Fig. 1). This is a well-preserved 23 km diameter (Osinski and Spray, 2005) 23 Myr. old (Young et al., 2013) meteorite impact structure, which is a well established Mars analogue terrain, and has been the focus of numerous planetary analogue studies including crater morphology and erosion, periglacial landscape evolution on Earth and Mars, and evolution of ancient lake beds, among other activities (Lee and Osinski, 2005). The location provides access to both exposed ~~tunnel valleys and river valleys~~subglacial channel and river networks, allowing for systematic comparisons of their geometry and longitudinal profiles. Geologically, the study area lies entirely within carbonate strata of the Upper Ordovician Allen Bay Formation, specifically the Lower Member, which comprises a uniform succession of medium bedded to massive limestone with dolomitic labyrinthine mottling ~~(Osinski and Spray, 2005; Thorsteinsson and Mayr, 1987)~~(e.g., Osinski and Spray, 2005; Thorsteinsson and Mayr, 1987), and is overlain by quaternary glacial till (e.g., Dyke, 1999; Osinski and Spray, 2005). ~~Constructional~~ Depositional landforms such as eskers, and glacial deposits including glacier moraines and striations are rare on the plateau surface of Devon Island (Roots et al., 1963) and only occur sporadically within the Haughton impact structure (Osinski and Spray, 2005).

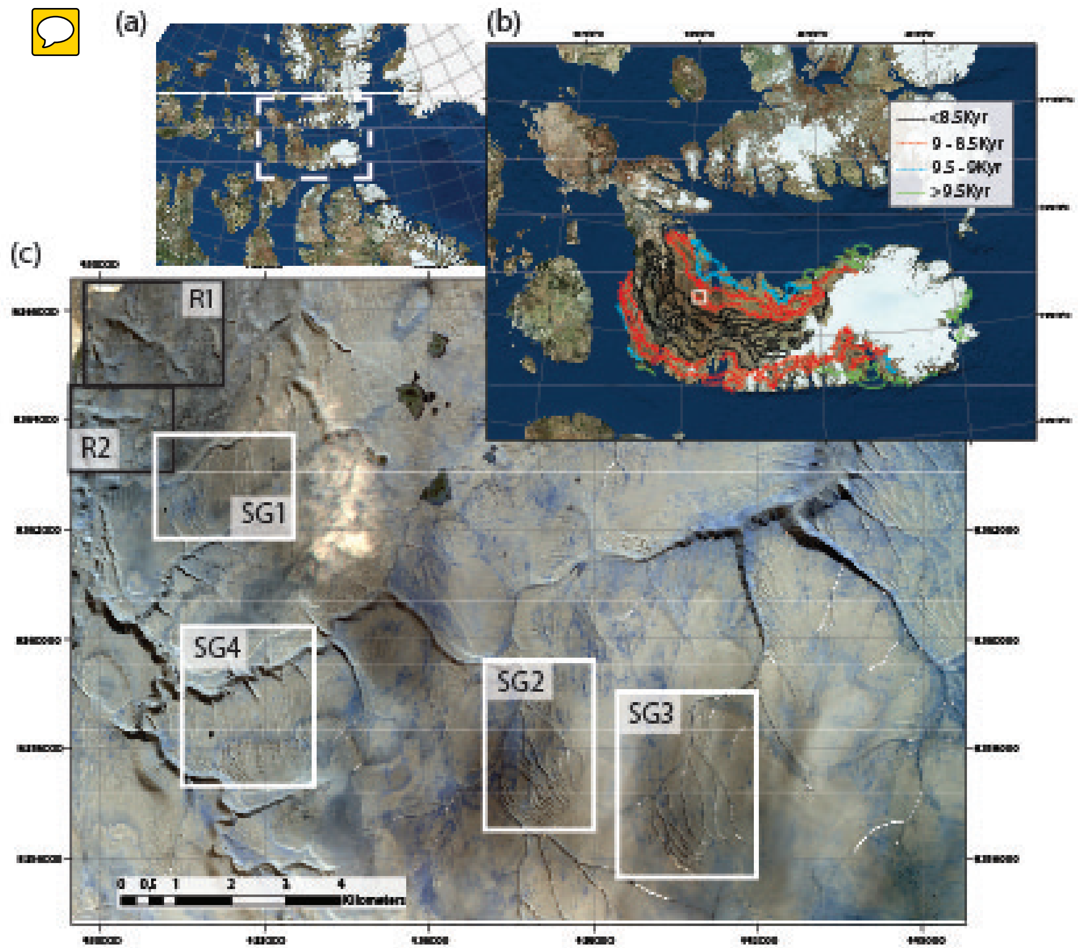

Figure 1. (a) satellite imagery of Devon Island within the Arctic Archipelago (white box). (b) satellite image of Devon Island, with a white box indicating the selected field site. The map also shows the Innuitian ice sheet terminus lines digitalized from Dyke (1999), with age reference in the legend (refer to radiocarbon years). (c) Field site (UTM zone 16), with boxes around each network investigated. White boxes are for sublgacial networks (SG1, SG2, SG3, and SG4), whereas black ~~arrows showing the mapped groups of tunnel~~ boxes indicate fluvial networks (R1 and ~~river valleys.~~R2)

2 Methodology

2.1 Preliminary remote sensing characterization

Figure 1(a) shows a Digital Globe satellite image of the Canadian Arctic including Devon Island and the rest of the Arctic Archipelago for context. ~~This panel also shows~~ Also shown is the Innuitian ice sheet termini as digitized from the work by Dyke (1999). Figure 1(b) shows a high resolution satellite view of our selected field area. Our target locations consist on 4 distinct ~~groups of tunnel valleys~~ subglacial channel networks and 1 ~~group of fluvial valleys~~fluvial network. To identify the areas ~~incised by subglacial erosion, we used criteria (1) and (4) in Kehew et al. (2012) (i.e.,~~ with potential subglacial incision, we looked for highly directional channel networks parallel to former ice flow lines ~~and close to other subglacial features)~~ in areas easily accessible from the Haughton structure, and also based on the locations where Dyke (1999) found evidence for ~~subglacial~~ meltwater channels. ~~We located individual tunnel valleys with criteria (1) and (2) (i.e., channel direction and undulating longitudinal profiles) using~~ Using high resolution WorldView imagery of the site ~~with a resolution of 2m~~(resolution of 2 m/ pixel~~, a~~), CDEM (0.15 arc-sec ~~CDEM which corresponds~~ DEM corresponding to 20 by 36 m/ pixel at a latitude of 75° N, obtained from the Natural Resources Canada website (http://geogratis.gc.ca/site/eng/extraction), and the recently released Arctic DEM (release 5 ~~)~~ at a resolution of ~~2m~~2 m/pixel available for free at https://www.pgc.umn.edu/guides/arcticdem/distribution/) we chose 6 channel networks, from which we inferred 4 to be subglacial and 2 to be fluvial.

~~We~~ From these 6 channel networks, we selected and visited 20 ~~drainage systems~~ individual channels for detailed, in situ ~~characterizations, of which 14 are tunnel valleys and 6 are rivers for comparison~~ characterization (see Fig. 1). For this study, we selected only first order tributaries and ~~studied~~ characterized them from the origin until the first junction. ~~Downstream of the first junction~~In most occasions, meltwater accumulates into streams and fluvial incision is apparent from field and remote sensing data in the profiles and cross sections of the channels once the network develops a stream order of 2 or more. In addition to in situ data, we acquired helicopter airborne imagery of sites located in central and eastern Devon Island, and identified ~~tunnel valleys~~ subglacial channels as they are exposed by the current retreat of the ice cap at its terminus.

2.2 Longitudinal profile data

~~To detect topographic undulations in the target drainage systems,~~ A distinctive characteristic of subglacial channels is the presence of vertical undulations in their profiles (e.g., Sissons, 1961; Sugden et al., 1991; Greenwood et al., 2007). To detect these features we obtained longitudinal ~~profiles~~ profile data (i.e., elevation vs. distance data) of the 20 ~~tunnel and river valleys~~ target channels using a GARMIN gpsmap 64s with a ~~horizontal resolution on the range 1-3m~~ 1-3 m horizontal resolution, depending on polar satellite availability, and a vertical barometric resolution of 3-6 m. We acquired the data by walking or driving ~~along each tunnel or river valley~~ an All Terrain Vehicle (ATV) along each inferred river or subglacial channel from the head until the first junction, and averaging the multiple profiles acquired in two to three runs.

To minimize the effects of the variable GPS resolution in processing the data, we grouped the channels into 5 groups that correspond to sites visited on the same day during the season. We also recorded the speed of the traverse during the collection of the longitudinal profiles, which varied between walking speed ($v_{walk} \sim$ 3-5km/h) and ~~All Terrain Vehicle speed (ATV)~~

(ATV speed ($v_{drive} \sim$ 10-15km/h). We then use this information to filter the GPS data in each group of tunnel and river valleys accordingly corresponding to each field day (Fig. 1 and Fig. 43).

We processed the GPS raw data by high pass filtering the signal with an upper frequency of twice the Nyquist sampling size, which corresponds to 1 GPS point per 3 seconds in the hiking traverses and 1 point per second in the ATV traverses, and a lower frequency corresponding to the inverse of the time required to drive/ walk along the channel length, that is, $1/v_{drive}$ L/v_{drive} in ATV traverses and $1/v_{walk}$ L/v_{walk} in hiking traverses (where L is the channel length). This filtering operation removes the data spikes related to avoiding obstacles on traverses including stream paths, large boulders, and snow patches.

2.3 Airborne imagery and photogrammetry

We complemented our in-situ channel characterizations with an extensive collection of high resolution aerial photography of over 50 tunnel valleys subglacial channels throughout the island, from which we derived Digital Surface Models (DSM). DSM generation through stereo-photogrammetry processing of image data involves the reconstruction of a three-dimensional body employing measurements in two or more overlapping images, acquired from different positions. Accurate reconstructions require an overlap of more than 50% between each image on a basis of at least 10 images per location, common features identifiable in different images for reference, and detailed spatial coordinates for each site.

For this purpose, we acquired over 1000 helicopter airborne images to capture the topography of multiple tunnel valleysinferred subglacial channel networks. To build this image database, we used a GPS-referenced CANON EOS 6D with an image resolution of 72ppp (5472 by 3648 pixels) (e.g., Smith et al., 2009). The built-in GPS has a horizontal spatial resolution of $\sim$ 10m and a vertical resolution of $\sim$ 5m. Although the camera GPS resolution also depends on polar satellite availability, resolution variations are minimal given the very small time lapse of image acquisition of all helicopter data.

To construct a Digital Surface Model (DSM), we obtained geo-referenced helicopter borne images for more than 50 channels including the centre-east of the island and the margin of the Devon Island ice cap(black arrows in Fig. 1). . Significantly, this survey includes imagery of tunnel valleys subglacial channels currently emerging under the active Devon Island ice cap margin (Fig. 2(d)), which enabled us to ground truth our identification scheme. Figure 2 includes examples of these images acquired at different points in the island.

We process the data in several steps. For each site, we first upload the images into AGISOFT software (e.g., Tonkin et al., 2014), together with the camera-generated EXchangeable Image Format (EXIF) files that include the geo-reference information. The software automatically aligns the imagery using the overlap existent between images. We improve the initial automated alignment with manual alignment of the images by selecting and matching common features (control points). Next, we produce a dense point cloud, a meshed surface model, and a surface model with ground texture. At this stage, we use the recently released Arctic DEM (available for free download at http://www.agic.umn.edu/arcticdem) to manually introduce markers in the model with known coordinates and elevation. This step improves the resolution of the final product by an order of magnitude. With this improved 3D model, we produce an orthophoto and the Digital Surface Model (DSM). In turn, at the final stages of processing we manually crop the DSM to remove noisy areas.

The DSM model reconstructions range in resolution between 0.4 m/pixel to 10 m/pixel depending on helicopter elevation and

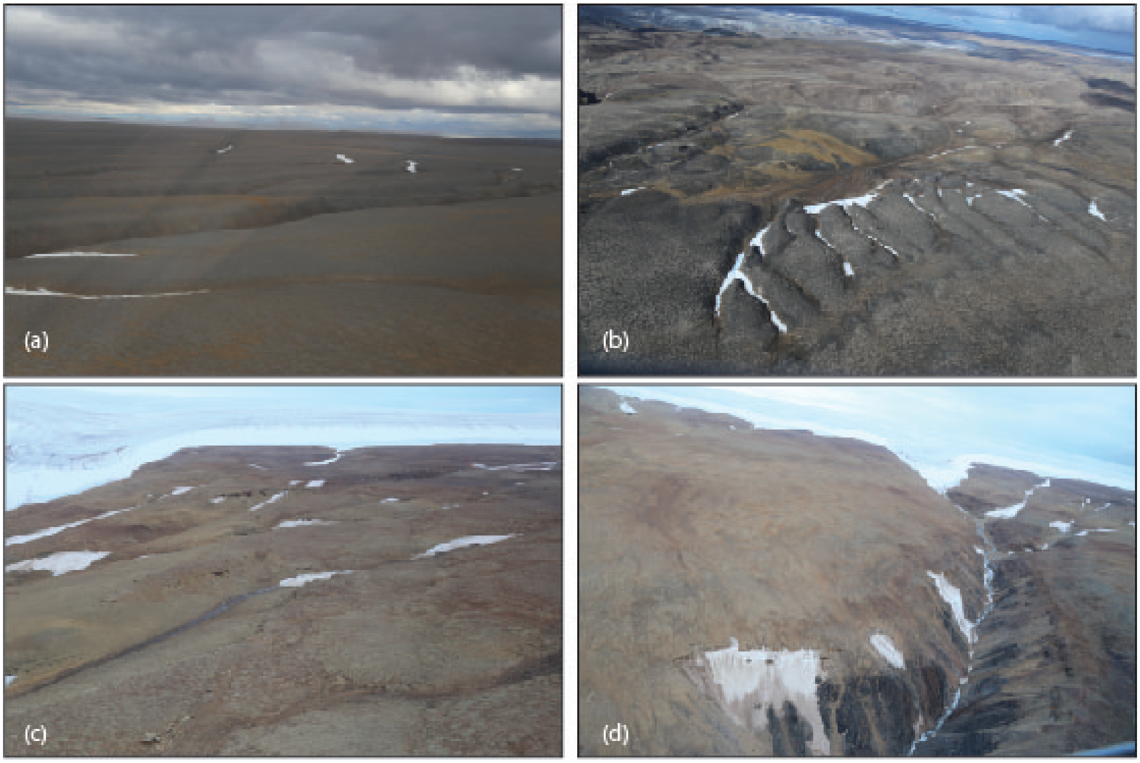

Figure 2. Aerial and field imagery of ~~tunnel~~ subglacial channels and ~~river valleys~~rivers. 2(a) corresponds to helicopter imagery of a group of ~~tunnel valleys~~ subglacial channels (~~89.08~~89.13° W,75.28° N), channel widths approx. 35 m. 2(b) corresponds to a groups of ~~tunnel valleys~~ subglacial channels located at 89.37° W, 75.18° N, network is approx. ~~Notice the recurrent parallel direction and scale~~300 m wide. 2(c) corresponds to a ~~group of tunnel valleys~~ subglacial channel emerging underneath the Devon Island ice cap, notice the similar morphology to 2(a) and 2(b), each channel being approx. 30m wide. 2(d) shows ~~a tunnel valley located at 85.18° W, 75.17° N following a direction perpendicular to~~ the ~~local topographic gradient (black arrow). 2(e) shows the~~ cross section of a deeply incised canyon emerging from under the ice cap. ~~2 (f) shows the~~ Canyon cross section ~~of a tunnel valley located 89.6° W and 75.17° N~~measures 200 m approx.

speed, number of images captured at each site and their overlap, the number of manually introduced control points, and other factors. All products are available upon request from the authors in point cloud (.LAS) and Geotiff (.tif) formats.

2.4 Kinematic LiDAR Scan acquisition

We used a novel kinematic backpack LiDAR scanning (KLS) system to capture the ~~the detail of tunnel valley~~ detail of subglacial channel topography from the ground. This study is the first time the KLS system has been deployed in the Arctic, and the first time it has been applied to detailed ~~tunnel valley morphometry~~ subglacial channel morphometric measurements. The goal of the survey was to reproduce the surface topography at cm resolution, but also to make a proof of concept for the capabilities of kinematic LiDAR. The system consists of a LiDAR scanner, a GNSS/GPS positioning system, and an inertial measurement unit (IMU) which are mounted within a backpack frame, allowing the user to make ultra-high-resolution LiDAR point clouds (>5,000 $\mathrm{points/m^2}$) of features traversed by the user. KLS enables the reproduction of surface topography at cm resolution (2 cm/pixel; Fig. 4), which is a higher level of accuracy compared to e.g. airborne LiDAR data, which would also be expensive to obtain in remote areas such as the high Arctic. The KLS dataset and derived surface models improve cross sectional and longitudinal profile analysis and comparison with river valleys, and are a ground-truth for hand-held GPS topographic data acquisition.

The LiDAR data was acquired using the AkhkaR3 kinematic backpack LiDAR developed at the Finnish Geospatial Research Institute, which is an updated version from those presented in Kukko et al. (2012) and Liang et al. (2015). The system is based on GNSS-IMU (Global Navigation Satellite System-Inertial Measurement Unit) positioning system, consisting on Novatel SPAN: Flexpak6 receiver, UIMU-LCI inertia measurement unit and 702GG antenna, a 360 degrees of field of view cross-track profiling laser scanner (Riegl VUX-1HA) synchronized to the positioning and operated by a tablet computer (Panasonic Toughpad ZF-G1).

River and ~~tunnel valley topography data was~~ subglacial channel topography data were collected by traversing the centreline of the channel by ATV, with the operator carrying the LiDAR system on his/her back. Continuous scanning was done using 150 Hz profiling, and 500 kHz pulse repetition frequencies. With these settings the maximum range was about 200 m from the scanner (i.e. a 400m-wide channel could be completely scanned), and the along-track line spacing about 1 cm with angular resolution of 1.8 mrad.

For accurate trajectory computations we set up a GNSS base station (Trimble R10) at the Haughton river valley base (75° 22.42’ N, 89° 31.89’ W) constituting of about 5 km base line length to the target channels. The raw GNSS observables were recorded at 5 Hz frequency, as were those at the KLS mapping system. The altitude data for the KLS system were recorded at 200 Hz data rate, and the positions and altitude trajectory were computed in a post-processing step for the point cloud generation. For post-processing we used the base station position using PPP method and the tightly coupled KLS trajectory Waypoint Inertial Explorer 8.60 (NovAtel, Canada).

To produce an elevation model the raw point cloud data was further processed: the points resulting from multiple reflections were removed as well as points with weak return signal (intensity less than 800 in the scanner scale). Some remaining points resulting from the laser beam hitting the rear of the ATV during the capture were manually cleaned out of the data using CloudCompare software. Post-processed data was exported as .LAS files.

The final DEMs (see example in Fig. 4 (c) and (d)) from the georeferenced LiDAR point clouds were created using .LAS Dataset tools in ArcGIS (LAS Dataset to Raster: Bin, Avg, Simple). The effective pixel resolution of 2cm/pixel ~~represents~~ in the DEMs represent the average value of the point cloud within a 2 cm bin (typically 5-10 LiDAR points, depending on proximity to the scanner). Due to the very high spatial coverage of the LiDAR points, minimal interpolation was needed, except in areas of LiDAR shadow. These areas were interpolated using the simple interpolation method outlined in the ArcGIS help section.

3 Results: Quantitative characterization of river and subglacial channels

3.1 ~~Tunnel~~ River and ~~river valley~~ subglacial channels longitudinal profiles

Reliably identifying ~~tunnel valleys~~ subglacial channels on the basis of the criteria ~~reviewed in Kehew et al. (2012)~~listed in Greenwood et al. (2007) and summarized in table 1, and in particular recognizing sections where the subglacial flow eroded ~~up~~ against topographic gradients ~~requires quantitative field longitudinal profile observations~~ (e.g., Sissons, 1961; Sugden et al., 1991; Glasser et al., 1999) requires measuring longitudinal profiles in the field. Figure 3 shows the longitudinal profiles of ~~the different channels in each group~~ different channels visited within the field area (see Fig. 1 and Table ~~1~~ 2 for location reference). In this figure, SG Network 1 consists of a group of inferred subglacial channels. R Network 1 is an inferred river system with 2 investigated channels, and R Network 2 includes 4 investigated river channels. SG Network 2 - D group is a group of inferred subglacial channels, with 2 channels investigated, and so is SG Network 3 - P group. SG network 4 - CAMF group consists of inferred subglacial channels, of which we visited 5.

From these data we ~~calculate the ratio of the elevation gain in an undulation , defined~~ identify the channels that display undulating profiles, as well as quantify the maximum undulation in each profile which we define as the elevation difference between the local minima at the beginning of a section with positive topographic gradient h_{min}, and the local maxima that follows it h_{max}, to the total topographic loss ~~h_{max}: $\psi = (h_{max} - h_{min})/\Delta h_{total}$.~~ ΔH, that is: $\psi = (h_{max} - h_{min})/\Delta H$ (see Fig. 10 for a cartoon representation). We refer to this magnitude as the magnitude of undulation ψ and we use it herein to quantify differences between the fluvial and subglacial longitudinal profiles. Table ~~1~~ 2 shows the magnitude of undulation ψ of the different ~~systems~~ channel networks in Fig. 3, together with their detailed coordinates.

Channels in ~~group~~ SG Network 1 (j201, j202, j204, j233, and j234) show magnitudes of undulation ψ corresponding to 24%, 3%~~and~~, 27%, $\psi = 3\%$, and $\psi = 0\%$ respectively of the total topographic loss, which is equivalent to 6.6 m, 1.5 m~~and~~, 6.5 m, 1.6 m, and 0 m respectively for j201, j202~~and~~, j204, j233, and j234. Channels j201 and j204 display the largest undulations that we ~~analyzed. Group 2 corresponds to longitudinal profiles of currently active river valleys, acquired and analyzed~~ analysed. R Network 1 corresponds to inferred fluvial systems, which we investigated and analysed for comparison. In ~~all the rivers in group 2~~ this network, no undulations are detected above the GPS confidence level~~. River~~, and in fact the profiles show a steady decrease of elevation with distance ~~,~~ that is much more consistent with ~~other examples~~ profiles of fluvial channels in the literature ~~(e.g., Whipple and Tucker, 1999). Group 3~~ (e.g., Howard, 1994; Sklar and Dietrich, 1998; Whipple and Tucker, 1999; Whipple, 2004). R Network 2 shows two profiles corresponding to active rivers (j231 and j232)~~and two corresponding to tunnel valleys (j233 and j234). The first two streams~~, which show $\psi = 4\%$ and $\psi = 0\%$ ~~, and the last two show $\psi = 3\%$ and $\psi = 0\%$ respectively. Tunnel valleys in group 3 and 4~~ respectively. Subglacial channels in SG Networks 2 and 3 were identified on the basis of their similar morphology and orientation to ~~tunnel valleys in other groups~~subglacial channels in other networks, but do not present significant undulations. Within ~~this group 4~~SG Networks 2 - D and 3 - P, channels j251 and j253 display undulations of $\psi = 7\%$, j252 has $\psi = 1\%$, and j254 displays $\psi = 3\%$. Finally, ~~group 5~~ SG Network 4 - CAMF displays 5 channels with different levels of undulation, respectively $\psi = 0\%, \psi = 13\%, \psi = 4\%, \psi = 4\%$ and $\psi = 0\%$. Based on similar morphology and proximity to other channels with large ψ within the same ~~group~~network, and recurrent $N - NW$ to $S - SE$ orientation, we conclude that all channels in ~~group 5 to be~~ SG Network 4 to have originated in the subglacial regime.

Additionally, Fig. 3 ~~offers~~ provides a comparison of LiDAR (solid orange line) and GPS-acquired (dashed line) longitudinal profiles. This was a useful indicator of the reliability of the hand-held GPS profile dataset within the GPS resolution range. We discuss the LiDAR results in more detail below. We also performed an additional comparison of our data (LiDAR and GPS) with corresponding longitudinal profiles extracted from the Arctic DEM at ~~5m~~5 m/pixel resolution (Fig. 3 green lines). In most of the profiles the ~~agree~~ agreement is excellent and well within the GPS precision margin. However, profiles j201, j211, j213, j214, j263 and j264 show significant deviations. Profiles j201, j202, j203, and j253 are also significantly noisier than the rest of Arctic DEM derived data. We attribute the discrepancy, in particular the difference in concavity in profiles j263 and j264 with our data, to the presence of snow covering the ~~tunnel and river valleys~~ rivers and subglacial channels during the acquisition of the photogrammetry data used to derive the Arctic DEM. We did not observe in the field any of the spikes present in the Arctic DEM profiles j201, j202, j253, and j254, and therefore we argue that they are DEM artefacts. However, this figure also proves that channel profile analyses based on Arctic DEM are reliable within the DEM limitations, and therefore subglacial channels can be identified and their undulations quantified using remote sensing high resolution topography.

3.2 LiDAR observations

Kinematic LiDAR Scanning (KLS) was acquired in 5 ~~tunnel valleys~~ subglacial channels and one river~~valley~~. The LiDAR dataset provides very high resolution topography data, which adds robustness to GPS-based undulation observations~~, targeting criteria (2) in Kehew et al. (2012)~~. Furthermore, KLS highlights a difference in cross sectional shape, scale, and downstream evolution that has not yet been considered as a distinctive characteristic of subglacial erosion, and is not appreciable from GPS profile data.

Figure 4 shows the results of using the kinematic backpack LiDAR approach to imaging the topography of a channel. The first panel 4(a) shows the point cloud files produced when investigating the channel cross section. The data is coloured by back scattered intensity at a laser wavelength of 1550 nm used in the KLS LiDAR system, resulting in darker values for wet snow and ice as seen in the image. ~~The ATV (roughly 1.75m long) gives a scale for the illustrations.~~ Panel 4(b) shows the trajectory of the KLS user in blue lines ~~, with the ATV again for scale~~overlapped to the point cloud product for a reference of coverage. Panel 4(c) shows the raster derived from the point cloud files for a river valley (corresponding to j231), and 4(d) shows the raster for the ~~tunnel valleys in group 1.~~ subglacial channels analysed in network 1, at a resolution of 9cm/pixel. Point spacing in 4(a) and 4(b) corresponds to 6 cm, with a total point count of 117,147,558 points for the river valley and for the subglacial channels. Raster resolution corresponds to 9 cm in the subglacial channels in network 1, and 10cm in the river valley corresponding to j231.

Panels (c) and (d) offer a clear comparison of cross sectional scale, shape, and evolution in the case of river valleys (c) and ~~tunnel valleys~~ subglacial channels (d). In (d), ~~tunnel valley~~ subglacial meltwater 1st order tributaries ~~form with~~ have widths of 5-7 m, and maintain a remarkably constant cross sectional scale as the channels evolve downstream. The cross-sectional shape is flat bottomed with steep-sided walls at the angle of repose ($\sim 15-20^{\circ}$) as shown in panel (b) ~~, with the ATV for scale~~and described in more detail in next section. In comparison, the river valley cross section starts narrower but increases significantly towards the end of the channel, as shown in panel (c). Other features such as the absence of internal channels inside the ~~tunnel valley~~ subglacial channel flat bottoms are also evident in LiDAR observations.

3.3 Photogrammetry observations

DSM rasters produced with the technique described in section 2.1.2 allow for a detailed topographic study at higher resolution than the CDEM (~~30m~~30 m/pixel) or the Arctic DEM (~~2m~~2 m/pixel), but lower than the LiDAR observations. The advantage of this dataset over LiDAR and GPS observations is the mobility of the aircraft, which allowed for topographic data acquisition in different parts of the island. Stereo imagery and photogrammetry results include Digital Surface Maps (DSM), point clouds, and ~~texture~~ textured orthomosaics for an additional 10 ~~tunnel valleys~~subglacial channel networks. These datasets complement the LiDAR observations in different parts of the ~~Island and~~ island at lower resolution, and are available at variable resolutions upon request as point clouds and Geotiff rasters. Figure 5 shows two DSM models and textured orthoimages of two different ~~tunnel valley~~ subglacial channel networks.

Surface models acquired through photogrammetry ~~show the transition between the tunnel valley erosional regime to the river valley erosional regime (black arrows)in terms of cross sectional shape and deepening of the channels. The orthoimage in panel (b) highlights the similar width of all~~ enable the differentiation of three regimes in a channel network (Fig. 5 (a)). In the first regime (zone (1)), subglacial tributaries originate as smooth depressions in the plateaus, merging into the topography and without clearly distinguishable heads. During the second zone (2), channels evolve into well developed systems ~ 15 m across and ~ 4 m deep in this network, keeping the width remarkably constant as they deepen downstream (see orthoimage below for better reference). Finally, in the last zone (3), tributaries merge into a deeper channel where fluvial incision by seasonal metlwater streams is apparent (notice the deepening in the DEM). In Fig. 5(b), DSM and orthoimage highlight the evolution of the tributary channels mostly by deepening as opposed to cross section widening (see particularly the scale of tributaries and main stem in the orthoimage). This high resolution local DEM highlights the size of the first order tributaries, which ~~starts increasing after the junction (see black arrow)~~are $10-20$ m from the origin with no small scale channels or tributaries visible, their quasi-periodic spacing, and the smooth merging with local topography at the origin, which is an example of use of the topography data produced. Snow and ice ~~packs~~ accumulations were a common view in some channels, particularly closer to the Devon ice cap. This was an issue at processing the DSM and textured image, although in some channels the thickness of the snow pack could be estimated. ~~The high resolution product highlights the size of the first order tributaries, that are $10-20$m in width from the origin, with no small scale channels or tributaries visible (see DEM and orthoimage in panel (a)). The photogrammetry dataset and observations also highlight the drainage characteristics of tunnel valley networks. Notice, for example, how a cluster of 12 tunnel valleys merges into a single, meltwater fed river in Fig. 5 (a). Order 1 tunnel valleys throughout the island are generally parallel to each other during the first few hundred m, although we also observed braiding in some tributaries (see Fig. 5 (a) but also 4 (d)).~~

3.4 Morphometric comparison of tunnel valleys and river valleys

4 Identification of subglacial channel networks

Morphological differences between river and tunnel valleys

4.1 Morphometric comparison of river and subglacial channels

Morphometric differences between rivers and subglacial meltwater channels are apparent even before evaluating the criteria exposed before (Kehew et al., 2012), including analysing the longitudinal profiles in fig. 4, only from the correlation to former ice margins , and direction consistent with estimated ice flow lines , and analysis of the presence of undulations in their longitudinal profilesof subglacial channels (Dyke, 1999). On remote sensing data including satellite imagery and topography of the field site and surrounding area, tunnel valleys inferred subglacial meltwater channels appear in groups of 5 to $\sim$ 10, parallel to each other and consistently in the N-NW to S-SE direction. Moving to the east of the island, channel directions change on average from W to E, remaining oriented radially towards the current day Devon Island ice cap.

Characteristic tunnel valley lengths are $\sim$ 1inferred subglacial channel lengths are $\sim 1-2$ km throughout the distinct targeted channel groups, all incised into the lower member of the Allen Bay formation. The channel networks. The typical cross section is shallow, flat bottomed, and steep-sided, with widths that are $\sim 5-10$m approximately constant from the origin until at least the first junctiontrapezoidal, with widths of $\sim 40-60$ m at the initiation stages ($\sim$ 150 m downstream) that contain flat floors $\sim$ 20 m wide, and depths of $\sim 3-5$m, deepening in the downstream direction. under 5m. Downstream (> 1.3 km), cross sections evolve to a better defined trapezoidal shape and deeper channels (> 10 m), preserving roughly the same width (Fig. 6). In comparison, the geometry of inferred river valleys on the island displays major differences. In particular, river valley cross sectional River widths vary continuously downstream by one to two orders of magnitude from the origin ($\sim 5-10$ cm) until the first junction ($1-5$m) 60 m across, $\sim$ 5 m deep) $\sim$ 150 m downstream from the headwater (i.e., Fig. 4(c) and (d)), consistent with observations elsewhere (e.g., Parker, 1978a, b). River ; Fig. 6 initiation stages). Downstream, river valleys deepen up to $\sim 20-50$m from the origin until the first junction and form $\sim$ 60 m and grow in width up to 400 m, forming deeply incised canyons with V-shaped cross sections (see Fig. 2(f) 6, developed stage and Fig. 4). The evolution of bankfull channel width we observe is consistent with observations elsewhere (e.g., Parker, 1978a, b), and with the well-established hydraulic relationship for flow in river channels (e.g., Leopold and Maddock, 1953; Parker et al., 2007; Gleason, 2015), relating the channel bankfull width to the discharge:

$$W = K_w Q^b \qquad (1)$$

Where for a gravel bed such as the ones considered, Parker et al. (2007) showed that $K_w = 4.63 g^{-7/10} D_{50}^{-5/2}$ and $b = 0.467$, with D_{50} the medium value of the grain size distribution, and discharge that increases as tributaries merge into the main channel.

The morphometrical characterization of the cross sectional differences between rivers and subglacial channels can be captured with a shape factor, $F = W_T/D$, defined as the ratio between channel top width and the depth

(Leopold, 1970; Williams and Phillips, 2001) (see Fig. 10 for a reference cartoon). We measured channel top width following Grau Galofre and Jellinek (2017) as the distance between two points of maximum curvature along a cross sectional line for consistency, which corresponds with valley width for rivers and the width of the entire cross section in subglacial channels. We present shape factor results in table 2, column 6, where all measurements correspond to cross sections before tributary junctions. These results highlight the fundamental differences between fluvial and subglacial cross sections: whereas subglacial shape factors are in the range $4.5-31$, with an average $< F_{SG} > \pm\sigma = 13.5 \pm 9$, fluvial shape factors are much smaller, in the range $2-4.6$ with an average $< F_{SG} > \pm\sigma = 3.4 \pm 1$. Furthermore, according with our observations in figure 6, we expect the variation of this shape factor to be considerable for subglacial channels as the top width remains constant and the channel deepens, and less important for river valleys, as both cross section and width increase downstream.

Another geometrical distinction between both erosional regimes is the width of first order tributaries (Grau Galofre and Jellinek, 2017). Even at the tip of the channel, ~~tunnel valley widths amount~~ subglacial channel widths are up to tens of metres (consistent with arguments in Weertman (1972)), as opposed to widths of first order river channels which are typically ~~sub-metre in scale .We observed in~~ sub-meter in scale (Grau Galofre and Jellinek, 2017).

4.2 Comparison of lateral and subglacial meltwater channels

Along with the distinction from river systems, it is relevant to distinguish subglacial channels from channels formed by meltwater accumulated and released at the ice margins, i.e., lateral meltwater channels (i.e., Greenwood et al. (2007); Syverson and Mickelson (2009); Margold et al. (2013)), which have also been identified in the area (Dyke, 1999). We follow the criteria presented in Table 1, Greenwood et al. (2007), to this end. Focusing now only on the meltwater channel networks and ignoring rivers, the systems we investigate present a number of characteristics that exclude lateral meltwater drainage: (1) they do not follow contour lines, but rather run parallel or slightly oblique to topographic gradients (Fig. 7) (e.g., Price, 1960; Greenwood et al., 2007); (2) their longitudinal profiles often contain stepped sections (e.g., Sugden et al., 1991; Greenwood et al., 2007) (Fig. 3), and may or may not display significant undulations (Fig. 3); (3) they display anastomosing patterns, with channel sections that split in two to join again further downstream (anabranching) (e.g., Sugden et al., 1991); and (4) potholes and shallow depressions are a common sight (e.g., Sugden et al., 1991; Greenwood et al., 2007). Figure 7 below shows a hillshade map with contour lines representing each of the networks under study, both derived from Arctic DEM stripes at a resolution of 5 m/pixel. The boxes at the bottom right corner of each figure give information about the direction of the regional slope (red arrow) and the channel direction (black arrow).

Comparing both directions, and taking into account that the channel networks we study are perpendicular to, and feed into, large canyons (see networks 1, 2, and 4) instead of forming terraces at their rims, we conclude that a lateral meltwater origin is unlikely. We discuss more details regarding the morphology and characteristics of these networks in the next subsection, which also suggest the emplacement of these features in subglacial conditions.

5 Detailed morphology of subglacial channels in Devon Island

Based on the field and remote sensing observations presented above, we build a detailed description of the morphology of the 4 networks of subglacial meltwater channels we visited while in Devon, as specified in Fig. 7.

5.1 Network characteristics

The overall channel systems range from 2.5 to 0.9 km long and 1.6 to 1 km wide. They are all incised into dolomite bedrock and coarse gravel. Regional slopes in the plateaus where the networks are incised are very small (see table 3), and the number of tributaries varies from 5 in network 4 to 17 in network 2, consistent with networks elsewhere in the island. Table 3 contains a summary of morphological field observations of subglacial channels.

The general pattern of the 4 subglacial channel networks studied is dendritic (in that channels merge to produce larger channels) with a main channel that wraps around the exterior of the network and tributaries that flow parallel to it, merging at acute angles (see networks 1 and 3 in Fig. 7), which gives the system of channels a finger-like appearance. In a few cases in networks 1, 2, and 3, tributaries bifurcate to give the network an anastomosing pattern. All subglacial channel networks observed terminate in deeply incised canyons that predate glaciation through hanging valleys or very steep chutes.

We observed at different sites on the island how the melting of snow ~~packs in tunnel valleys~~ accumulations within subglacial channels leads to the formation of meltwater ephemeral streams, which merge at the channel junctions into larger streams. This transition is often associated with a gradual change in cross section, from the ~~sallow~~ shallow flat-bottomed ~~characteristic of tunnel valleys~~ form characteristic of subglacial channels to a deeply incised V-shape. Fig. 2(e) and 5 exemplify this morphological transition from a ~~group of tunnel valleys~~ network of subglacial channels to a single meltwater fed river.

5.2 Channel characteristics

5.2.1 Main channel

Main stems are 1.5 – 2 Km in length and follow a NE-SW direction for about 1 Km before bending around tributaries. The profiles of these channels are stepped, with steps consisting on 2-3 segments about 300 – 500 m long separated by sections of steeper gradient (Fig. 3, see channels j201, j252, j254). In some occasions, there is a short section of reverse gradient following these steps. Main stem cross sections are generally trapezoidal, with flat bottomed floors and steep sided walls ($\sim 20°$ degrees). Variations in width from the channel origin until the junction are small, accounting for no more than a few meters of change in any of the networks (c.f., Fig. 4 and fig. 5).

5.2.2 Tributaries

All tributaries in each network typically formed at the same elevation and incised the substrate parallel to, or oblique to, the topographic gradients to meet the main channel (Fig. 7, table 2 column 5). Typically, the subglacial channel networks we observe consist of 10 to 17 tributaries oriented in the NE-SW direction. Within the same network tributary depth can vary between $< 1 - 10$ m. This differential incision is particularly evident in networks 1 and 2, although this property is noticeable in all networks within the resolution of this study (Fig. 8).

In general, tributaries display the same trapezoidal flat bottomed, steep sided shapes that are characteristic of the main channels, although cross sectional asymmetries appear here with more frequency than in the main stems. In particular, tributaries in network 3 are incised more deeply in the eastern side than the western side, allowing for shallow depressions to form along the steeper side (Fig. 7, right panel). Developed tributaries (at a distance of $\sim$ 1km from their origin) are around $\sim$ 10 m in depth, with a flat floor $\sim$ 10 m across and steep sided walls up into the plateaus, as shown in the examples of fig. 7. ~~At a network scale, tunnel valleys occur in clusters of 5-10 channels with finger-like patterns including a large curved channel surrounding the group of tunnel valleys,~~ Longitudinal profiles of tributaries are complex and vary across the different networks (Fig. 3). Tributaries in networks 1 and ~~several smaller parallel internal systems. Examples of this pattern are in Fig. 2(b)~~ 4 grade into the main channel continuously, whereas in networks 2 and 3 some confluences present hanging valleys followed by shallow potholes in the junctions between smaller and larger tributaries (see an example in fig. 8 (c)). Profile curvature is variable even within the same network: channels j202, j232, ~~3(a)~~j261, ~~(d)~~j262, ~~and (e) . The branching pattern of subglacial channels often differs from the tree-like typical of rivers, also apparent from Fig. 2. Channels also intersect with and diverge from each other over relatively short lengthscales (~ 100m~~ j265 display concave profiles, whereas channels j231, ~~see tunnel valleys in Fig. 1 as an example of this anastomosing pattern) . Generally, tunnel valleys also show very few or no tributaries (notice this pattern in Fig. 2(a)~~j234, ~~(~~j251, j263, and j264 display convex profiles. Shallow potholes ($\sim$ 1m deep) filled with water or snow are a common view across all networks, as detailed later.

5.3 Other characteristics

5.3.1 Anastomosing patterns

Although the shape of the networks is mostly dendritic (channels merge to produce larger channels), anabranching (bifurcation followed by re-junction downstream) patterns occur frequently at the beginning of the networks, typically before 1 km. Examples of this anabranching behavior are shown in networks 1, 3, and 4, where channels split to rejoin anywhere between $5 - 250$ m downstream. Figure 7 shows a hillshade map of the subglacial networks, where the anastomosing patterns are easily identified. Also of interest here, fig. 8 shows a high resolution cross section taken across an anabranching section in network 1. The section clearly shows how one of the channels (in this case the eastern channel) is more deeply incised than the western one, which may suggest a time-transgressive emplacement of the system (e.g., Beaney and Shaw, 2000; Brennand, 1994).

5.3.2 Potholes

Potholes appear frequently in the subglacial channel networks explored in the field (Fig. 9), and they are also evident from the photogrammetry and LiDAR DEMs we produced, falling at resolution edge of the Arctic DEM. They are shallow depressions (50cm to 2 m deep) typically filled by water that grade into the channel floors, and that vary in dimensions between $\sim$ 5-50m long by $\sim$ 2-30 m across, with a particular example in network 1 where dimensions are up to $\sim$ 125 m and $\sim$ 40 m across (Fig.

9 panel (b)). We observed them to occur (1) at the junction of two tributaries, (2) in the middle of a tributary channel associated with a channel widening, or (3) at the channel headwater area. Typically, the larger sizes appear in case (1), whereas the smaller depressions occur in (2). Figure 9 shows field images of potholes of several sizes, fitting into type (1) (panel c and b), 5(a)), rarely achieving a stream order higher than class (2)(panel d), class (3, much lower than typical values for river valleys.) (panel a). The location of these features is indicated in the aerial images at the side with a camera icon.

6 Discussion

6.1 An additional metric for tunnel valley identificationUndulations, obliquity, shape factor, and the remote sensing characterization of subglacial channels

In section 3.1 we introduce the magnitude of undulation ψ and discuss its role in identifying tunnel valleys. We argue here that subglacial channels. This is a useful metric, but it requires the acquisition of very high resolution topographic data. At lower resolution, in addition, differences among channel direction and local topographic gradients are also can also be indicative of subglacial erosionin areas where the , as long as ice erosion rate by sliding is lower than the meltwater erosion rate (Weertman, 1972; Paterson, 1994). (e.g., Weertman, 1972; Shreve, 1972; Paterson, 1994). Observations of channels incised oblique to topographic gradients are common in the literature (e.g., Sissons, 1961; Walder and Hallet, 1979; Sugden et al., 1991; Livingstone et al., 2017). Quantifying and measuring these deviations in a set of subglacial channels to stablish a quantitative base for channel categorization has, however, not been done. We consider Considering the confined flow of pressurized water in a subglacial channel at the base of an ice sheet to follow the x direction, with y perpendicular to ice flow and z perpendicular to the ground surface, so that z_b and z_i are the bed and ice surface elevations respectively. At steady-state, water flow at the base of the ice is driven by the water pressure potential gradient $\nabla\phi$:

$$\nabla\phi = -\rho_i g \nabla z_i - \Delta\rho g \nabla z_b + \nabla N. \tag{2}$$

Here ρ_i is the ice density, $\Delta\rho = \rho_w - \rho_i$ is the density difference between water and ice, g is the gravity, and $N = p_i - p_w$ is the effective pressure, where $p_i = \rho_i g(z_i - z_b)$ is the local hydrostatic pressure related to ice thickness and p_w is the water pressure. The topography of Devon Island's plateaus is mostly flat, which implies that the controls in effective pressure gradient arise mostly from variations in ice surface slopes, ∇z_i, and not from surface topographic gradients ∇z_b. This picture is true generally if ice surface slope is more important than bed topography, such that $\rho_i g \nabla z_i / \Delta\rho g \nabla z_b >> 1$. Although ice surface slope is correlated with topography at a regional scale it can depart from it topography at the scale of individual channels (Fig. 10), driving both channelized and distributed meltwater accordingly. We thus expect tunnel valleys to potentially deviate from local topographic gradientsThis explains the slight deviations we observe between subglacial channel direction and local topographic angles in our field site, recorded in table 2.

However, where ice topography is nearly flat or bed slopes are important, $\rho_i g \nabla z_i / \Delta\rho g \nabla z_b << 1$, bed topography dominates incision and drives meltwater flow. Under these conditions, undulations or departures from topographic gradients cannot occur. In this case, neither metric will identify channels as subglacial, and their characterization will depend on other observations~~such as their individual and drainage geometries and directionality with respect to former ice lines. Criteria (4) in Kehew et al. (2012) can also provide a guide for interpretation in the last case, with an example of that in Fig. 4 group 5. In this group of tunnel valleys, 2 of the channels display no undulations above the GPS detection limit, whereas the other 3 channels do (see Table 1). According with criteria (4) in Kehew et al. (2012), and given the geometrical similarity of all channels in that same cluster and their recurrent direction, it is reasonable to propose that if three channels in the area were incised under the ice sheet, then the other 2 must have a similar subglacial origin.The advantage of using channel directionality as opposed to undulations lies in its straightforward application, by contrasting the topographic contour lines with channel direction.It is, however, limited by the assumption that channels formed under slow sliding or cold based ice body~~, such as cross sectional characteristics or morphology. Morphological criteria include the presence of anabranching patterns, consistent direction with former ice flow lines, and correlation with other subglacial features (i.e., eskers, moraines, outwash fans) (Greenwood et al., 2007; Kehew et al., 2012, e.g.,).

6.2 Identification of ~~tunnel valleys~~ subglacial channels from remote sensing data

We distinguish ~~tunnel valleys~~ subglacial channels in our field area on the basis of four properties, which are measurable at the Arctic DEM resolution: (1) consistent N-NW to S-SE direction, radial to the paleo-ice margins (Dyke, 1999, Fig. 8) near our field area, changing to W to E near the ice cap margin; (2) Topographic undulations in the longitudinal profiles (Fig. 4 and Table ~~1~~2), and channel incision with orientations not parallel to the local topographic gradient (Fig. ~~2(d))~~7); (3) Cross-section size and shape, i.e., shallow ~~wide flat-floored for tunnel valleys~~ trapezoidal for subglacial channels and deeply incised V shape for river valleys(Fig. 8, quantified in table 2 column 6 in the shape factor), which evolve in rigorously distinguishable ways (Fig. 6; and (4) large 1st order channel widths on the order of $\sim$ 10 m ~~.~~ (Fig. 4). Not all channels we identify as ~~tunnel valleys~~ subglacial from their morphology and direction have undulations in their longitudinal profiles. However, none of the river ~~valley~~ profiles show any detectable ~~undulation~~undulations. We conclude that the magnitude of the undulation index $\psi > 0$ unequivocally distinguishes ~~tunnel valleys~~subglacial erosion, but $\psi = 0$ does not necessarily preclude ~~subglacial incision. In revisiting the guidelines reviewed in Kehew et al. (2012) and their application to remote sensing data, we find that we can target criteria (2) undulations in the longitudinal profile, with high resolution topographic data (i.e., GPS tracks in Fig. 4, and KLS LiDAR data in figure 5), and criteria (1) consistent directionality relative to active or former ice flow lines, with imagery and topography (i.e., consistent and parallel channel direction, which does not follow topography in Fig. 1). The remote sensing data applications of criteria (3) are limited, as they require additional geological constrains on the location and margins of former ice bodies. We assessed criteria (4) with the morphological similarity among tunnel valleys within the same group~~it. Similarly, deviations from local topographic gradients for subglacial channels are much larger ($> 5°$) than for rivers.

~~To these well-established criteria, we introduce three useful~~ We add three remote sensing indicators of subglacial ~~channel erosion from remote sensing data. The first is the difference between tunnel valley direction and topographic gradients, as exemplified in Fig. 2 (d) and discussed in section 4.1. This criteria is straightforward to evaluate, and requires only a measure of the angle between the topographic gradient direction (i.e., perpendicular to contour lines) and channel direction. The second~~

erosion to the criteria in Greenwood et al. (2007). The first indicator is the large cross-section widths at the origin of order 1 ~~tunnel valleys~~ channels (i.e., Fig. ~~5~~4) which are orders of magnitude larger than in river systems. The ~~third and last criteria~~ second criterion is the minimal variation in width downstream, from the beginning of the channel until the first junction, as visible from Fig. ~~5~~4, comparison of panels (c) and (d)~~.~~, and Fig. 6. The third is the remarkable difference between shape factors (top width to depth ratios) between river valleys and subglacial channels.

7 conclusions

In this study we describe a ~~series of tunnel valleys~~ population of subglacial channels (N-channels) exposed on Devon Island, Canadian Arctic Archipelago~~, that were emplaced during the retreat of the Devon Island ice cap to its present day location, 8-9.5kyr ago~~. In particular, we discuss the use of remote sensing techniques to distinguish between systems of ~~river and tunnel valleys~~rivers, lateral meltwater channels and subglacial channels, which serves as a complement to existing field based methods. We provide detailed field descriptions of 20 ~~tunnel valleys~~individual channels, including their longitudinal profile characteristics, cross sectional geometry, channel directionality and drainage network morphology, to then revisit and expand the identification methods ~~reviewed by Kehew et al. (2012)~~listed in Greenwood et al. (2007). Our field observations include GPS mapping of subglacial and fluvial incised channels longitudinal profiles, photogrammetry, kinematic ~~mobile~~ LiDAR data (KLS), and aerial imagery, allowing for both a qualitative and quantitative description.

We find that a quantitative measure of undulation ψ, defined as the topographic loss (local minima to local maxima of the undulation) at an upstream section to the total topographic loss, reliably distinguishes ~~tunnel and river valley profiles~~ fluvial and subglacial longitudinal profile (Fig. 4), although the lack of undulations does not rule out subglacial erosion. We also argue that the departure in channel direction from local topographic gradients also reflects subglacial erosion ~~.~~ (table 2), as well as a large top width-to-depth ratio (shape factor F, compiled in table 2.) We then discuss the limitations of both these metrics in identifying ~~tunnel valleys~~subglacial channels. If both metrics fail, other morphological observations such as channel direction, ~~clustering in groups of parallel, closely spaced tunnel valleys, and spatial correlation with other subglacial features, i. e., other tunnel valleys, are key to identify the channels.~~ anastomosing networks, cross sectional scale and downstream evolution, serve as a categorization guide.

With our data and observations, we revisit the guidelines ~~reviewed by Kehew et al. (2012) to improve identification of tunnel valleys~~ listed in Greenwood et al. (2007) to improve quantitative identification of subglacial channels from remote sensing data. We conclude with the following target characteristics of interest: (1) undulations in the longitudinal profile and changes in channel direction with respect to local topographic gradients, (2) consistent channel direction ~~radial from present or former ice sheets and~~ following former ice flow lines, close to the ice margin, and with the possible presence of other subglacial features in the area, (3) order 1 channel widths on the 5-10 m scale ~~that show~~ with minimal variation downstream, with wide ~~, flat-bottomed~~ and trapezoidal cross sections, and (4) presence of ~~other subglacial features in the area.~~ anabranching sections.

Data availability. All datasets described in this paper are available upon request from the lead author (contact agraugal@eos.ubc.ca). This includes photogrammetry generated digital elevation models (.tif format), LiDAR data (.tif and .LAS formats), airborne geo-referenced imagery (.jpg format), and GPS elevation tracks (.txt format).

Author contributions. Anna Grau Galofre and A. Mark Jellinek designed the field campaign and collected hand-held GPS and photogrammetry data. G. Osinski is the principal investigator for this campaign, provided logistical and technical support, and aided in collecting hand-held GPS data. A.Kukko and M.Zanetti collaborated equally in collecting and processing LiDAR data. The body of the manuscript was written by A. Grau Galofre, with additions from all collaborators. The authors declare that they have no conflict of interest.

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Table 1. Magnitude Diagnostic criteria for the identification of vertical undulation ψ subglacial channels

heightTunnel valley origin Distinctive characteristics	references
Undulations in the longitudinal profiles	Sissons (1961); Greenwood et al. (2007); Kehew et al. (2012), this study
Direction oblique to topographic gradient	Sissons (1961); Sugden et al. (1991); Greenwood et al. (2007), this study
Presence of other subglacial landforms	Greenwood et al. (2007); Kehew et al. (2012)
Cavity systems and potholes	Sugden et al. (1991), this study
Stepped confluences	Sugden et al. (1991), this study
Abrupt beginning and end	Sissons (1961); Glasser et al. (1999)
Absence of alluvial fans	Sissons (1961), this study
Other characteristics	**references**
Presence of abandoned loops	Clapperton (1968), this study
High sinuosity	Clapperton (1968)
Bifurcating and anastomosing patterns	Clapperton (1968); Sugden et al. (1991); Greenwood et al. (2007), this study
Variety of size within the same system	Sissons (1960)
Presence of steep chutes	Sissons (1961), this study

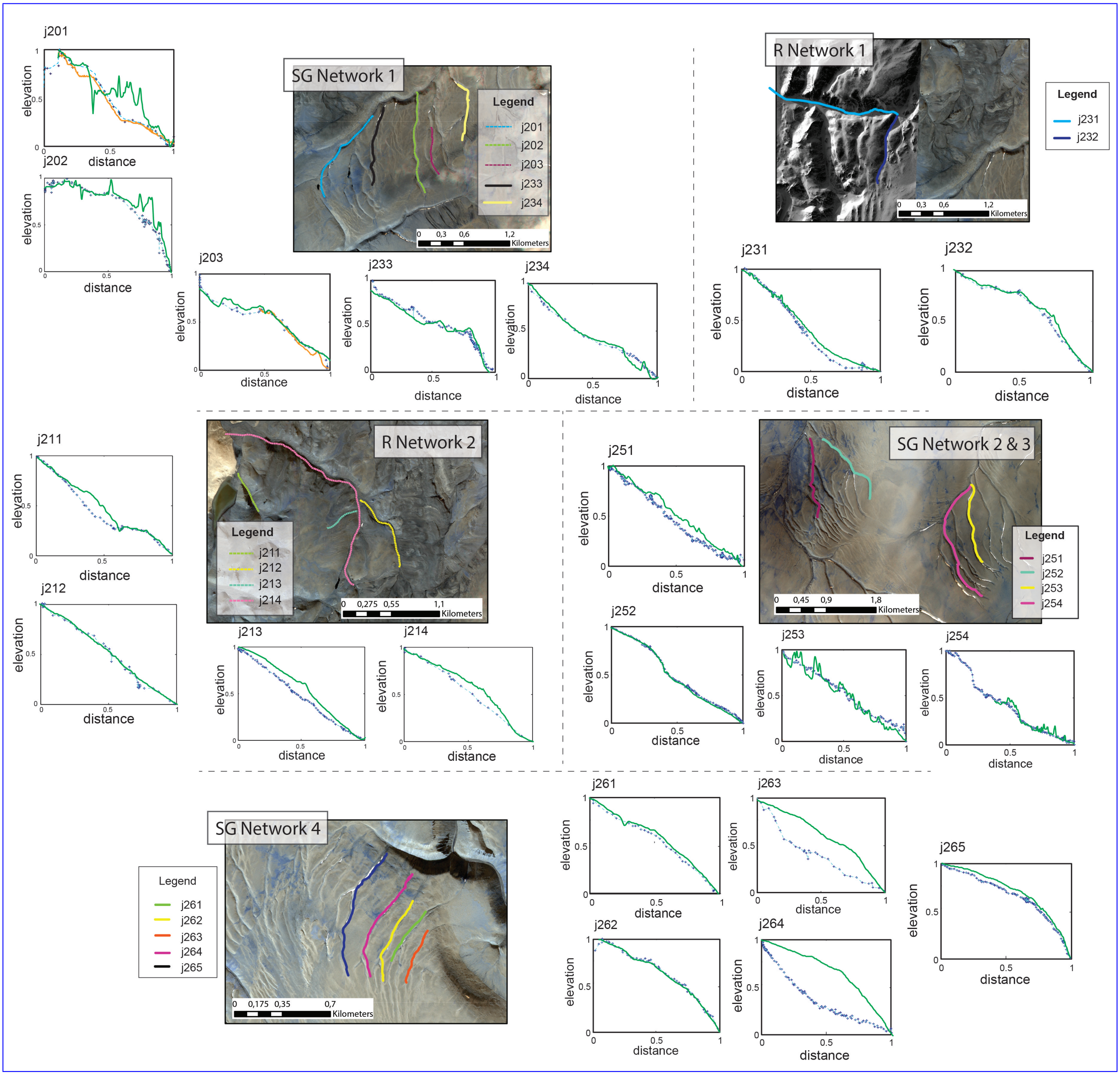

Figure 3. Longitudinal profiles of tunnel and river valleys and subglacial channels normalized to total topographic loss and length along the channel, with context WorldView satellite imagery for each channel groupnetwork. Group 1 consists of 3 tunnel valleys. Group 2 includes 4 rivers. Group 3 is in the same location than group 1 (see Fig. 1) but consists on 2 rivers (j231, j232) and 2 tunnel valleys (j233, j234). Group number 4 includes 4 tunnel valleys. Group 5 consists of 5 tunnel valleys. In the longitudinal profiles, blue crosses represent the raw GPS data for each channel, blue dashed lines are the data after filtering, and orange solid lines represent the LiDAR sections that overlap GPS data for comparison. The profiles obtianed with the Arctic DEM at 5m 5 m resolution are shown in green color.

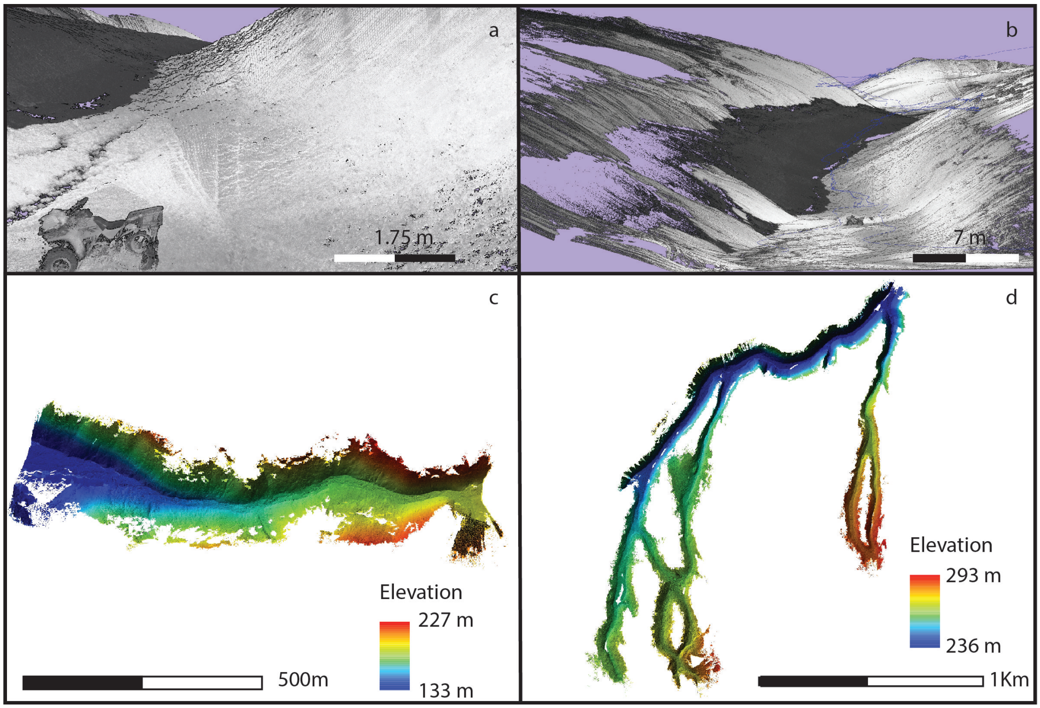

Figure 4. KLS LiDAR observations. Panels (a) and (b) show the color coded point cloud files ~~color coded according to back scattered intensity~~ (dark is low return), see the scale for spatial reference. Panel (b) shows the trajectory of the KLS user~~overlapped to the point cloud product for a reference of coverage~~. Panels (c) and (d) show the raster produced using the point clouds~~, at a resolution of 9cm/pixel~~. ~~The black arrows in panels (a) and (b) point at the ATV for scale. Point spacing in 4(a) and 4(b) corresponds to 6 cm, with a total point count of 117,147,558 points for the river valley and for the tunnel valleys in group 1. Raster resolution corresponds to 9 cm in the channels in group 1, and 10cm in the river valley corresponding to j231.~~

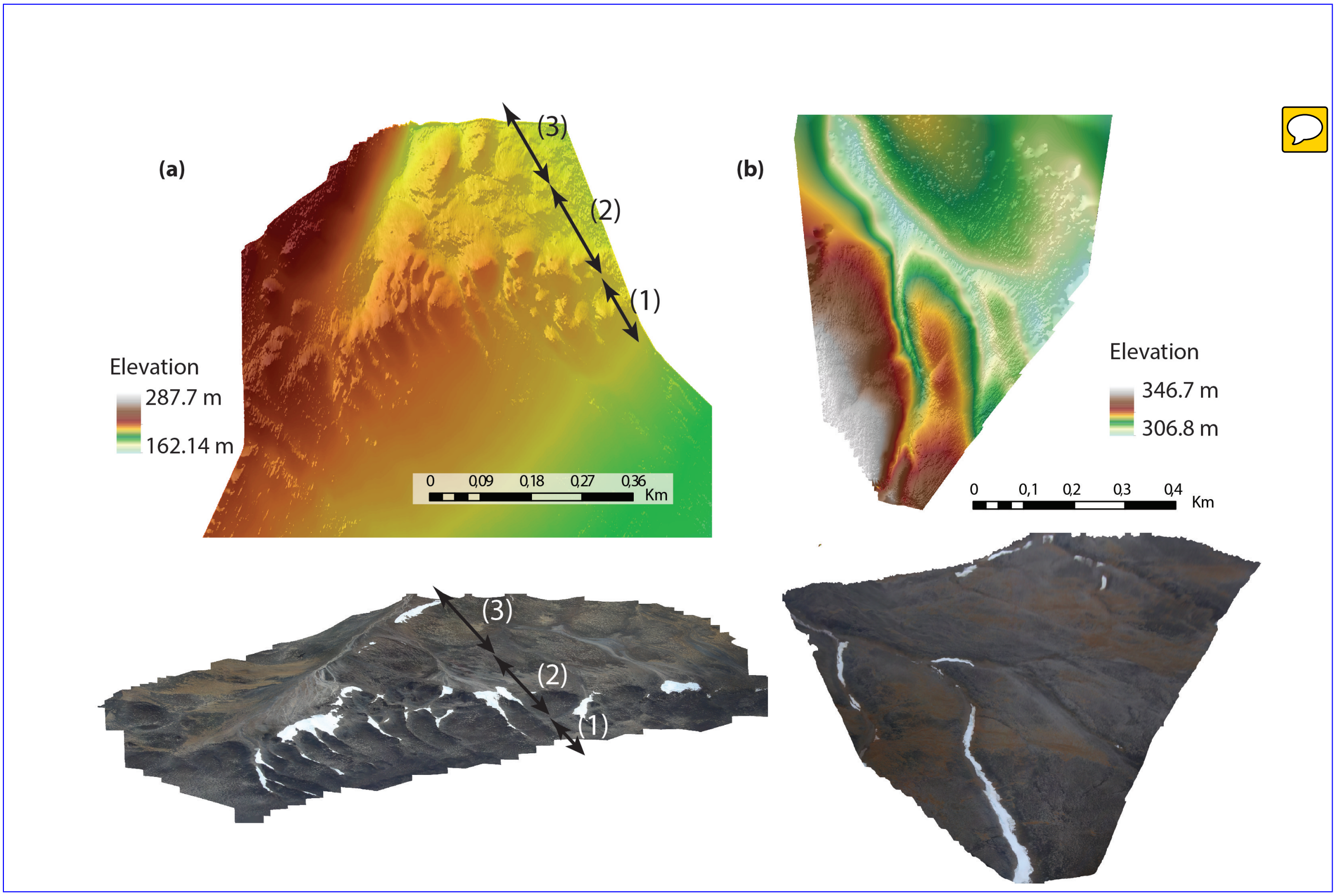

Figure 5. Stereo-photogrammetry ~~products~~ derived from helicopter borne photography. The top panels (a) and (b) show the digital elevation model (DEM) at a resolution of 0.48 and 0.56 m/pixel respectively, with the colorbar indicating the elevation of the model surfaces. The images underlying the panels correspond to the textured orthoimages in both locations.

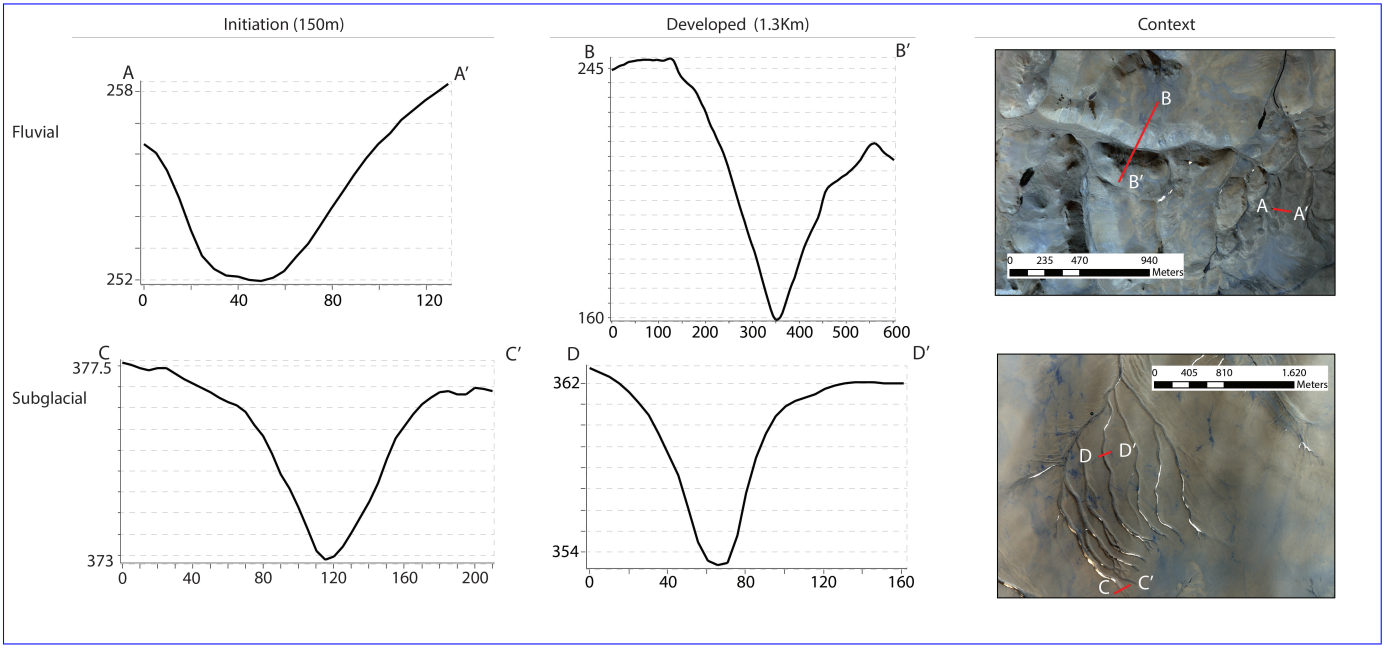

Figure 6. Cross sectional evolution of a fluvial (upper row) and subglacial (bottom row) channel, with satellite imagery for context on the right column. In the subglacial case, the initial width and the shape remain largely unchanged over length, whereas the river cross section grows monotonically both in width and depth with distance. Notice the differences in depth and length in the section scale bars.

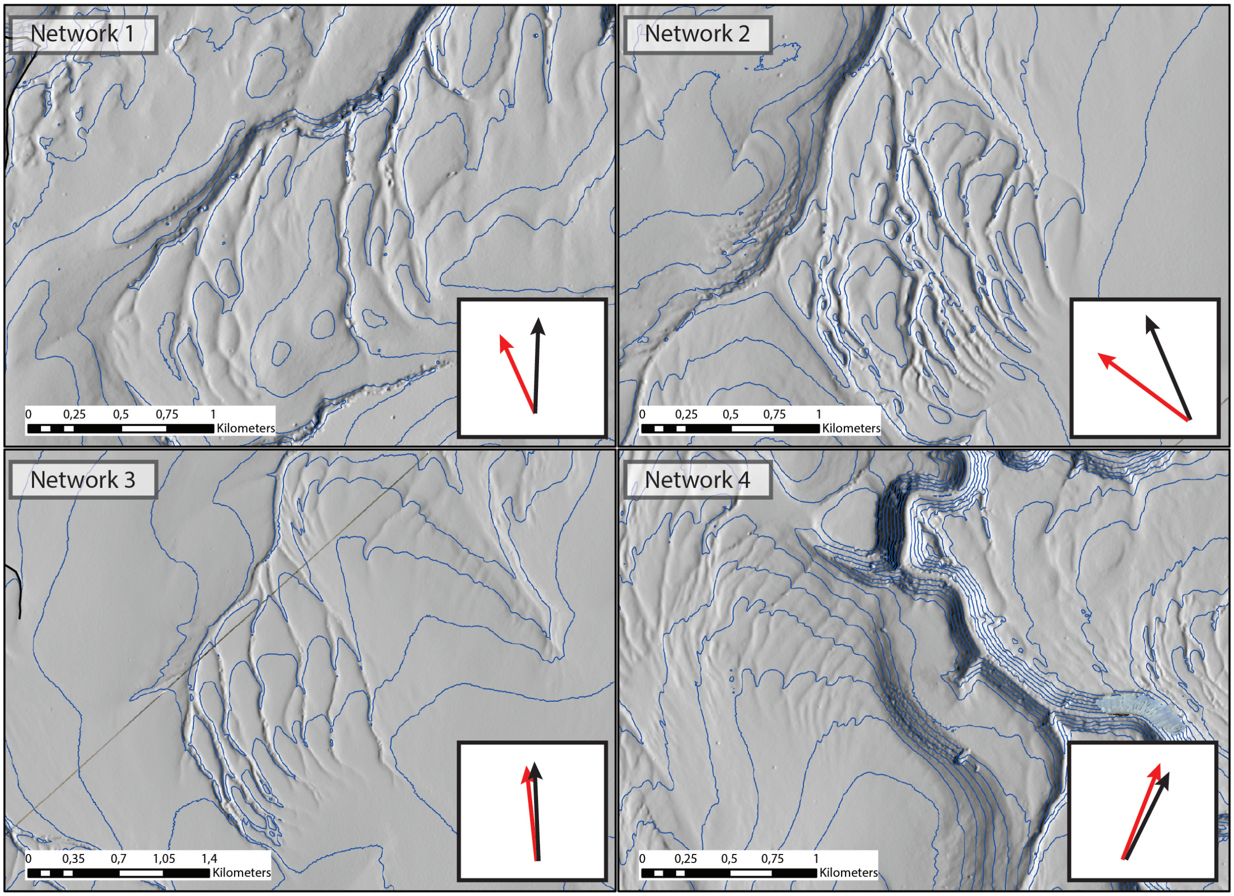

Figure 7. Hillshade and contour map of the 4 subglacial channel networks investigated. Contour lines are separated 15 m, and hillshade resolution is 2 m/pixel. In the bottom right corner, the black arrows indicate the overall direction of the channels in the networks, whereas red indicates the regional slope direction.

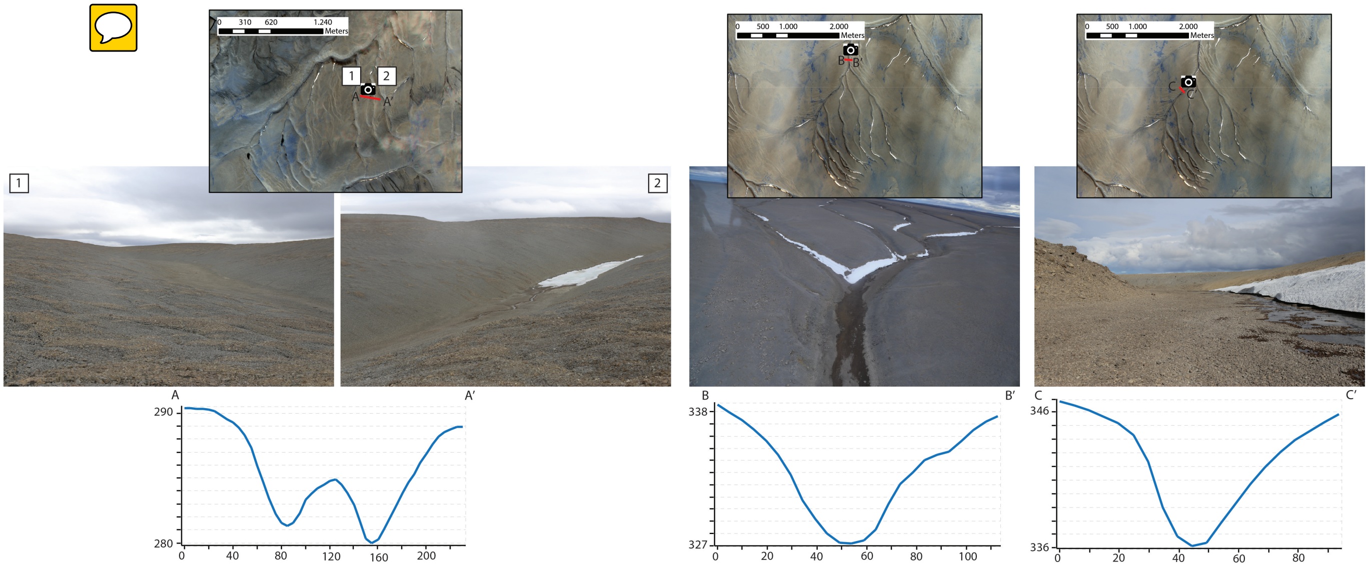

Figure 8. Cross section field imagery and profiles. Upper row shows a satellite imagery context on the location where the image and the cross section are obtained, together with a scale reference. Middle row shows images of four cross sections, obtained by this expedition on July 24th and 25th, 2017. The middle panel corresponds to a main channel whereas the other three images correspond to tributaries. Cross section profiles below show elevation (m) vs. distance (m) obtained from the Arctic DEM at 2 m/pixel.

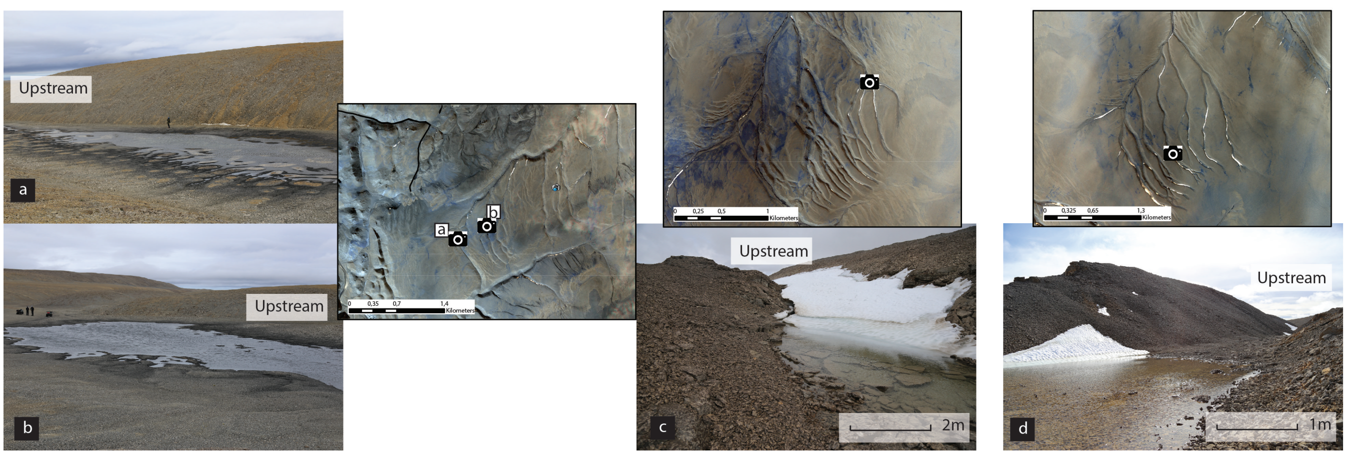

Figure 9. Field images of the shallow depressions and potholes observed. Satellite imagery provide context for the photographies through the camera icons. In photos (a) and (b), notice the human figures for scale. Photos (c) and (d) contain a scale bar for reference. Image (c) is an example of an overhanging valley (here covered in snow) followed by a pothole.

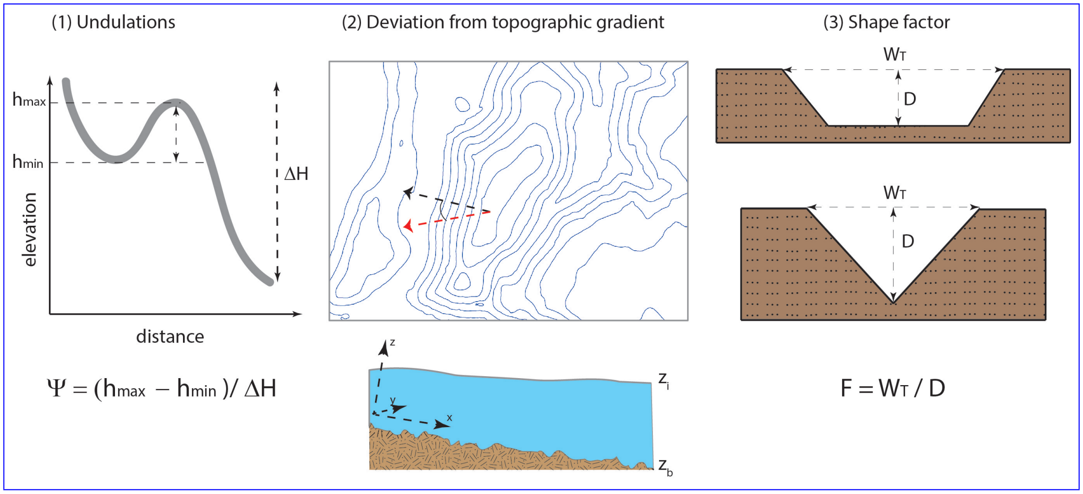

Figure 10. Cartoon representing ~~an ice body sliding over its bed~~the definitions of the three remote sensing based metrics proposed in this study. (1) Shows our definition for longitudinal profile undulations Ψ, ~~showing~~ where the grey line represents the longitudinal profile of a channel (elevation vs. distance). (2) Represents the deviation between the direction of a set of channel networks (red arrow) and the topographic gradient (black arrow), together with the axis notation ~~for reference,~~ and the ice and topographic surfaces z_i and z_b in equation 2. (3) Shows the definition of shape factor with two cartoons representing a trapezoidal and a V-shaped cross section, where top width W_T and depth D are represented (adapted from Williams and Phillips (2001)).

Table 2. Morphometric characteristics

Individual channel	latitude	longitude	ψ	deviation from topography	F
~~group~~ SG Network 1				27°	
j201	75° 20' 0"	89° 25' 5"	0.24		4.5
j202	75° 20' 3"	89° 23' 13"	0.03		8
j204	75° 20' 11"	89° 22' 49"	0.27		7
j233	75° 20' 14"	89° 22' 19"	0.03		10
j234	75° 20' 02"	89° 24' 44"	0		10
height~~group 2~~ R Network 1				-	
j211	75° 21' 35"	89° 27' 40"	0		2
j212	75° 21' 28"	89° 28' 42"	0		3
j213	75° 21' 12"	89° 25' 22"	0		4
j214	75° 21' 25"	89° 27' 10"	0		4
j215	75° 21' 04"	89° 26' 24"	0.01		3
~~group 3~~ R Network 2				-	
j231	75° 20' 56"	89° 27' 5"	0.04		4.5
j232	75° 20' 25"	89° 27' 39"	0 ~~j233~~	~~75° 20' 14"~~	~~89° 22' 19~~
~~j234 75° 20' 02" 89° 24' 44"0~~height~~group 4~~ SG Networks 2 - D				30°	
j251	75° 17' 27"	89° 11' 41"	0.07		5.5
j252	75° 17' 39"	89° 9' 42"	0.01		30.5
heightSG Networks 3 - P				4°	
j253	75° 16' 43"	89° 4' 55"	0.07		6
j254	75° 17' 06"	89° 5' 17"	0.03		5.5
~~group 5 (CAMF)~~ SG Network 4 - CAMF				6°	
j261	75° 17' 28"	89° 27' 41"	0		17
j262	75° 17' 23"	89° 27' 48"	0.13		17.5
j263	75° 17' 23"	89° 27' 26"	0.04		31
j264	75° 17' 24"	89° 28' 01"	0.04		18
j265	75° 17' 24"	89° 28' 22"	0		17
height					

Table 3. Summary of morphological characteristics

Characteristic	SG network 1	SG Network 2 - D	SG Network 3 - P	SG Network 4- CAMF
tributary n°	10	17	10	5
regional slope (%)	1.8	2.0	1.3	5.5
plungepools?	yes	yes	yes	yes
anabranching sections?	yes	yes	yes	no
hanging valleys?	no	yes	yes	no
network length (km)	1.5	2.1	2.5	0.9
network width (km)	1.6	1.3	1.5	1
stepped profiles?	yes, j201	yes, j252	no	no
network shape	dendritic	dendritic	dendritic	parallel
presence of other subglacial bedforms	no	no	no	no
height				