

Chris R. Stokes

5 Editor

The Cryosphere

Québec City, 23 Januray 2019

10 Dear Prof. Stokes,

Please find enclosed our revised manuscript entitled "*Ice-stream switching by up-ice propagation of instabilities along glacial marginal troughs*" co-authored by Etienne Brouard and Patrick Lajeunesse, submitted for publication in the journal *The Cryosphere*.

15 All the comments and concerns are addressed in the responses-to-comments letter. We greatly appreciate these comments that allowed us to improve this manuscript.

The data and conclusions presented in this paper have never been published. All authors have approved the submission of the manuscript. This manuscript contains 7654 words and 9 figures.

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Best regards,

25 **Etienne Brouard, Ph.D.**

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## RESPONSE TO THE DECISION LETTER

35 First, we would like to thank the editor and the reviewers for insightful and valuable comments. Our revisions are described as follows.

### **EDITOR:**

#### **Comments to the Author:**

40 *I would like to thank both reviewers for taking the time to provide two well-informed reviews. It is clear that they are generally supportive of publication, subject to some important revisions. I share their concerns about the brevity of the manuscript and would ask the authors to consider adding greater detail in terms of both the context and the results and discussion (if they decide to undertake revisions). As noted by one of the reviewers, this would also be facilitated by a more orthodox structure to the manuscript.*

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#### **Response:**

We thank the editor for the positive comment. We did revise the manuscript to improve the text and figures while incorporating most of the suggestions proposed by the reviewers. We did change the manuscript to a more standard structure (introduction, regional setting, methods, results, discussion, conclusions) and added details in all the sections to better support the interpretations. Below lies the point-by-point response to the reviewers.

50

## REVIEWER 1:

### 55 **Comment 1:**

*For the most part the manuscript clearly explains the authors' interpretation, although in my opinion it should be couched more as such – an interpretation – and not quite as factual as the authors tend to make it seem. The paper is well illustrated. The writing is mostly good; I provide some comments that would help clean it up a little.*

### 60 **Response:**

We acknowledge that some parts of the text are based on interpretations and we tried to make it clearer in the text where inferences and interpretations were made. We have changed the title to better explain that we found a probable cause (interpretation) for the morphology of the trough system.

### 65 **Comment 2:**

*The manuscript is also fairly brief. I do not think that this is any sort of serious flaw – the contribution comes across as a note, or a case study, and I think that is fine*

### **Response:**

70 Following comments by the editor and reviewer 2, we did change the manuscript to a more standard structure (introduction, regional setting, methods, results, discussion, conclusions) and added various details in all the sections to better support the interpretations.

### **Comment 3:**

75 *However, I found the manuscript to be lacking in its description of the glacial history of the study region and in covering the published literature on the evolution of fjords, which seems relevant to this topic (even though these are offshore troughs). I would suggest that the authors consider adding some text to their manuscript on these two topics (glacial history and fjord evolution).*

### 80 **Response:**

We have added a glacial history into a regional setting section (lines 61-85). We have also added some text on fiord/trough/overdeepening evolution, mainly on headward erosion processes, in the section *Erosion of Hecla & Griper Trough* to support the interpretations (lines 266-290).

### 85 **Comment 4:**

*I have one additional comment of note regarding the authors' main interpretation of ice piracy and flow switching. It strikes me that the authors' present one interpretation, and perhaps a very reasonable one given the likely nature of troughs to propagate in the headward direction over repeated glaciations. That said, can one really rule out an alternative? One alternative being that the topographic situation has always been the same as it is today – that the Hecla and Griper marginal trough funneled ice into the Scott system from day 1, and that only during the most extensive glaciations did Sam Ford ice spill onto the shelf fronting the entrance to Sam Ford Fiord. This led to a*

95 *less developed (shallower) cross shelf trough and lack of a trough mouth fan. I think unless one drilled the Sam Ford Trough and found ancient tills, but not recent tills, one couldn't rule out this alternative scenario. For this reason, I really encourage the authors to use looser terms, couching their piracy mechanism as an "interpretation" or "inference" . . .*

**Response:**

100 *We acknowledge concerns raised by the reviewer about alternative scenarios that would fit the morphology of the studied trough system. We have added alternative scenarios, including the one suggested by the reviewer in section 4.3 and explain why they cannot account for the trough morphologies (lines 297-315). We could, however, suggest a scenario where ice was partitioned between the two troughs, but that the up-ice propagation of ice streaming is still the main driver (lines 316-318).*

**Comment 5:**

105 *Title. I wonder if a title that more closely describes the inferences made in the paper (e.g., using words such as "evolution of shelf troughs," or "ice piracy and flow switching") would better advertise this nice case study.*

**Response:**

110 *We changed the title to 'Ice-stream flow switching by up-ice propagation of instabilities along glacial marginal troughs' following the reviewer suggestions.*

**Comment 6:**

*Line 13. Similar to what?*

115 **Response:**

*Changed to: Trough systems that are formed of cross-shelf troughs intersected by marginal troughs. (line 21).*

**Comment 7:**

120 *Overall abstract. Use of "marginal trough." I did not know what this was until it was defined later in the paper. Reading the abstract again made more sense after I learned the terminology. Given the broad audience of this journal, I wonder if the term can be defined – or a more descriptive term could be used – in the abstract?*

**Response:**

125 *We added a brief description of marginal troughs just after the mention in the abstract: ... through glacial erosion of a marginal trough, i.e., deep parallel-to-coast bedrock moats located up-ice of cross-shelf troughs. (lines 13-14).*

**Comment 8:**

130 *Line 16. Suggest “Ice-flow switching was first invoked. . .” instead of “Ice-flow switching has first been invoked. . .”*

**Response:**

*Changed to Ice-flow switching was first invoked. (line 24)*

135

**Comment 9:**

*Line 19. Can do without the word “then”*

**Response:**

140 *Removed.*

**Comment 10:**

145 *Line 25/26. I do not think that because a variety of driving mechanisms for flow switching have been described in the literature, that this means that the problem is poorly understood. All of the mechanisms might be valid in their various contexts. I also suggest that the sentence starting with “This wide range . . . “ should be removed.*

**Response:**

150 *We have changed the sentence to: The wide range of possible driving mechanisms outlines the fact that ice stream switching is a complex process that requires further assessment in order to model accurately the future behavior of modern ice sheets. (lines 33-34)*

**Comment 11:**

155 *Paragraph beginning on Line 35. Are the terms “Scott Trough” and “Sam Ford Trough” formally defined – do they appear on topographic/bathymetric charts? If not, and are defined here, authors should point out that they are “informally” called. . .*

**Response:**

160 *Scott Trough is defined on nautical charts of the Canada Hydrographic Survey as the extension of Scott Inlet. Scott Inlet is the toponym for the opening of Clark and Gibbs fjords to the Baffin Bay and therefore does not represent the bathymetric depression we analyse. Sam Ford Trough is defined as a prolongation of Hecla & Griper Trough on Nautical charts. However, Scott and Sam Ford Trough are informal names that are widely used in literature to represent the bathymetric depressions. These informal names were used for describing the bathymetric depressions for over 40 years and are still used today. We do not think adding this precision would benefit the text (e.g., Gilbert, 1985, Arctic; Osterman & Neilson 1989, CJES; Praeg et al. 2007, CGC, Bennett et al. 2014, Bull. Can. Petr. Geol., Brouard & Lajeunesse 2017, Scientific Report, Margold et al. 2015, Journal of Maps, 2018, QSR; Jenner et al. 2018, Marine Geology).*

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170 **Comment 12:**

*The spelling of the word “fjord.” It is fine to use the Scandinavian spelling when referring to fjords generally, but when referring specifically to the particular fjords on Baffin, they are proper place spelled “Fiord.”*

**Response:**

175 Every occurrence of ‘fjord’ has been changed to ‘fiord’.

**Comment 13:**

180 *Line 38. It would be more correct to write that the MSGSLs and a till unit that extend onto the TMF “have been interpreted” to indicate that the LIS reached the shelf break during the LGM (B and L, 2017). The evidence points to LGM ice cover, but it has not been confirmed with coring and dated sediments, for example?*

**Response:**

185 Jenner et al. (2018; Marine Geology) confirmed with cores along the slope off the shelf edge that the Laurentide Ice Sheet did reach the shelf edge as suggested (Brouard & Lajeunesse, 2017). We have added the Jenner et al. (2018) reference to support the point. (line 240)

**Comment 14:**

*Line 42. Replace “Last glacial episode” with “LGM”*

190 **Response:**

Changed to : *The last glacial stage (MIS2) reached its maximum around 25 cal. ka BP in Western Baffin Bay* (line 72)

**Comment 15:**

195 *Line 42. Is it really possible that a glacier lobe on the continental shelf could have been cold based? Would the bed have been below sea level or above? If below, I think cold-based is out of the question?*

**Response:**

200 That is a really good comment, as small parts of the continental shelf (Hecla & Griper Bank) may have been over sea-level during full glacial conditions, at least during the last glaciation. The inter fiord areas were characterized by cold-based areas (Briner et al. 2006, GSA Bull.) and it is reasonable to believe that part of the ice in between the troughs could have as well be in some parts cold-based. However, we acknowledge that cold-based ice is unlikely. We removed *cold-based ice*.

205

**Comment 16:**

Line 42. Should write more literally. “. . .slow-flowing or cold-based ice” (not “slow flow. . . ice”)

210 **Response:**

Changed to : slow-flowing ice (line 76).

**Comment 17:**

Line 43. “ice-flow” does not need a hyphen in this case

215

**Response:**

Hyphen removed.

220 **Comment 18:**

Line 44. Look up use of “that” versus “which.” Here and several instances throughout the manuscript the two are improperly used.

**Response:**

225 We revised every occurrence of ‘which’ and ‘that’ in the text so that they are properly used.

**Comment 19:**

230 *Line 45. This is a long and awkward – not entirely grammatically correct – sentence. I think there is a word or some words missing immediately in front of “bathymetric data are here used. . .” I found the info in the first half of the sentence to be too highly detailed about the methods to be appropriate for this paragraph. Rather than “... used to analyze an ice stream switching. . .” I would suggest that what the authors are really doing is “hypothesizing” ice stream flow switching.*

235 **Response:**

240 *This sentence was split in two and we added that we interpret an ice stream switch from the data.: Here, high-resolution swath bathymetry imagery combined with archived seismic reflection data and International Bathymetric Chart of the Arctic Ocean bathymetric data (IBCAO; Jakobsson et al., 2012) are used to analyze the morphology and stratigraphy of a single glacial trough network on the northeastern Baffin Shelf, in Eastern Arctic Canada. These data suggest that past ice stream switching occurred due to the ice-discharge piracy from an ice stream in a deep cross-shelf trough (Scott Trough) via the lateral extension of a marginal trough (Hecla and Griper Trough), which led to the shutdown of the ice stream occupying the neighboring cross-shelf trough (Sam Ford Trough). (lines 44-48)*

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**Comment 20:**

*Line 54. “realized” awkward verb to use*

250

**Response:**

The whole sentence was changed to: *Individual landforms were digitalized on the surface in ArcMap 10.2.... (line 96)*

**Comment 21:**

255 *Line 58. “. . . was used to analyze Sam Ford Trough. . .” “data were”*

**Response:**

*Changed was to were.*

260

**Comment 22:**

*Line 74. “. . .up to the middle of. . .” I can’t make sense of this, what does “up to” mean, starting from the shelf break or the continent?*

265

**Response:**

*Change to: ...grounding wedges in the trough...*

**Comment 23:**

270 *Line 77. 12 km long (not large)*

**Response:**

*Changed large to wide.*

275

**Comment 24:**



Line 90-97. Starting with the sentence “If the tributary. . .” I become lost about the points being made. I think these sentences could be re-written. I also think that studies of fjord evolution, by headward erosion, should be discussed in this section.

280

**Response:**

This is now in section 4.2, lines 266-290. Sentences were rewritten in order to better explain that the morphology of Hecla & Griper Trough is a function of Scott Trough morphology rather than the morphology of Sam Ford Fiord. We explain it by headward erosion. We also discuss headward erosion throughout the section.

285

**Comment 25:**

Line 103. Here an anomalous high number of refs are used supporting the point

290

**Response:**

Less relevant references were removed.

**Comment 26:**

295 Line 140. “flow” switching

**Response:**

Added flow.

300

**Comment 27:**

Line 141. “Evidence” feels too strong for me. It is an interpretation. There are alternatives.

**Response:**

305

Changed to: ... can be interpreted as the product of...

**Comment 28:**

310 Line 159. The description of the “feedback” reminds me of the Kessler et al. (2008) paper on Baffin fiord evolution, which seems to be a quite relevant reference that doesn’t appear in this manuscript

**Response:**

Kessler et al. (2008) paper was added throughout the text to support key concepts.

315 **Comment 29:**

*Line 166. "in" both*

**Response:**

Added *in*.

320

**Comment 30:**

*Line 170. The discussion here seems to imply that ice piracy can take place within a single glacial cycle. I think it occurs over longer timescales? So I might argue that "surge" and "readvance" are not relevant here.*

325

**Response:**

The erosion of the through is a long-term process, while the switch is a point in time where ice discharge change direction. So, during the glacial cycle when the switch occurred, the winning ice stream gains mass balance and thus can equilibrate by advancing its margins.

330

Changed to : *The merging of ice streams through ice piracy should result in an increase in ice discharge and erosion rates in the "winning" trough. The winning ice stream gains mass balance and thus should equilibrate by advancing its margins (if it is not already at the shelf break).* (lines 393-396)

335 **Comment 31:**

*Line 170. I think a new paragraph could be started at "Although. . ."*

**Response:**

A new paragraph was started at line 397.

340

**Comment 1:**

350 *The manuscript of Brouard and Lajeunesse introduces an interesting topic that certainly merits discussion. However, as already noted by the editor, the manuscript is written in a short format style and has not been adapted to the regular format that is usually used in TC. Submissions to short format / high impact journals is a game we all sometimes play but, just for one's own self-respect, it shouldn't be obvious to the readers which manuscripts were originally submitted to journals other than where they ended up published. 'Dumping' a manuscript to a more field-specific journal without any changes – 'here you have it, if XY don't want it' – is disrespectful to readers. In addition, it misses a chance to make the manuscript a better paper, in this case to explain properly what has been done and to discuss the work against all the relevant literature. I would therefore advise to redraft the text into a more rigorous manuscript format that would have the standard sections of methods, results, and discussion. The methods should explain what was done and why; at present they are just a brief list of the software used for the various steps of data manipulation.*

360 **Response:**

We apologize for the minimum changes that were made on the original manuscript. We did change the manuscript to a more standard structure (introduction, regional setting, methods, results, discussion, conclusions) and added details in all the sections to better support the interpretations. We added what was done and why in the methods section.

365

**Comment 2:**

370 *In addition to a couple of minor points that I list further below, I have two comments on the interpretation of the geomorphology and the inferences made about the ice piracy both at the researched location and elsewhere. The authors state that 'the erosion and the morphology of the troughs of northeastern Baffin Shelf is a function of a competition for ice drainage basins' – while I agree with that statement, I consider their explanation, which infers a propagation of an instability wave upstream from the ice margin, as too simplistic. This is because the ice sheet is portrayed as a static feature through time while in reality its configuration was changing through time between very different states. Some ice configurations, such as an elongated ice field / ice cap / mountain ice sheet along the axis of Baffin Island favoured a denser ice drainage network draining small catchments via small ice streams, while the growth of the Foxe Dome and drainage of its ice across the high relief coast of Baffin Island likely favoured smaller number of larger ice streams. The analogue with the fluvial system is thus too simplistic. But I agree that once the Hecla & Griper Trough got eroded to its present depth, it prevented any ice being drained in the direction of the SF Trough.*

380 **Response:**

385 We added a discussion on fiord/trough formation showing other studies that found headward (up-ice) erosion to be a main driver in the erosion of overdeepened basins (section 4.2). The headward erosion creates feedbacks favoring ice-channeling and ice-flow acceleration. Channelization in troughs in flat areas such as continental shelves is likely to result into a smaller number of ice streams alike on Baffin Island Shelf. The headward erosion is very similar to channelization in fluvial systems. We acknowledge that the

analogue of the fluvial system is probably too simplistic to explain every occurrence of marginal troughs on formerly glaciated shelves. However, we cannot rule out that the headward erosion is most likely to result into a system similar to fluvial captures. For those reasons we maintain the fluvial analogue but added ... *An ice-drainage piracy mechanism similar to river captures in fluvial systems can probably not explain the occurrence of all the other abandoned cross-shelf troughs on most high-latitude continental shelves that do not extend up-ice to the coast or to fiords, mainly because each have different geological, glaciological and climatic contexts. However, the presence of morphologically similar systems can be observed on many formerly glaciated shelves: e.g.,...(lines 347-350).*

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395 **Comment 3:**

*Ice streaming in the study area has been a subject of multiple studies (Briner et al., 2006, GSA B; De Angelis and Kleman, 2007, QSR; Briner et al., 2008, Geomorphology; Kessler et al., 2008, NG) and I find it unfortunate that none of these get any mention.*

400

**Response:**

We incorporated the reference suggested by the reviewers in the text to better support some interpretations.

**Comment 4:**

405 *The authors state that 'ice piracy through the switching of ice streaming most probably occurred early during Pliocene-Pleistocene glaciations' in the case of the studied pair of cross-shelf troughs. By analogue, the authors infer that at other locations where similar trough configuration is observed, it might also be stemming from ice piracy. However, it's been shown that some parts of the continental shelf adjacent to high relief coasts are composed largely of Quaternary sediments and have undergone a much more complex dynamics than ice piracy through a few tributary ice streams (e.g. Montelli et al., 2017, MPG). The authors should thus indicate more clearly how deep is the transition between the crystalline bedrock and the sedimentary strata on the shelf and what is the thickness of the unconsolidated Quaternary sediments to rule out a more complex evolution of the drainage network than portrayed in their study. This in turn applies also to their generalisation about other similar trough configurations where a caveat should be inserted that unless it's been proven that the layer of Quaternary deposits is shallow, the inferences based on geomorphology might be incomplete and the longer term evolution of the ice drainage network might be recorded in the sedimentary sequences of the continental shelf.*

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415

**Response:**

We added the thickness (< 100 m) of unconsolidated Quaternary sediments on the Baffin Shelf in Section 2. We added a caveat at the of the beginning (see response to comment 2) and at the end of the generalization to other glaciated continental shelves: *However, further investigations are needed to confirm that competition between ice stream played a role in the development of these trough systems.* (lines 359-360).

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**Comment 5:**

*Minor points: Line 18-19 two levels of parentheses not needed*

**Response:**

430 This was a citation software problem. We revised the manuscript in order to correct similar errors.

**Comment 6:**

*Line 79 grounding zone wedges have been mentioned in the text before but the abbreviation has not been introduced.*

435

**Response:**

We added the abbreviation at the first mention.

**Comment 7:**

440 *Line 110 Scott Ice Stream – check the spelling*

**Response:**

We revised the manuscript for any spelling errors.

445 **Comment 8:**

*Line 136 No need to capitalise ‘World’*

**Response:**

Changed to world.

450

**Comment 9:**

*TC figure content guidelines state: ‘Labels of panels must be included with brackets around letters being lower case (e.g. (a), (b), etc.).’ ‘Coordinates need a degree sign and a space when naming the direction (e.g. 30° N, 25° E).’ This has not been followed.*

455

**Response:**

We revised thoroughly all the figures so that they follow all of TC figure content guidelines.

**Comment 10:**

460 *I would advise to place a black frame around the map figures, which would also subdivide the individual figure panels. The frame should be the same thickness as the coordinate ticks, ideally 0.5 pt.*

**Response:**

Black frames and coordinate thicks are now all black and have all a thickness of 0.5 points.

465

**Comment 11:**

*Fig. 2 The grounding zone wedge is supposed to be marked in red in panel A but I cannot see that. The location of the seismic profile, drawn in Fig. 1, should be noted in the Fig. 2 caption.*

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**Response:**

Red was removed.

**Comment 12:**

475 *Move the letter A in panel A of Figure 4 somewhere out of the inset location panel. I suggest drawing the schemes of piracy on the shown DEMs in Figure 4. That would help the reader to see the examples you note in the text. Okoa Bay not Okao Bay in Fig. 4C*

**Response:**

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The letter was moved outside of the inset location. We draw white arrows showing the assumed ice stream tracks. Okoa Bay has been corrected.

# 485 **Ice-stream flow switching by up-ice propagation of instabilities along glacial marginal troughs**

Etienne Brouard<sup>1\*</sup> & Patrick Lajeunesse<sup>1</sup>

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490 Correspondence to: Etienne Brouard (etienne.brouard.1@ulaval.ca)

**Abstract.** Ice stream networks constitute the arteries of ice sheets through which large volumes of glacial ice are rapidly delivered from the continent to the ocean. Modifications in ice stream networks have a major impact on ice sheets mass balance and global sea level. Reorganizations in the drainage network of ice streams have been reported in both modern and palaeo-ice sheets and usually result in ice streams switching their trajectory and/or shutting down. While some hypotheses for the reorganization of ice streams have been proposed, the mechanisms that control the switching of ice streams remain poorly understood and documented. Here, we interpret a flow switch in an ice stream system that occurred during the Pliocene-Pleistocene on the northeastern Baffin Island shelf (Arctic Canada) through glacial erosion of a marginal trough, i.e., deep parallel-to-coast bedrock moats located up-ice of cross-shelf troughs. Shelf geomorphology imaged by high-resolution swath bathymetry and seismostratigraphic data in the area points to the extension of ice streams from Scott and Hecla & Griper troughs towards the interior of the Laurentide Ice Sheet. Up-ice propagation of ice streams through a marginal trough is interpreted to have led to the piracy of the neighboring ice catchment that in turn induced an adjacent ice stream flow switch and shutdown. These results suggest that competition for ice discharge between ice streams, which implies piracy of ice-drainage basins via marginal troughs, was the driving mechanism behind ice flow-switching in the study area. In turn, the union of ice catchment by piracy increased the volume and discharge of Scott Ice Stream, allowing it to erode deeper and flow farther on the continental shelf. Similar trough systems observed on many other glaciated continental shelves may be the product of such a competition for ice discharge between catchments.

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## **1 Introduction**

Ice flow switching was first invoked to explain the recent stagnation of the Kamb Ice Stream—previously known as Ice Stream C—in West Antarctica Ice Sheet (Conway et al., 2002). Following this discovery, episodes of ice stream switching were also inferred to have occurred throughout the Pleistocene and in various palaeo-ice sheet settings (e.g., Dowdeswell et al., 2006; Vaughan et al., 2008; Winsborrow et al., 2012). Several driving mechanisms were proposed to explain the switching of ice streams: i) sediment accumulation causing a topographical change downstream (Dowdeswell et al., 2006); ii) local variations in bathymetry coupled with relative sea-level change (Stokes et al., 2009); iii) spatial and temporal variations in basal thermal regime (Ó Cofaigh et al., 2010); iv) presence of sticky spots, subglacial meltwater rerouting and ice thickness variations (Alley

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515 et al., 1994; Anandakrishnan et al., 2001; Anandakrishnan and Alley, 1997); v) competition for ice discharge and drainage  
basins (Greenwood and Clark, 2009; Payne and Dongelmans, 1997); and vi) topographic focusing (Sarkar et al., 2011; Storrar  
et al., 2017). The wide range of possible driving mechanisms outlines the fact that ice stream switching is a complex process  
that requires further assessment in order to model accurately the future behavior of modern ice sheets. Empirical data from the  
palaeo-ice sheet record is therefore needed to better constrain the mechanism of flow-switching. Networks of glacial troughs  
520 on continental shelves may offer such insights for identifying and understanding the flow-switching mechanism as they were  
overdeepened by past ice streams. These networks generally consist of cross-shelf troughs often interconnected up-ice to  
marginal troughs (Anderson, 1999; Batchelor and Dowdeswell, 2014; Nielsen et al., 2005). While cross-shelf troughs are  
broadly aligned with fiords, marginal troughs are aligned parallel-to-coast. Marginal troughs are generally located along the  
boundary between harder crystalline bedrock in the inner portion of the shelf and softer sedimentary rocks in the offshore  
525 portion of the shelf (Nielsen et al., 2005). They have been inferred to result from glacial erosion because they represent an up-  
ice extension of glacially eroded cross-shelf troughs (Nielsen et al., 2005), but no mechanism has been proposed to explain  
their formation. Here, high-resolution swath bathymetry imagery combined with archived seismic reflection data and  
International Bathymetric Chart of the Arctic Ocean bathymetric data (IBCAO; Jakobsson et al., 2012) are used to analyze  
the morphology and stratigraphy of a single glacial trough network on the northeastern Baffin Shelf, in Eastern Arctic Canada.  
530 These data suggest that past ice stream switching occurred due to the ice-discharge piracy from an ice stream in a deep cross-  
shelf trough (Scott Trough) via the lateral extension of a marginal trough (Hecla and Griper Trough), which led to the shutdown  
of the ice stream occupying the neighboring cross-shelf trough (Sam Ford Trough).

## 2 Regional setting and Glacial History

The analyzed troughs are located on the northeastern Baffin Island Shelf in Western Baffin Bay, Eastern Arctic Canada. The  
535 trough system is characterized by two cross-shelf troughs—Scott and Sam Ford—interconnected by one marginal trough:  
Hecla & Griper Trough (Fig. 1). Scott and Sam Ford troughs are aligned with the major fiords of northeastern Baffin Island:  
Scott Trough extends northeast from the mouth of Clark and Gibbs fiord while Sam Ford Trough extends northeast from Sam  
Ford and Eglinton fiords (Fig. 1). These four fiords were eroded in Precambrian crystalline bedrock that extends eastward  
under the sedimentary bedrock strata. Precambrian basement is characterized under the shelf by half-grabens and grabens  
540 associated with rifting and spreading in Baffin Bay (Hosseinpour et al., 2013; Oakey and Chalmers, 2012). Post-rifting  
Cretaceous and Paleocene sedimentary rock strata overlay Precambrian bedrock on most of the shelf (Fig. 1) and are overlain  
by a relatively thin (<100 m) cover of unconsolidated Quaternary deposits (MacLean et al., 2014; Praeg et al., 2007). Previous  
studies have proposed that the cross-shelf troughs of Western Baffin Bay have a fluvial origin linked to a pre-Quaternary sea-  
level lowstand (Fortier and Morley, 1956; Pelletier, 1964) much like the troughs of the Labrador Shelf (Josehans and  
545 Zevenhuizen, 1987). However, most of the erosion associated with the overdeepening—reaching up to 350–450 m in Scott  
Trough—may be attributed to subsequent glacial erosion (Løken and Hodgson, 1971). The erosion of the troughs is



intrinsically linked to the erosion of the deep fiords of northeastern Baffin Island, which modeling suggests were eroded to present-day depths in ~1 Myr (Kessler et al., 2008). The glacial overdeepening of the troughs probably began during the late Pliocene (~3.5 Ma; Srivastava et al., 1987) and all traces of preglacial fluvial systems were erased during the Pleistocene (Løken and Hodgson, 1971).

Not much is known on pre-Late Wisconsinan ice streams flowing through Baffin Island into Baffin Bay. To produce well-developed fiords, the position of these ice stream was probably stable throughout most of the Pleistocene, i.e., through few fiords and converging into fewer cross-shelf troughs. Glacial advances—and ice streams—of marine isotope stages (MIS) 5d/b and MIS4 were probably less extensive than during MIS2 (Ganopolski et al., 2010; Simon et al., 2014; Stokes et al., 2012); therefore, ice streams may not have reached the shelf edge between ~130 ka and 25 ka BP. The last glacial stage (MIS2) reached its maximum around 25 cal. ka BP in Western Baffin Bay, with the LIS reaching the shelf edge between Lancaster Sound and Home Bay (Fig. 1; Jenner et al., 2018). During the MIS2 (25 – 16 cal. ka BP), Scott and Hecla & Griper troughs were inundated by ice streams of the LIS (De Angelis and Kleman, 2007; Briner et al., 2006b; Brouard and Lajeunesse, 2017; Margold et al., 2015a) that extended to reach the shelf break at the mouth of the troughs, while Sam Ford Trough was under slow-flowing ice (Brouard and Lajeunesse, 2017).

Laurentide ice occupied most of the shelf until 14.1 cal. ka BP and deglaciation of the continental shelf was completed by ~15 – 12 cal. ka BP as coastal forelands emerged from the glacial ice cover (Briner et al., 2005, 2006a) and LIS outlets retreated to the fiord mouths after 14 ka cal BP (Brouard and Lajeunesse, 2017, 2019; Jenner et al., 2018). Paraglacial and postglacial sedimentation has been prevailing in the troughs from at least ~12 cal. ka BP and probably up to 14 cal. ka BP, which marks a minimum age for presence of outlets at the fiord mouths (Jenner et al., 2018; Osterman and Nelson, 1989; Praeg et al., 2007). Outlet glaciers of the LIS occupied the entire fiords until ~11.4 cal ka BP (Dyke, 2004) before rapidly retreating inland towards the fiord heads (Briner et al., 2009). Finally, glacial scouring observed inland of fiord heads indicates that (i) fast flowing ice streams may have extended inland of fiord heads and (ii) the fiords were efficient conduits for ice flow and erosion through the coastal mountain range of Baffin Island (Briner et al., 2008).

## 570 **2 Methods**

Swath bathymetric data collected using Kongsberg Simrad EM-300 (12 kHz) and EM-302 (30 kHz) multibeam echosounders onboard the CCGS Amundsen by the Ocean Mapping Group (University of New Brunswick) and the Laboratoire de Géosciences Marines (Université Laval) during 2003–2016 ArcticNet Expedition were used to analyze the seafloor of the Scott-Sam Ford trough system. The specifics of acquisition for each expedition can be obtained from Géoindex+ (geoindex-plus.bibl.ulaval.ca) and Ocean Mapping Group websites (omg.unb.ca/Projects/Arctic/ArcticMetadata.html). The multibeam bathymetry data were processed using Caris Hips & Sips and merged using the MB-System software, in order to provide a bathymetric surface at a 10 m-grid resolution for interpretation and analyses. The 10-m gridded surface was plotted over the International Bathymetric Chart of the Arctic Ocean data (Jakobsson et al., 2012) to provide a complete, but lower resolution,

coverage of the seafloor in between multibeam tracks. The complete surface was transferred in ESRI ArcMap 10.2 software  
580 geomorphological mapping and topographic analyses. Individual landforms were digitalized on the surface in ArcMap 10.2  
and interpreted based on their apparent character (width, length, orientation, etc.) and on recent literature (e.g., Dowdeswell et  
al., 2016b). The interpretation of landform types is detailed in the results section.

We interpreted seismic reflection data from the Marine Data Holding public repository of National Resources Canada  
(Geogratis.gc.ca) in order to provide a subsurface view of the architecture of the shelf. Seismic reflection data were analyzed  
585 and extracted using the LizardTech GeoViewer software. Seismic reflection data were enhanced using the Brightness/Contrast  
tool in Adobe Photoshop CS5 for a clearer visualization. Maps and seismic reflection data were transferred to the Adobe  
Illustrator 2018 CC software for figure production and editing. BEDMAP2 data was used for analyzing Antarctica, in search  
of morphologically similar trough pattern systems and for map production (Fretwell et al., 2013).

### **3 Results**

#### **590 3.1 Troughs morphology**

##### **3.1.1. Scott Trough**

Scott Trough is 62 km long, 12 km wide and 850 m deep. A longitudinal profile across the trough shows that it has a general  
trend of depths increasing from the shelf edge (~720 m) to the fiord sills (~900 m), forming a typical glacial overdeepening  
(Figs. 2–3). The trough is also characterized by a Precambrian bedrock sill that forms two bathymetric highs (~488 m) at about  
595 15 km from the seaward extent of the trough (Figs. 1–2). The overdeepened basin between the Precambrian bedrock highs and  
the fiord sill is therefore overdeepened by at least ~360 m, when sediments are not considered. Sediment accumulations over  
bedrock in Scott Trough are thin, generally <10 m except for small patches in longitudinal basins showing up to 70 m of  
hemipelagic sediments, turbidites and mass failure deposits (Fig. 3). The sediments in Scott Trough basins were interpreted as  
relict (prior to the last glaciation, i.e., pre-Late Wisconsinan) deposits that have been preserved from glacial erosion (Praeg et  
600 al., 2007); alternatively, they could result also from ice-proximal sedimentation of an ice margin anchored at the fiord mouths,  
similar to deposits observed in Sam Ford Fiord (Brouard and Lajeunesse, 2019). The sediments in Scott Trough are mostly  
confined within longitudinal depressions that have up to ~130 m relief to bedrock (Fig. 3). The longitudinal depressions show  
erosional surfaces that indicate that they are not of structural origin. Airgun profiles on the ridges in-between the depressions  
show that although their upper portion consists of an unconsolidated unit, the basement is marked by strong reflections and  
605 hyperbola that are typical of bedrock. The overdeepening in Scott Trough is divided into 4 longitudinal basins separated by 3  
bedrock and sediment ridges (Fig. 3). The 2 western basins are aligned with Clark and Gibbs fiords while the 2 eastern basins  
are prolonged into Hecla & Griper Trough. Scott Trough is bounded by steep sidewalls, longitudinal bathymetric highs (Fig.  
4) and, at its seaward end, by a fan-shaped bathymetric bulge interpreted as a trough-mouth fan (Fig. 1; Brouard and  
Lajeunesse, 2017). The transition from the fiords to Scott Trough is marked a steep wall and a drop of >450 m (Figs. 1–2).

610 The transition from the fiords to the trough marks also the transition from the Precambrian crystalline basement to Sedimentary  
(Cretaceous and younger) bedrock (Fig. 1; Praeg et al., 2007).

### 3.1.2. Hecla & Griper Trough

Hecla & Griper Trough is 27 km long, 9 km wide and 780 deep. A longitudinal profile through the trough shows that it has a  
general trend of depths decreasing from the junction with Scott Trough (~840 m) to Sam Ford Fiord sill (~450 m; Fig.  
615 1). Hecla & Griper Trough is bounded on its southwest side by a steep wall of Precambrian crystalline bedrock (Figs. 1). The  
northeastern wall is less steep than the western wall and consists of sedimentary rock. The crystalline-sedimentary contact is  
not apparent on airgun data but, however, sedimentary structures and layers (parallel inclined reflectors) are apparent below  
sediments forming the seafloor of Hecla & Griper Trough, indicating that most of the rock underlying the trough is sedimentary  
(Fig. 5). Hecla & Griper Trough can be divided into 2 longitudinal basins separated by a ridge that extends into Scott Trough.  
620 This latter ridge is composed of sediments without any bedrock ridge underneath, implying less geologic control over the  
development and position of the ridge, and is interpreted as a medial moraine (Fig. 5). Other similar ridges occur in Hecla &  
Griper Trough but are carved in sedimentary bedrock. The transition between Hecla & Griper Trough and Sam Ford Fiord is  
marked by a 12 km large and 350–400 m deep plateau to the southwest, by bedrock shoals to the northeast and a 1.5 km-wide  
depression in-between (Fig. 1).

### 625 3.1.3. Sam Ford Trough

Sam Ford Trough is 77 km long, 13 km wide, and 370 m deep. Similarly to Scott Trough, the bathymetric profile through Sam  
Ford Trough shows generally increasing depths landward, but only from the middle shelf. However, the middle shelf  
bathymetric high in Sam Ford Troughs is not of bedrock origin, but coincides with an accumulation of glacial sediments  
constructed during the stabilization of an ice margin (Fig. 6; Praeg et al., 2007). The bedrock excavation of Sam Ford Trough  
630 exceeds by at least 75 m modern water depths for most of its length and is overdeepened by about 200 m landward. The  
accumulation of glacial sediments appears on the swath bathymetry imagery as 3 distinct lobes with one broadly aligned  
parallel to the trough. Sam Ford Trough is bounded laterally by longitudinal ridges that extend from Sam Ford Fiord sill up to  
the shelf break (Figs. 1–7). The sill at the mouth of Sam Ford Fiord marks the transition where the fiord becomes the trough.  
This sill is characterized by a >470 m depression to the south (Fig. 1) and plateau to the north. The southern depression extends  
635 to form Sam Ford Trough. The plateau on the northern part of the sill is mainly characterized by crystalline bedrock ridges  
and flat sediment-filled basins.

## 3.2 Ice-flow landforms

### 3.2.1. Crag-and-tails

Crag-and-tails are flow-oriented positive landforms with an identifiable bedrock “crag” at the head and a drift tail (Evans and  
640 Hansom, 1996). A total of 202 crag-and-tails occur within the trough system and on Sam Ford Fiord sill (Fig. 7). The crag-  
and-tails have lengths ranging between 98 m and 5935 m with a mean length of ~1071 m. They occur between 254 m and 836  
m depths and most of them are located seaward of fiord sills and seaward of bedrock highs in Scott Trough (Bennett et al.,  
2014). Crag-and-tails have been widely used in paleoglaciological reconstructions as indicators of ice-flow orientation (e.g.,  
(Brouard et al., 2016; Brouard and Lajeunesse, 2017; Hogan et al., 2010; Jansson et al., 2003; Kleman et al., 2007). In  
645 association with mega-scale glacial lineations, drumlins and grooves, the presence of crag-and-tails generally indicates fast  
ice-flow conditions, i.e., ice streaming. Overdeepened curvilinear depressions (crescentic scours) occur in some cases upstream  
of crag-and-tails (Fig. 8). The presence of crescentic scours in front of crag-and-tails probably indicates the presence of  
meltwater (Graham et al., 2009; Graham and Hogan, 2016).

### 3.2.2. Drumlins

650 Drumlins are smooth, asymmetric, oval-shaped hills (positive landforms) with a steeper stoss side and a more gentle-sloping  
lee side (Clark et al., 2009). These landforms occur at depths ranging from 179 m to 755 m. The 486 mapped drumlins have  
length ranging between 78 m and 1856 m with a mean of ~ 357 m, and are mostly located on the sills of the fiords (Fig. 7).  
Drumlins have a long axis oriented parallel to ice flow and occur in clusters and in association with glacial lineations, crag-  
and-tails, whalebacks and meltwater channels. Grouped into flow sets, drumlins can reveal palaeo-ice-flow orientation.  
655 Patterns of elongation and convergence of drumlins (together with other ice-flow landforms such as mega-scale glacial  
lineations and crag-and-tails) can be used as a relative indicator of ice-flow velocity and can therefore be used to identify ice-  
stream tracks (Stokes and Clark, 2002a). Drumlins are formed under wet-bed glaciers (King et al., 2007) and occur in  
association with meltwater-related landforms such as meltwater channels or crescentic scours (Fig. 8). Overdeepened  
curvilinear depressions (crescentic scours) are in some cases present upstream of drumlins (Fig. 8).

### 660 3.2.3. Glacial lineations or mega-scale glacial lineations (MSGL)

Glacial lineations are highly elongated (apparent elongation ratio 1: 10) parallel ridges (positive landform) formed in glaciogenic  
sediments (Clark, 1993). Most glacial lineations are observed in Scott and Hecla & Griper Trough (Fig. 7) where they have  
lengths ranging from 156 m to 8664 m with a mean of ~1026. Glacial lineations occur in the troughs at depths between 218  
m and 840 m. They are generally oriented parallel to the troughs. Usually observed in sets, these landforms have a soft and  
665 mostly regular texture that likely reflects a sedimentary character (Ó Cofaigh et al., 2005, 2013). In some cases, ridges have a  
rougher texture that may imply a bedrock character or very thin sediment cover. MSGLs are indicators of fast ice flow  
suggesting palaeo-ice stream activity (Clark, 1993; Stokes and Clark, 2002a). Accordingly, they also indicate ice-flow

orientation. Cross-cut by grounding-zone wedges, mega-scale glacial lineations are interpreted to reflect time-transgressive ice flows occurring during the landward retreat of an ice stream (Brouard and Lajeunesse, 2017; Dowdeswell et al., 2008).

#### 670 **3.2.4. Grooves**

Grooves are linear to curvilinear negative landforms observed both in sediments and in bedrock. Grooves usually occur in association and aligned with mega-scale glacial lineations, crag-and-tails and drumlins. Alike the lineations, the grooves were mostly mapped in Scott and Hecla & Griper troughs (Fig. 7). The 465 mapped grooves have lengths ranging between 84 m and 5882 m, with a mean of 944 m. They occur at depths between 127 m and 838 m. Produced by keels beneath glacial ice eroding the underlying substrate, grooves record palaeo-ice flow direction (Graham et al., 2009; Livingstone et al., 2012). Their presence alongside MSGs under present-day ice streams suggests that they are the product of fast ice flow, i.e., an ice stream (Jezek et al., 2011; King et al., 2009).

#### **3.2.5. Ice stream lateral moraines (ISLMs)**

Ice stream lateral moraines are curvilinear ridges (positive landform) observed on the sides of cross-shelf troughs. Ice stream lateral moraines are characterized by a gentle slope on their trough side and a steeper shelf side (Batchelor and Dowdeswell, 2016). Ice-stream lateral moraines are present on both sides of cross shelf troughs, but are not observed on the sides of Hecla & Griper Trough, probably because of the lack of decent data (Figs. 1–7). ISLMs in the study area are up to 61 km-long and 8 km wide. Ice-stream lateral moraines are believed to be formed subglacially at the shear zone between fast-flowing ice and slower-flowing ice or ice-free terrain (Batchelor and Dowdeswell, 2016). They can therefore be used to delineate the lateral extent of an ice stream (Brouard and Lajeunesse, 2017; Margold et al., 2015b; Stokes and Clark, 2002b).

#### **3.2.6. Meltwater channels**

On swath bathymetry imagery, meltwater channels take the shape of sinuous longitudinal depressions (negative landform) that are generally carved in bedrock (Lowe and Anderson, 2003; Nitsche et al., 2013; Slabon et al., 2018). The 235 mapped meltwater channels occur at depths ranging between 202 m and 718 m (Fig. 7). Their length varies from 126 m to 4.1 km. Some channels are characterized by a flat bottom that indicates sediment infill (Brouard and Lajeunesse, 2019; Smith et al., 2009). They form anastomosing networks often extending in-between ice-flow landforms (MSGs, drumlins, crag-and-tails). The presence of these channels indicates abundant meltwater that could favor ice-bed decoupling, enable basal sliding, and generate ice streaming (Anandkrishnan and Alley, 1997; Engelhardt et al., 1990; Lowe and Anderson, 2003; Reinardy et al., 2011).

#### 695 **3.2.7. Subglacial medial moraines**

Subglacial medial moraines are large curvilinear sediment ridges (positive landform) with a smooth character and are ice flow oriented. On swath bathymetry imagery, they can be overprinted by iceberg ploughmarks, MSGs and grooves. Subglacial

medial moraines are thought to be formed subglacially under constraints created by coalescing glaciers (Dowdeswell et al., 2016a). They therefore reflect the downstream movement of ice and act as indicators of ice-flow direction. Subglacial medial moraines were first identified in Scott Trough (Fig. 7; Dowdeswell et al., 2016a). Subglacial medial moraines were mapped in Scott and Hecla & Griper troughs (Fig. 7), where they reach up to 55.5 km in lengths.

### 3.2.7. Whalebacks

Whalebacks are rough, asymmetric and oval-shaped hills (positive landforms) with a steeper stoss side and a more gentle-sloping lee side (Evans and Hansom, 1996; Roberts and Long, 2005). A total 321 whalebacks were identified. They occur at depths between 170 m and 700 m and have lengths varying between 61 m and 1044 m. The whalebacks have a flow-oriented long axis and are generally observed in clusters. In the study area, they occur in association with glacial lineations, crag-and-tails, drumlins and meltwater (Fig. 7). The whalebacks, grouped into flow-sets can be used to reveal palaeo-ice-flow direction (Krabbendam et al., 2016). Eroded into bedrock they can result of multiple glacial erosion cycles and therefore record multiple ice flows. Alike for drumlins and crag-and-tails, overdeepened curvilinear depressions (crescentic scours) can also be present upstream of some whalebacks.

### 3.3 Grounding-zone wedges

Grounding-zone wedges (GZW) are asymmetric tabular bathymetric wedges (positive landform) that are perpendicularly aligned to trough or fiord orientation. GZW are characterized on swath bathymetry imagery by an extensive stoss side with low gradients and a steeper and narrower lee side. Grounding-zone wedges occur in Scott (n=4) and Sam Ford troughs (n=3), forming bathymetric mounts (Figs. 1–7). GZW are formed by the accumulation of subglacial sediments at the grounding zone of an ice stream during temporary standstills of an ice margin (Dowdeswell and Fugelli, 2012; Lajeunesse et al., 2018). They have also been associated with the presence of ice shelves (Dowdeswell and Fugelli, 2012). The presence of an ice-shelf is believed to restrict vertical accommodation space for sediments in favor of sediment progradation, which explains the low-amplitude and horizontally extensive (up to 139 km<sup>2</sup>) character of GZWs.

## 4 Discussion

### 4.1 Ice stream tracks

In Scott Trough, the presence of mega-scale glacial lineations (MSGs) extending to the shelf break, together with a till unit extending on the trough-mouth fan and glacial debris flows on the shelf edge, indicate that the Laurentide Ice Sheet (LIS) reached the shelf break during the Last Glacial Maximum (LGM; Brouard and Lajeunesse, 2017; Jenner et al., 2018). MSGs, crag-and-tails and drumlins mapped in this region indicate that during the LGM, a tributary ice stream of the Scott Ice Stream extended from Sam Ford Fiord to Scott Trough through Hecla & Griper Trough (Brouard and Lajeunesse, 2017). Accordingly, the medial moraine ridges are interpreted to be the product of differential ice-stream erosion. In a same way, coalescence of

multiple ice streams probably favored the formation of subglacial medial moraines over the ridges (Dowdeswell et al., 2016a). While the glacial origin of Scott Trough is obvious from its overdeepening and numerous ice-flow landforms, the glacial origin of Sam Ford Trough is confirmed by the presence of (1) ice stream lateral moraines and (2) grounding-zone wedges in the trough and a small overdeepened basin on Sam Ford Fiord sill (Figs. 1-6-7-8). However, the absence of ice-flow landforms in Sam Ford Trough suggests that the trough was occupied by slow-flow ice during the last glacial episode. The slow ice flow contrasts with a recent glacial reconstruction stating that in full glacial conditions, Sam Ford and Scott troughs were characterized by separate ice streams that drained approximately comparable areas from the LIS (Batchelor and Dowdeswell, 2014). The presence of ISLMs on the sides of Sam Ford Trough together with an overdeepened basin and a 75 m-thick GZW (Figs. 6-7) in the trough also indicate that an ice stream originating from Sam Ford Fiord has also been, at some point, efficient enough to excavate the trough and to flush enough subglacial sediment to construct the multiple GZWs. However, the ice streams in Sam Ford Trough were not efficient enough to build a trough-mouth fan at the seaward end of the trough. The general thickness of paraglacial and postglacial sediments (~40 m) in Sam Ford Trough also suggests that the GZWs are older than the last glaciation (i.e., pre-Late Wisconsinan) and confirms the occurrence of slow-flowing and less erosive ice in Sam Ford Trough during the last glaciation. In comparison, paraglacial-postglacial sediments in Scott Trough, outside of the basins, never exceed 10 m in thickness.

Glacial bedforms on the sill of Sam Ford Fiord indicate that an ice stream flowed from Sam Ford Fiord through Hecla & Griper Trough. Although Hecla & Griper Trough has a structural origin since it was eroded along the crystalline-sedimentary contact, glacial lineations, crag-and-tails and grooves within the trough and on the sill of Sam Ford Fiord indicate that it was eroded by an ice stream (Brouard and Lajeunesse, 2017). The bathymetric profile in Hecla & Griper Trough (Fig. 2) showing depths increasing towards Scott Trough implies that ice-stream erosion was the most effective at the junction between Hecla & Griper and Scott troughs.

#### **4.2 Erosion of Hecla & Griper Trough**

Erosion of fiords, troughs and bedrock basin overdeepenings has been proved to be a function of topography, ice discharge, subglacial hydrology, basal thermal regime, basal ice debris and glacier size (Cook and Swift, 2012; Kessler et al., 2008; Ugelvig et al., 2018). Overall, higher velocities together with thicker ice will generate more basal melt and will accelerate basal sliding and sediment flushing (e.g., Cook and Swift, 2012; Jamieson et al., 2008). Kessler et al. (2008) also demonstrated that topographic steering along was sufficient to produce overdeepened fiords and troughs. Analyses of bedrock basins of Antarctica and Greenland also indicated a similar erosion process where ice-flow confinement leads to deeper overdeepenings (Patton et al., 2016). This suggests that if an ice stream—and the associated erosive power—originated from Sam Ford Fiord, it should be expected that at equivalent ice velocity Hecla & Griper Trough would be the deepest at its narrowest section, i.e., in-between the shoals and the shelf. However, Hecla & Griper Trough is the deepest at its widest, i.e., at its junction with Scott Trough. The erosion of Hecla & Griper Trough was therefore more dependent on down-ice dynamics occurring in Scott Trough rather than up-ice in Sam Ford Fiord. The down-ice dependence of Hecla & Griper Trough erosion is in agreement with an

inferred strong relationship in the development of interconnected marginal troughs and cross-shelf troughs (Nielsen et al., 2005). Coincident with the contact between crystalline and sedimentary bedrock, Hecla & Griper Trough is therefore interpreted to result from a tributary ice stream of Scott Ice Stream eroding sedimentary bedrock along a weakness line, resulting in a morphology that is similar to other marginal troughs (Anderson, 1999; Nielsen et al., 2005). The down-ice dependence of erosion in Hecla & Griper also indicates that most effective erosion occurred in an up-ice direction. Similarly, analyses of overdeepenings in Antarctica and Greenland showed that below sea-level, most of the erosion of overdeepening occurs by headward erosion (Patton et al., 2016). Upstream propagation of high velocities—and erosional power—in ice streams is mainly dependent of instabilities at the ice margin or at the grounding zone; i.e., an acceleration of ice flow can propagate up-ice the main trunk of the ice stream and up-ice in the tributary ice streams (De Angelis and Skvarca, 2003; Hughes, 1992; Kleman and Applegate, 2014; Payne et al., 2004; Retzlaff and Bentley, 1993). Such up-ice progression of an ice stream can create a positive ice-erosion feedback, in which erosion of the overdeepening causes the headwall to steepen and therefore further enhances sliding velocity and erosional power up-ice the ice stream (Herman et al., 2011). Therefore, Hecla & Griper Trough as a host to a tributary ice stream can have facilitated upstream propagation of ice streaming up to Sam Ford Fiord sill, forming a mature marginal trough.

#### 775 **4.3 Ice stream switching**

The presence of ice-flow landforms on Sam Ford Fiord Sill that are oriented towards Hecla & Griper Trough implies that ice discharge through Sam Ford Fiord was not oriented towards Sam Ford Trough. Sam Ford Trough is, however, interpreted as the product of an ice stream mainly originating from Sam Ford Fiord and in a minor way from Eglington Fiord (Margold et al., 2015a). Eglington fiord is interpreted as a minor contributor to Sam Ford Ice Stream because of the presence of a GZW (medial subglacial moraine?) attached to the junction between the fiords and clearly indicating that most of the ice discharge came from Sam Ford Fiord (Fig. 7). A possible scenario for the occurrence of landforms associated with an ice stream flowing from Sam Ford Fiord to both Scott and Sam Ford troughs would be that ice flow from Sam Ford Fiord was partitioned between Scott and Sam Ford troughs. Recent research suggests that if Sam Ford and Scott troughs were both occupied by comparable ice streams during full glacial conditions, they would have had similar drainage areas (Batchelor and Dowdeswell, 2014), similar width and therefore similar ice discharge (Stokes et al., 2016). The medial moraines in Scott Trough indicate that half of the ice that eroded the trough came from Sam Ford Fiord. Therefore, ice from Sam Ford Fiord would be responsible for about half of Scott Trough excavation, while also being responsible for the excavation of Sam Ford Trough. Accordingly, ice discharge through Sam Ford Fiord would need to have been twice the ice discharge of combined neighbouring Clark and Gibbs fiords. However, a 2:1 ratio of Sam Ford ice discharge over and Scott ice discharge is not compatible with estimates of paleo-ice discharge (1.04:1) and drainage area (1:1) that can be derived from recent models (Batchelor and Dowdeswell, 2014; Stokes et al., 2016). Another possible scenario that could explain the occurrence of landforms related to an ice stream flowing from Sam Ford Fiord to both troughs would be that Sam Ford Fiord ice discharge has always been directed towards Hecla & Griper Trough and that Sam Ford Fiord is the product of most extensive glaciations. During most extensive glaciations, a part of Sam



Ford Fiord ice discharge could be spilled towards Sam Ford Trough to form a shallower trough. This is unlikely to be the case because the last glaciation (MIS-2) was the most extensive glaciation in North America since MIS-6 (<130 ka BP; Ganopolski et al., 2010; Simon et al., 2014; Stokes et al., 2012) and one of the most extensive throughout the Pleistocene (Ehlers and Gibbard, 2003); yet there is no evidence for an ice stream in Sam Ford Trough during the last glacial episode. Also, if ice discharge from Sam Ford Fiord has always been directed towards Hecla & Griper Trough, it is expected that ice would erode, by topographic steering, an overdeepening at the narrowest section of Hecla & Griper Trough (See section 4.2). However, it is possible that a small part of Sam Ford ice discharge could have been advected towards Hecla & Griper Trough from its very beginning and facilitated ice piracy by promoting the up-ice propagation of high velocities into an already fast-flowing ice system.

Therefore, partitioned ice discharge from Sam Ford Fiord in both troughs is possible but it cannot account for the trough morphology and for the full-scale erosion of both Sam Ford and Scott troughs. It is easier to propose a mechanism where ice from Sam Ford Fiord switched from one trough to the other. Sam Ford Ice Stream would have first eroded Sam Ford Trough and then switched orientation to flow through Hecla & Griper Trough. Following this ice flow-switching, the erosion in Sam Ford Trough ceased while the erosion in Scott Trough was enhanced by increased ice discharge; the difference in erosion volume between Sam Ford and Scott troughs can thus be explained by this mechanism.

As mentioned earlier, several mechanisms have been proposed to explain the switching behavior of an ice stream. Here we propose a mechanism that incorporates some of these mechanisms but where the flow switch of Sam Ford ice stream is due long-term erosion of up-ice propagating ice streams (i.e., Scott Ice Stream). Ice streams propagating upstream and eroding Hecla & Griper Trough have eventually eroded the marginal trough up to a point where it extended up-ice to reach the Sam Ford Fiord mouth. The changes in fiord depth-to-bedrock resulting from the erosion of the marginal trough and associated with the upstream propagation of Scott Ice Stream in Sam Ford system led to the: 1) reorganization of the ice drainage system; 2) switching of Sam Ford Ice Stream from Sam Ford Trough to Scott Trough; and ultimately, 3) shutdown Sam Ford Ice Stream in Sam Ford Trough (Alley et al., 1994; Anandakrishnan and Alley, 1997; Graham et al., 2010) (Alley et al., 1994; Anandakrishnan and Alley, 1997; Graham et al., 2010). Such ice piracy through the switching of ice streaming most probably occurred early during Pliocene-Pleistocene glaciations; it could explain the absence of a trough-mouth fan at the seaward end of Sam Ford Trough and also why Sam Ford Trough is more than two-times shallower than Scott Trough. It is probable that ice streaming in Sam Ford Trough only occurred during a short period at the beginning of early (Late-Pliocene—Early Quaternary?) glaciations, before its ice discharge was captured by the Scott Ice Stream. As this process repeated itself throughout glacial cycles, it accentuated the depth of Hecla & Griper Trough, which in turn facilitated the capture of Sam Ford Ice Stream by Scott Ice Stream during subsequent glaciations. The changes in depth-to-bedrock associated with the upstream propagation of Scott Ice Stream in Hecla & Griper also led to a point in time when the Sam Ford Fiord ice discharge switched to be topographically diverted towards Hecla & Griper (i.e., the 1.5 km-wide depression). From that point on, ice-streaming conditions were unlikely to occur in Sam Ford Trough. Taken together, these observations suggest that the erosion and the morphology of the troughs of northeastern Baffin Shelf is a function of a competition for ice drainage basins. This process

shares striking similarities with fluvial drainage-basin reorganizations linked to river captures (Bishop, 1995): where in the northeastern Baffin Island case, a dry valley (Sam Ford Trough) with fluvial deposits (here glacial, i.e., the GZW) and a knickpoint (the 1.5 km-wide depression at the head of Hecla & Griper Trough).

An ice-drainage piracy mechanism similar to river captures in fluvial systems can probably not explain the occurrence of all the other abandoned cross-shelf troughs that do not extend up-ice to the coast or to fiords, mainly because each have different geological, glaciological and climatic contexts. However, the presence of morphologically similar systems can be observed on many formerly glaciated continental shelves: e.g., small troughs along the Antarctic Peninsula (Fig. 9a) and Pennell Trough on West Antarctica Shelf; Unnamed Trough on Disko Bank on West Greenland Shelf (Fig. 9b); Okoa Bay on the Baffin Shelf (Fig. 9c); small cross-shelf troughs off the coast of Labrador and Newfoundland (Canada; Fig. 9d); or Angmagssalik Trough on East Greenland Shelf. Much alike Sam Ford Trough, these cross-shelf troughs are shallow and oriented towards a fiord that probably fed an ice stream during full glaciation. However, these shallower troughs do not reach the fiord mouth because they are all intersected by the marginal trough of a deeper adjacent cross-shelf trough reaching the shelf break, suggesting that (i) they were cut-off from their glacial ice supply and (ii) their ice stream was probably shutdown, as with the Sam Ford Ice Stream. The presence of the such abandoned and less eroded cross-shelf troughs—which are also intersected by marginal troughs—on most formerly glaciated continental shelves of the world possibly result from a similar mechanism to Scott-Sam Ford system. However, further investigations are needed to confirm that competition between ice stream played a role in the development of these trough systems.

#### 4.4 Competition for drainage basins and ice sheet stability in marine environments

Although competition for ice-drainage basins between ice streams has long been recognized as a driver for changes in ice sheet geometry (Greenwood and Clark, 2009; Payne and Dongelmans, 1997), it has not been given much attention compared to other hypotheses for switching as this idea has only been derived from modeling studies. However, the geomorphology, pattern and glacial trough assemblages in the Scott-Sam Ford system provide for the first time an empirical context where adjacent ice streams on a continental shelf could have interplayed in a competition for ice discharge during the Pliocene-Pleistocene. The erosion profile of Hecla & Griper Trough indicates that (i) this competition was dependent of glaciodynamics occurring down-ice, probably at the marine-based ice margin, and (ii) the upstream propagation of ice instabilities (or ice acceleration) occurring down-ice play a fundamental role in organizing ice-flow routes within the ice sheet. Felikson et al. (2017) modeled such up-ice propagation of a wave of thinning linked to changes in ice margin thickness. The hypothesis of instability waves propagating upstream in ice streams and outlet glaciers has also been mentioned in a series of recent papers (e.g., Felikson et al., 2017; Nick et al., 2009; Price et al., 2011; Reese et al., 2018). The erosion of the Hecla & Griper marginal trough confirms such a wave theory: instability waves traveling up-ice were redirected along the line of weakness along sedimentary-crystalline contact, which enabled the formation of a tributary ice stream that eroded Hecla & Griper Trough. Redirection of the instability wave was probably due to: i) differential erosion and ii) the competition between advection and diffusion of the wave (Felikson et al., 2017). Differences in bedrock lithologies most likely favored differential erosion rates that eventually resulted in a

topographic step (steep bed profile) at the transition between crystalline and sedimentary bedrock. This topographic step favored relatively thin ice and a steep ice profile, where down-ice advection dominated and thus limited up-ice diffusion of ice streaming from that location. Conversely, the cross-shelf trough forms a relatively flat bed with flat-ice profiles where diffusion of the wave could have dominated. In this setting, the diffusion of the wave was redirected on the shelf along the transition  
865 between crystalline and sedimentary bedrock where the bed profile was the flattest. Long-term erosion along the bedrock contact could then have led to the erosion of a marginal trough. The development of a marginal trough was a key structural element to produce a positive feedback that facilitated redirection and diffusion of up-ice acceleration. The competition between adjacent ice streams on the continental shelf was therefore “won” by the ice stream that was the most efficient at diffusing up-ice its fast flow through its tributaries, i.e., through a marginal trough.

870 The competition between ice streams and their switching on and off imply important configuration changes in ice stream and ice sheet geometries. As inland thinning of ice sheets can be controlled by ice margin geometry (Felikson et al., 2017), the competition for the ice drainage basin represents a major driver in the growth and decay of an ice sheet. Accordingly, abrupt changes in ice stream networks are also expected to influence ice sheet stability. Where ice stream switching occurs and lead to the merging of two ice streams, ice-flow acceleration can propagate upstream in both glacial drainage basins (i.e.,  
875 in both Scott and Sam Ford in the study area). Merged ice streams can then affect a greater area of the ice sheet and provoke ice-divide migration (Greenwood and Clark, 2009). Such flow-switching of ice streams can provide more efficient and rapid pathways for continental ice to reach the ocean, possibly leading to a more rapid drawdown of the ice sheet. The merging of ice streams through ice piracy should result in an increase in ice discharge and erosion rates in the “winning” trough. The winning ice stream gains mass balance and thus should equilibrate by advancing its margins (if it is not already at the shelf  
880 break).

Although the overdeepened bedrock basin of Scott Trough and its seaward extent to the shelf break cannot be unequivocally attributed to ice stream-switching, the longitudinal basins in Scott Trough that are related to ice flow from Sam Ford Fiord represents almost half of the width of Scott Trough. The presence of these basins suggests the switching could account for up to half of the erosion of Scott Trough. The mechanism of ice stream switching through marginal troughs can  
885 therefore lead to more extensive glaciations and to the erosion of deeper glacial troughs on high latitude continental shelves: merging ice streams would allow the glacial ice to extend farther and erode deeper on these shelves. The increasing depths in troughs behind grounding zones are known to create a positive feedback during glacial retreat that result in more rapid retreat of the ice margin in progressively deeper waters (Joughin and Alley, 2011; Mercer, 1978; Schoof, 2007). Therefore, a flow switch caused by marginal trough erosion is expected to make ice sheets occupying similar trough systems on continental  
890 shelves more sensitive to climate forcing, on both short (within a glacial cycle) and long term (over multiple glacial cycles).

## 5 Conclusions

The swath bathymetry imagery and the geophysical data collected in a simple trough network of the Northeastern Baffin Island Shelf (Arctic Canada) provide evidence for the flow switch of a ice stream that occurred during the Pliocene-Pleistocene on the northeastern Baffin Island shelf (Arctic Canada) through glacial erosion and overdeepening of a marginal trough. The glacial geomorphology of the seabed and the erosion profiles of the troughs network provides for the first time an empirical context where adjacent ice streams could have interplayed in a competition for ice discharge. This competition for ice discharge between ice streams was dependent of dynamics occurring at the marine-based ice margin (i.e., the grounding zone), indicating that the upstream propagation of high glacial velocities plays a fundamental role in organizing ice-flow routes and catchments within ice sheets. Such a union of glacial ice catchments by switching provides more efficient and rapid pathways for continental glacial ice to reach the ocean, enhancing the extent and erosive action of ice streams on high latitude continental shelves. These results suggest that the up-ice propagation of high ice velocities is a major driver of changes in the geometry of ice sheets during their growth and decay; it can therefore affect ice sheet stability. The hypothesis that the ice stream switching mechanism plays a major role on the geological evolution of formerly glaciated continental shelves through the extension of marginal troughs is supported by other examples from continental shelves located at the former margins of the Laurentide, the Greenland and the West Antarctica ice sheets. These trough systems show striking morphological similarities with the through networks described in the study area and could also result from a competition between adjacent ice streams. As Laurentide Ice Sheet palaeo-dynamics inferred from Canadian Arctic continental shelves can be used as an analogue to understand how modern marine-based ice-sheets will respond to future climate change and sea-level fluctuations, these results highlight the need for further investigations and further modeling studies that should include ice-drainage competition between ice streams and the resulting flow capture as a major control on ice sheet stability.

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## 7 Authors contribution

E.B. and P.L. developed the study. E.B. interpreted the geophysical datasets, wrote the paper, and prepared the figures. P.L. helped with the interpretation and analysis, and contributed to the writing and editing of the paper.

## 920 **8 Competing Interests**

The authors declare that they have no competing interests.

## **9 Data availability**

The multibeam bathymetry dataset can be visualized and requested on the Université Laval Géoindex+ website (geoindex-plus.bibl.ulaval.ca). The seismic reflection data along with the acquisition specifics are available on the Geological Survey of  
925 Canada website (ftp.maps.canada.ca/pub/nrcan\_rncan/raster/marine\_geoscience/Seismic\_Reflection\_Scanned/).

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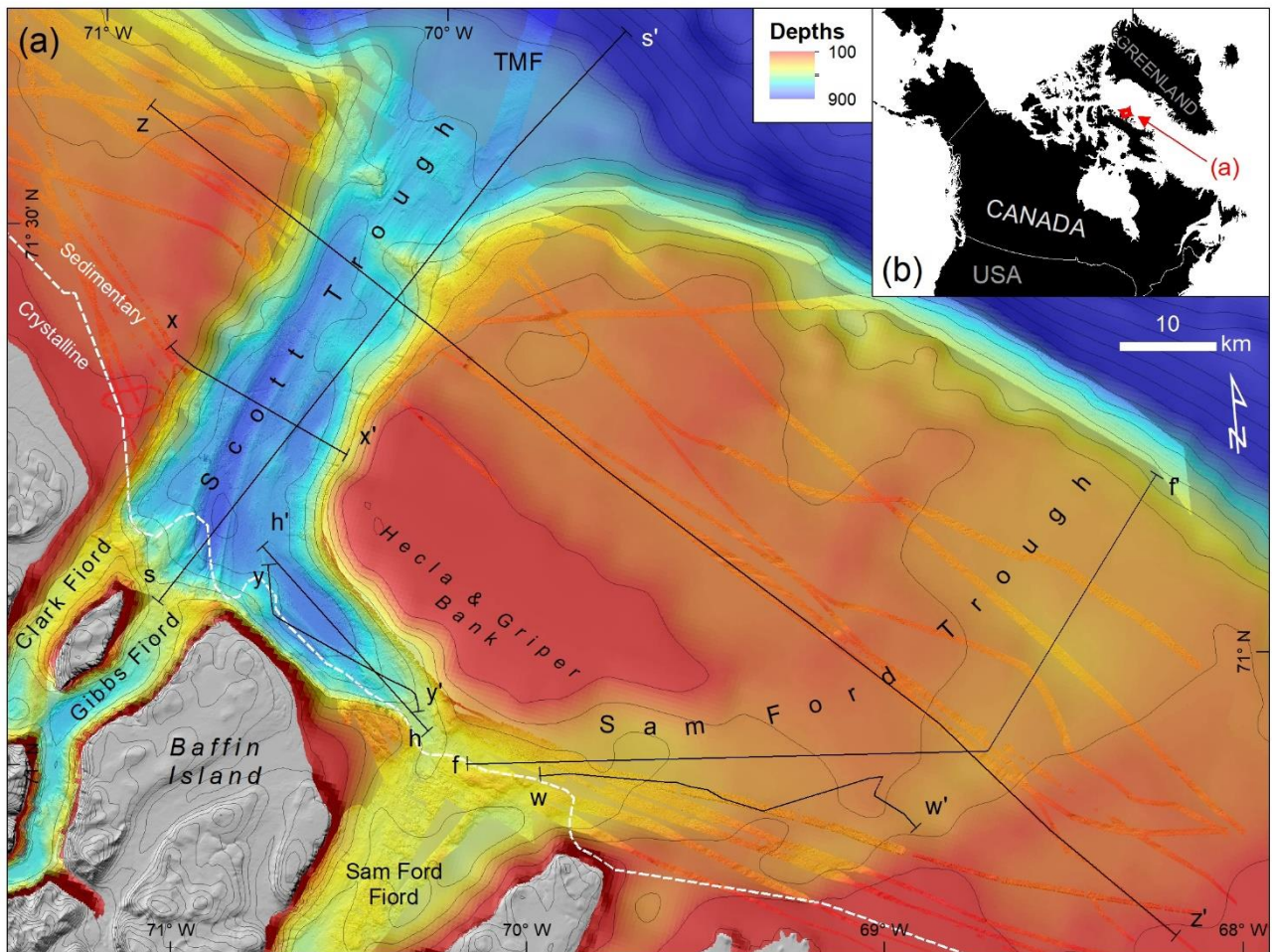
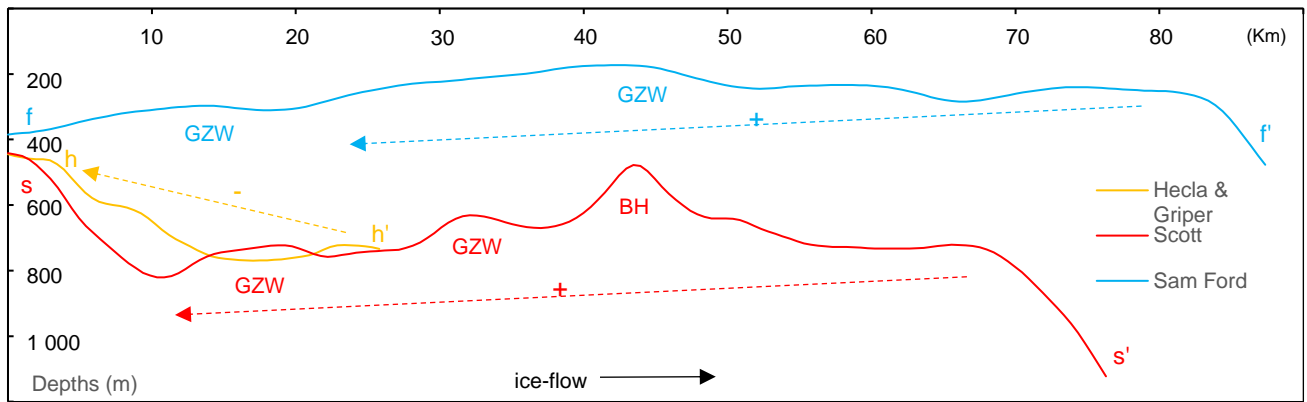


Figure 1 A. Map showing the high-resolution bathymetric data collected by ArcticNet program (2003–2016) draped on the International Bathymetric Chart of the Arctic Ocean data (IBCAO; Jakobsson et al., 2012) map on the northeastern Baffin Island shelf. The black dashed-line shows the approximate limit between sedimentary and crystalline bedrock. HGT: Hecla & Griper Trough. Light-gray lines: 100 m contours. Dashed black lines: Ice-stream lateral moraines on the sides of Sam Ford Trough. B. Location of the study area.



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Figure 2. A. Longitudinal depths profile along ice-flow route for each trough. Arrow with minus (-) symbol indicates a general up-ice decreasing profile of depths. Arrows with plus (+) symbol indicate a general up-ice increasing profile of depths (glacial overdeepening landward). BH: Bedrock high; GZW: Grounding-zone wedge.

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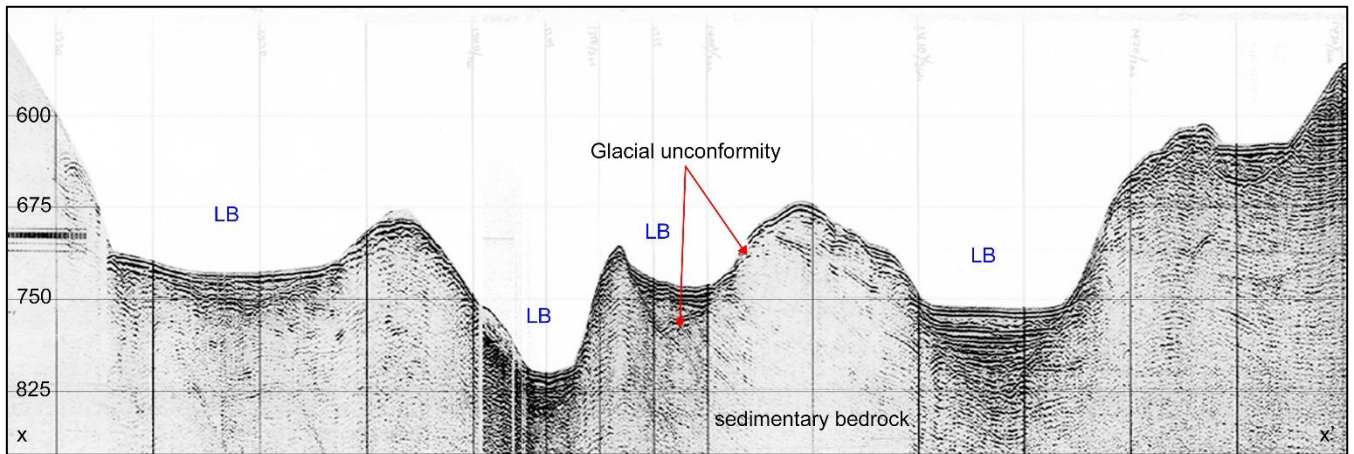
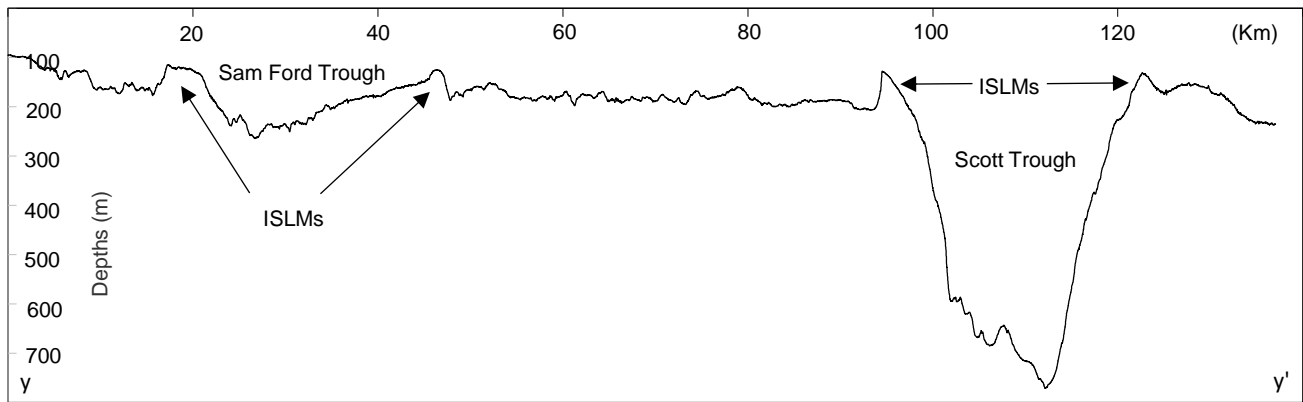
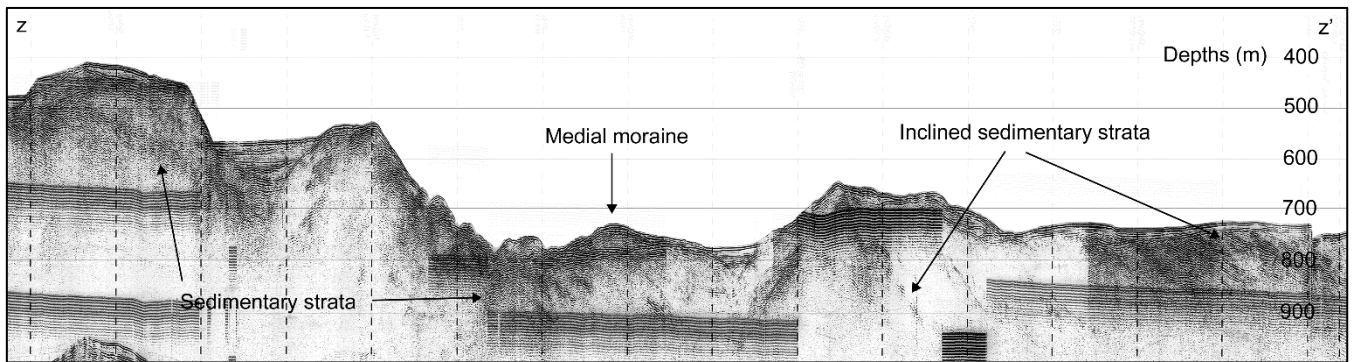


Figure 3. Airgun profile across Scott Trough showing glacially-eroded basins filled with sediments (LB) and residual bedrock ridges (Profile 78029\_AG\_266\_0758; NRCan).



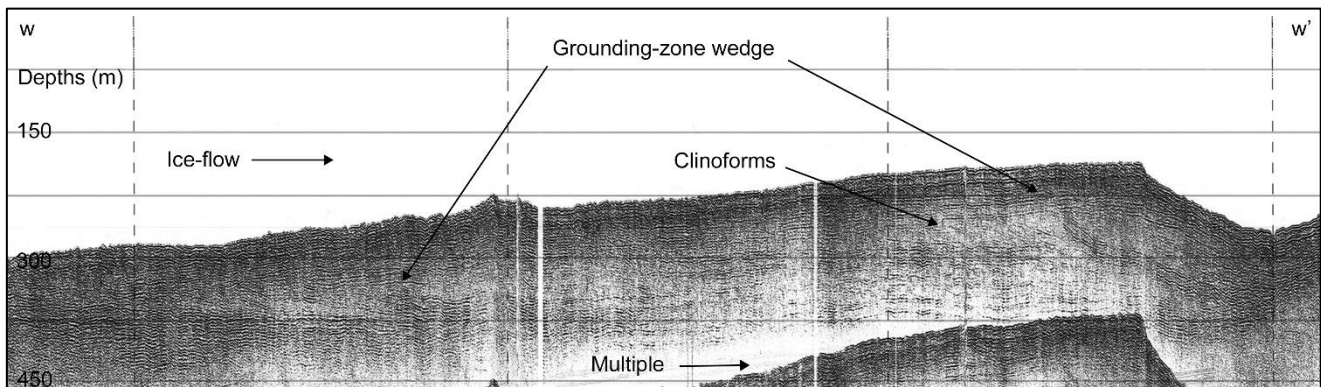
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**Figure 4. Bathymetric profile across the northeastern Baffin Island Shelf showing Sam Ford and Scott troughs. The profile also shows the ice-stream lateral moraines on both sides of each trough.**

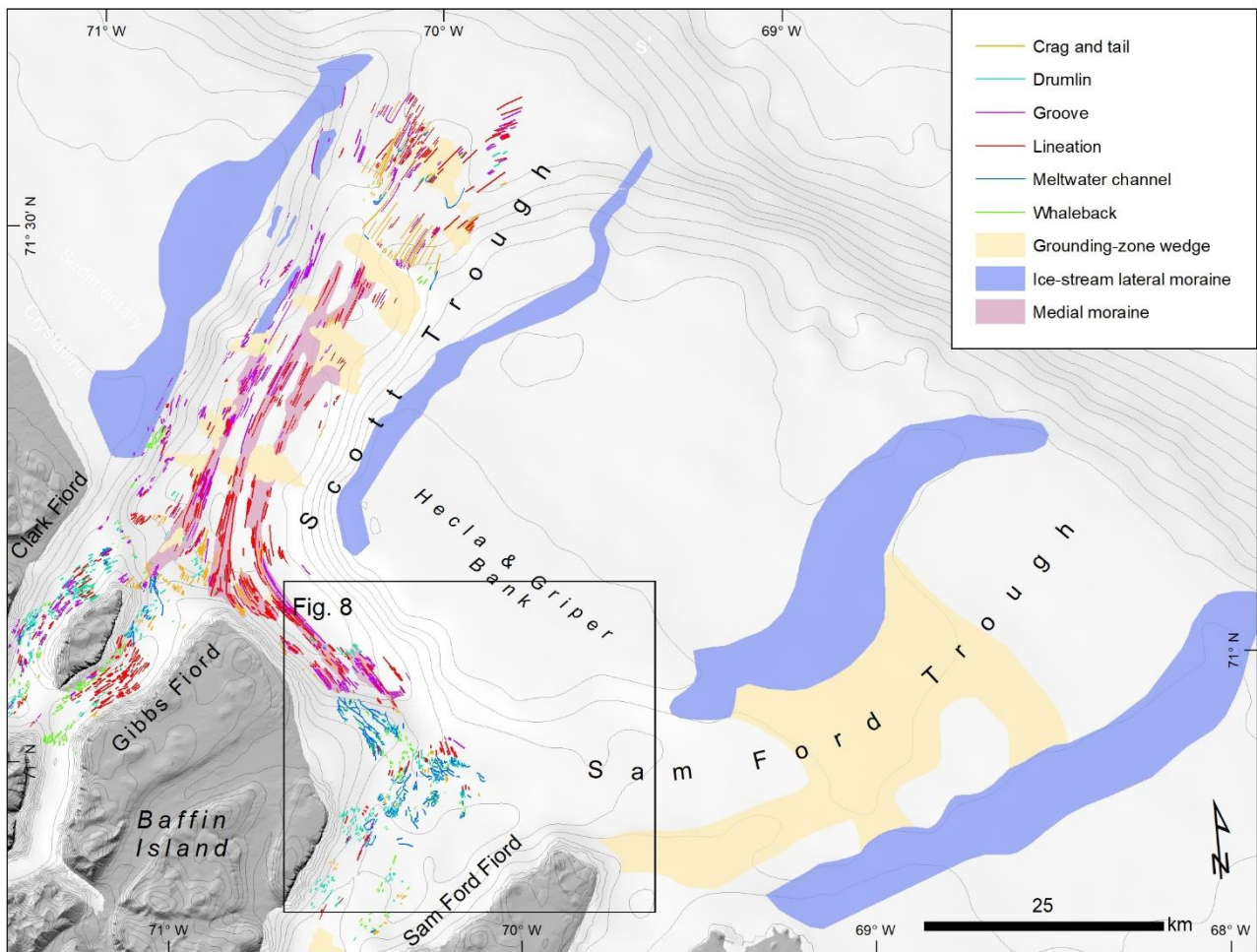


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**Figure 5. Airgun profile in Hecla & Griper Trough showing both sediment and bedrock ridges molded by glacial erosion (Profile 78029\_AG\_268\_0110; NRCan). The profile also shows inclined sedimentary strata that were eroded by glacial ice.**



**Figure 6. Seismo-stratigraphic (Airgun) profile showing a major 75 m-thick grounding-zone wedge (red) in inner-middle Sam Ford Trough (Profile 80028\_AG\_RAYT\_257\_0200; NRCan).**



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**Figure 7. Distribution of landforms related to ice-flow and to ice margin stabilization on the continental shelf and fiords of the study area, in northeastern Baffin Island, Eastern Arctic Canada.**

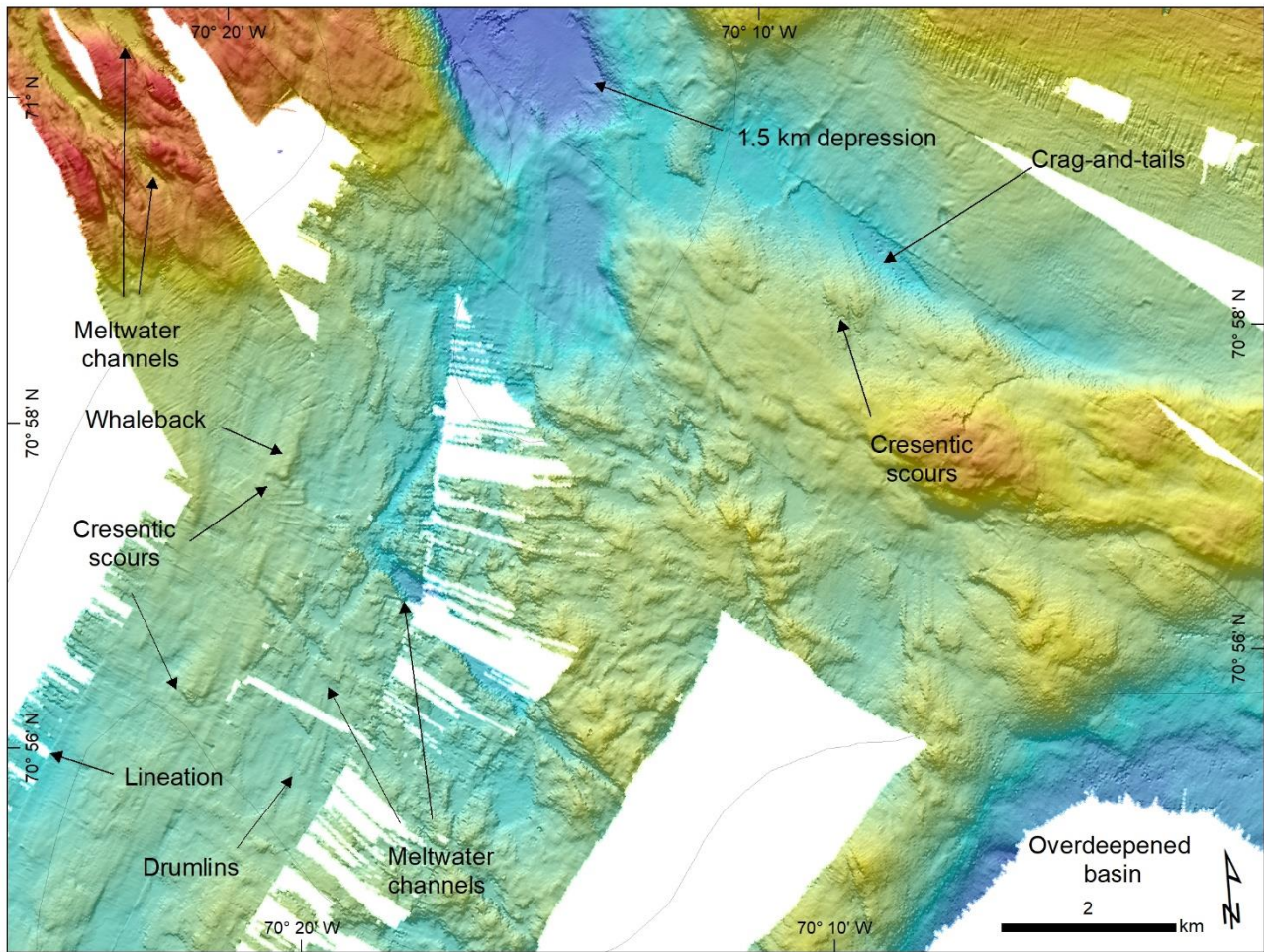
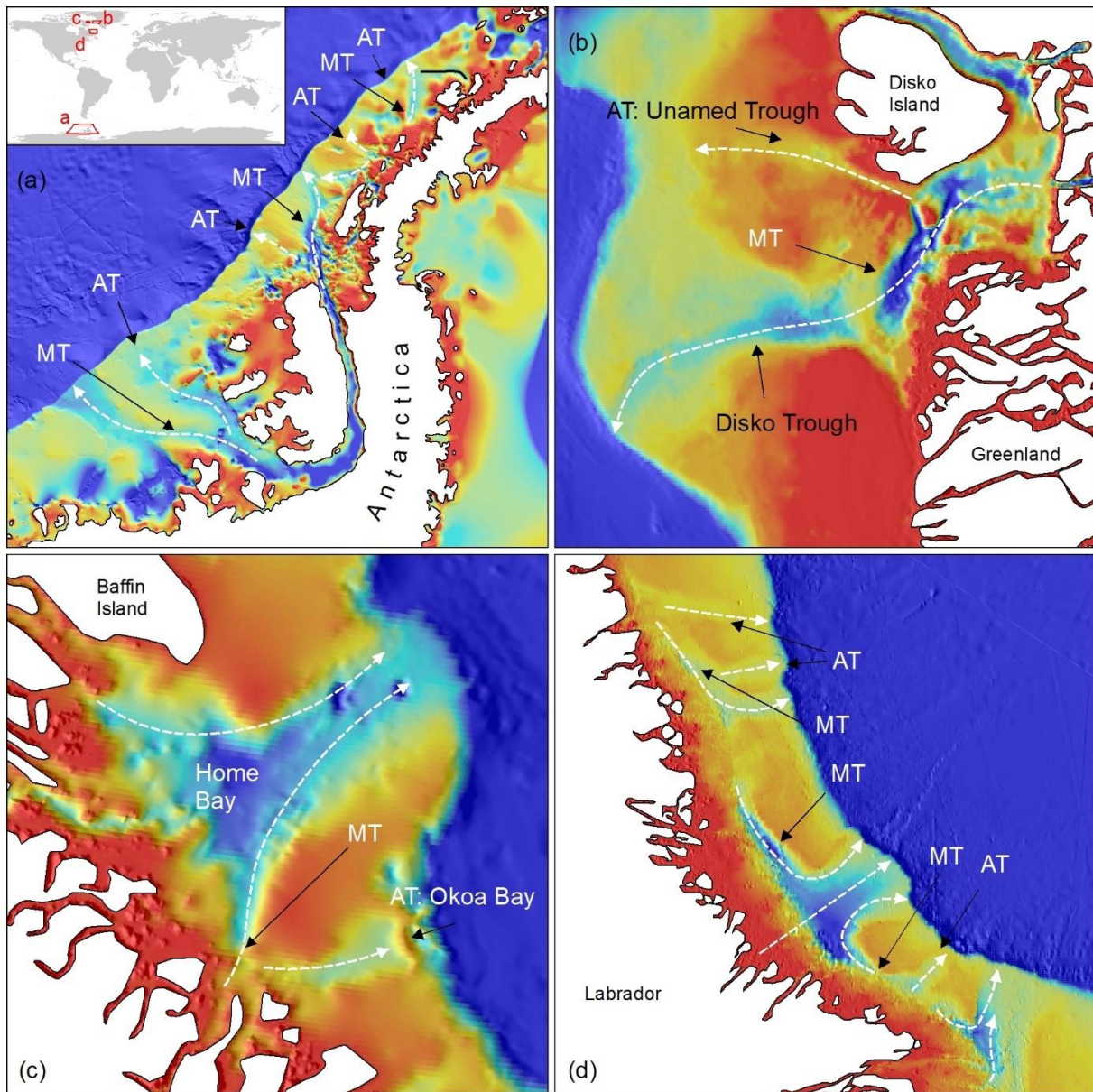


Figure 8. Examples of ice-flow landforms on Sam Ford sill that are oriented towards Hecla & Griper Trough, Eastern Arctic Canada.

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1180 **Figure 9. A.** Bathymetry (BEDMAP2; Fretwell et al., 2013) of the western continental shelf of the Antarctic Peninsula. MT: Marginal trough. AT: Abandoned trough. White dashed lines: Interpreted ice stream tracks. Inset: Location of figures A-D. **B.** Bathymetry (IBCAO) of Unnamed and Disko troughs off West Greenland. MT: Marginal trough. **C.** Bathymetry (IBCAO) of Okoa Bay, Home Bay and marginal troughs off eastern Baffin Island. **D.** Bathymetry (IBCAO) of Labrador Shelf troughs off Labrador, Canada.

# ~~A Race for Ice Discharge between Ice Streams on Glaciated Continental Shelves~~ Ice-stream flow switching by up-ice propagation of instabilities along glacial marginal troughs

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Abstract. Ice stream networks constitute the arteries of ice sheets through which large volumes of glacial ice are rapidly delivered from the continent to the ocean. Modifications in ice stream networks have a major impact on ice ~~sheet~~ sheets mass balance and global sea level. ~~However~~ Reorganizations in the drainage network of ice streams have been reported in both modern and palaeo-ice sheets and usually result in ice streams switching their trajectory and/or shutting down. While some ~~hypotheses for the reorganization of ice streams have been proposed~~, the mechanisms ~~controlling ice stream~~ that control the switching of ice streams remain poorly understood ~~and documented~~. Here, we ~~report~~ interpret a flow-switch in an ice stream system that occurred during the Pliocene-Pleistocene on the northeastern Baffin Island shelf (Arctic Canada) through glacial erosion of a marginal trough. ~~We find that up-ice propagation of ice streams through marginal troughs can lead to the piracy of neighbouring ice catchments, which in turn induce an adjacent ice stream flow switch and shutdown, i.e., deep parallel-to-coast bedrock moats located up-ice of cross-shelf troughs. Shelf geomorphology imaged by high-resolution swath bathymetry and seismostratigraphic data in the area points to the extension of ice streams from Scott and Hecla & Griper troughs towards the interior of the Laurentide Ice Sheet. Up-ice propagation of ice streams through a marginal trough is interpreted to have led to the piracy of the neighboring ice catchment that in turn induced an adjacent ice stream flow switch and shutdown. These results suggest that competition for ice discharge between ice streams, which implies piracy of ice-drainage basins via marginal troughs, was the driving mechanism behind ice flow-switching in the study area. In turn, the union of ice catchment by piracy increased the volume and discharge of Scott Ice Stream, allowing it to erode deeper and flow farther on the continental shelf.~~ Similar trough systems observed on many other glaciated continental shelves may be the product of such a competition for ice discharge between catchments.

## 1 Introduction

1210 Ice flow switching has first been invoked to explain the recent stagnation of the Kamb Ice stream — previously known as Ice  
Stream C — in West Antarctica Ice Sheet (Conway et al., 2002). Following this discovery, episodes of ice stream switching  
were also inferred to have occurred throughout the Pleistocene and in various palaeo-ice sheet settings (e.g., (Dowdeswell et  
al., 2006; Vaughan et al., 2008; Winsborrow et al., 2012)). Several driving mechanisms have then been proposed to explain  
the switching of ice streams: i) sediment accumulation causing a topographical change downstream (Dowdeswell et al., 2006);  
1215 ii) local variations in bathymetry coupled with relative sea level change (Stokes et al., 2009); iii) spatial and temporal variations  
in basal thermal regime (Cofaigh et al., 2010); iv) presence of sticky spots, subglacial meltwaters rerouting and ice thickness  
variations (Alley et al., 1994; Anandakrishnan et al., 2001; Anandakrishnan and Alley, 1997); v) competition for ice discharge  
and drainage basins (Greenwood and Clark, 2009; Payne and Dongelmans, 1997); and vi) topographic focusing (Sarkar et al.,  
2011; Storrar et al., 2017). This wide range of possible driving mechanisms outlines the fact that ice stream switching remains  
1220 poorly understood, which constitutes an obstacle in our ability to model accurately the future behavior of modern ice sheets.  
Empirical data from the palaeo-ice sheet record is therefore needed to better constrain the mechanism of flow switching.  
Networks of glacial troughs on continental shelves may offer such insights for identifying and understanding switching as they  
were overdeepened by ice streams. These networks generally consist of cross-shelf troughs often interconnected up-ice to  
marginal troughs (Anderson, 1999; Batchelor and Dowdeswell, 2014; Nielsen et al., 2005). Marginal troughs are generally  
1225 located along the boundary between harder crystalline bedrock in the inner portion of the shelf and softer sedimentary rocks  
in the offshore portion of the shelf (Nielsen et al., 2005). They have been inferred to result from glacial erosion because they  
represent an up-ice extension of glacially eroded cross-shelf troughs (Nielsen et al., 2005). While cross-shelf troughs are  
broadly aligned with fjords, marginal troughs are aligned parallel to coast.

This paper focuses on a single trough network on the northeastern Baffin Shelf in Eastern Arctic Canada that is  
1230 characterized by two cross-shelf troughs — Scott and Sam Ford — interconnected by one marginal trough: Hecla & Griper  
Trough (Fig. 1). In Scott Trough, the presence of mega-scale glacial lineations (MSGLs) extending to the shelf break together  
with a till unit extending on the trough-mouth fan indicate that the Laurentide Ice Sheet (LIS) reached the shelf break during  
the Last Glacial Maximum (LGM (Brouard and Lajeunesse, 2017)). MSGLs, crag and tails and drumlins mapped in this region  
indicate that during the LGM, a tributary ice stream of the Scott Ice Stream extended from Sam Ford Fjord to Scott Trough  
1235 through Hecla & Griper Trough (Brouard and Lajeunesse, 2017). In Sam Ford Trough, the absence of ice flow landforms  
suggests that during the Last glacial episode the trough was occupied by slow flow or cold-based ice. This slow ice flow  
contrasts with a recent glacial reconstruction stating that in full glacial conditions, Sam Ford and Scott troughs were  
characterized by separate ice streams which drained approximately comparable areas from the LIS (Margold et al., 2015).  
High-resolution swath bathymetry imagery collected over a period of 13 years onboard the CCGS Amundsen combined with  
1240 archived seismic reflection data from the Geological Survey of Canada and International Bathymetric Chart of the Arctic  
Ocean (IBCAO (Jakobsson et al., 2012)) bathymetric data are here used to analyze an ice stream switching that occurred in

the past due to the ice discharge piracy from Scott Ice Stream, which led to the shutdown of the ice stream occupying Sam Ford Trough.

## 2 Methods

Multibeam data were collected using Kongsberg Simrad EM 300 (12 kHz) and EM 302 (30 kHz) echo-sounders onboard the CCGS Amundsen by the Ocean Mapping Group (University of New Brunswick) and the Laboratoire de Géosciences Marines (Université Laval) for the ArcticNet program. The multibeam data were processed using the Caris HIPS & SIPS and MB-System softwares. Data visualization and mapping was realized using ESRI ArcGIS 10.2 software. Seismic reflection data were analyzed and extracted using the LizardTech GeoViewer software. Maps and seismic reflection data were transferred to the Adobe Photoshop 2018 CC software for figure production and editing. Seismic reflection data were enhanced using the Brightness/Contrast tool in Adobe Photoshop CS5 for a clearer visualization. International Bathymetric Chart of the Arctic Ocean data (Jakobsson et al., 2012) was used for analyze of Sam Ford Trough and for map production. BEDMAP2 data was used for map production (Fretwell et al., 2013).

## 3 Glacial imprint and ice stream switching

Scott and Sam Ford troughs are aligned with the major fjords of northeastern Baffin Island: the landward extent of Scott Trough begins at the mouth of Clark and Gibbs fjord while the landward extent of Sam Ford Trough begins at the mouths of Sam Ford and Eglinton fjords (Fig. 1). These four fjords were eroded in Precambrian crystalline bedrock that extends to the east under the sedimentary bedrock strata. Precambrian basement is characterized under the shelf by half grabens and grabens associated with rifting and spreading in Baffin Bay (Hosseinpour et al., 2013; Oakey and Chalmers, 2012). Post rifting sedimentary Cretaceous and Paleocene bedrock strata overlay Precambrian bedrock on most of the shelf (Fig. 1) and are overlain by unconsolidated Quaternary deposits (Praeg et al., 2007). Previous studies have proposed that the cross-shelf troughs of Western Baffin Bay have a fluvial origin linked to a sea level lowstand (Fortier and Morley, 1956; Pelletier, 1964) much like the troughs of the Labrador Shelf (Josenhans and Zevenhuizen, 1987). However, most of the erosion associated with the overdeepening—reaching up to 350–450 m in Scott Trough—may be attributed to subsequent glacial erosion (Løken and Hodgson, 1971). This glacial overdeepening began during the late Pliocene (~3.5 Ma (Srivastava et al., 1987)) and completely erased any traces of pre-glacial fluvial valleys (Løken and Hodgson, 1971). While the glacial origin of Scott Trough is obvious from its overdeepening and numerous ice-flow landforms, the glacial origin of Sam Ford Trough is confirmed by the presence of 1) ice stream lateral moraines, 2) grounding zone wedges up to the middle of the shelf and a small overdeepened basin on Sam Ford Fjord sill (Figs. 1–2–3). The sill at the mouth of Sam Ford Fjord marks the transition between Hecla & Griper Trough and Sam Ford Trough. This sill is characterized by a >470 m depression to the south (Fig. 3B) and a 12-km large and 350–400 m deep plateau to the north. The southern depression extends to form Sam Ford Trough. The occurrence of crag-

and-tails on the bottom of the depression imply a fast ice-flow towards Sam Ford Trough (Fig. 3). The presence of a 75 m-thick GZW (Figs. 1—2A) and an overdeepened basin in Sam Ford Trough also indicate that an ice stream originating from Sam Ford Fjord has also been, at some point, efficient enough to excavate the trough and to transport sediment to construct the GZW located in the trough, but not efficient enough to build a trough-mouth fan at the seaward-end of the trough.

The plateau on the northern part of Sam Ford Fjord sill is mainly characterized by crystalline bedrock ridges, sediment filled basins and a variety of ice-flow landforms; chiefly glacial lineations, drumlins, grooves and meltwater channels, that are mainly oriented towards Hecla & Griper Trough (Fig. 3A). The transition between the northern plateau and Hecla & Griper Trough is characterized by bedrock shoals and a 1.5 km depression in-between (Fig. 3B). A vast majority of ice-flow landforms on Sam Ford Fjord sill converges towards the depressions between the sill and Hecla & Griper Trough; only a few are oriented through the shoals on the north side of the depression. Glacial bedforms on the sill of Sam Ford Fjord indicate that an ice stream flowed from Sam Ford Fjord through Hecla & Griper Trough. Although Hecla & Griper Trough has a structural origin since it was eroded along the crystalline-sedimentary contact, glacial lineations, crag and tails and grooves within the trough and on the sill of Sam Ford Fjord indicate that it was eroded by an ice stream (Brouard and Lajeunesse, 2017). If the tributary ice stream—and the associated erosive power—originated from Sam Ford Fjord, we would expect at equivalent ice-velocities Hecla & Griper Trough to be deeper at its narrowest section, i.e., in-between the shoals and the shelf. However, the bathymetric profile in Hecla & Griper Trough (Fig. 2B) showing depths increasing towards Scott Trough implies that erosion was the most effective at the junction between Hecla & Griper and Scott troughs. Erosion of Hecla & Griper Trough was therefore more dependent of down-ice dynamics occurring in Scott Trough rather than in Sam Ford Fjord. The down-ice dependence of Hecla & Griper Trough erosion is in agreement with an inferred strong relationship in the development of interconnected marginal troughs and cross-shelf troughs (Nielsen et al., 2005). Coincident with the contact between crystalline and sedimentary bedrock, Hecla & Griper Trough is therefore interpreted to be the result of a tributary ice stream of Scott Ice Stream eroding sedimentary bedrock along the line of weakness, resulting in a morphology that is similar to other marginal troughs (Anderson, 1999; Nielsen et al., 2005). The down-ice dependence of erosion in Hecla & Griper also indicates that ice-velocities in Hecla & Griper tributary ice stream were mainly dependent of ice-velocities within the Scott Ice Stream. It has been demonstrated that upstream-propagation of high velocities—and erosional power—in ice streams is mainly dependant of instabilities at the ice margin or at the grounding line (De Angelis and Skvarca, 2003; Friedl et al., 2017; Howat et al., 2007; Hughes, 1992; Joughin et al., 2004; Kleman and Applegate, 2014; Payne et al., 2004; Retzlaff and Bentley, 1993; Rignot et al., 2002; Seehaus et al., 2015), i.e., an acceleration of ice-flow propagates up-ice the main-trunk of the ice stream and up-ice in the tributary ice streams. Therefore, Hecla & Griper Trough as a host to a tributary ice stream can have facilitated upstream-propagation of ice-streaming up to Sam Ford Fjord sill. Ice streams spreading upstream and eroding Hecla & Griper Trough have eventually eroded the marginal trough up to a point where it extended to Sam Ford Fjord mouth.

The changes in bathymetry through the erosion of the marginal trough associated with the upstream-propagation of Scott Ice Stream in Sam Ford system led to: 1) the reorganization of the ice-drainage system; 2) the switching of Sam Ford Ice Stream from Sam Ford Trough to Scott Trough; and ultimately, 3) the shutdown Sam Ford Ice Stream in Sam Ford Trough

(Alley et al., 1994; Anandakrishnan and Alley, 1997; Graham et al., 2010). Such ice piracy through the switching of ice streaming most probably occurred early during Pliocene–Pleistocene glaciations and would explain the absence of a trough-mouth fan at the seaward end of Sam Ford Trough and why Sam Ford Trough is more than two times shallower than Scott Trough. It is probable that ice streaming in Sam Ford Trough only occurred during a short time period at the beginning of early (Late Pliocene–Early Quaternary?) glaciations, before its ice discharge got collected by the Scott Ice Stream. As this process repeated itself throughout glacial cycles, it accentuated the depth of Hecla & Griper Trough which facilitated the capture of Sam Ford Ice Stream by Scott Ice Stream during subsequent glaciations. The changes in bathymetry associated with the upstream propagation of Scott Ice Stream in Hecla & Griper also led to a point in time where Sam Ford Fjord Ice discharge switched to be topographically diverted towards Hecla & Griper (the 1.5 km depression). From that point on, ice streaming conditions were unlikely to occur in Sam Ford Trough. Taken together these observations confirm that the erosion and the morphology of the troughs of northeastern Baffin Shelf is a function of a competition for ice drainage basins which has striking similarities with fluvial drainage basins reorganizations linked to river captures (Bishop, 1995): a dry valley (Sam Ford Trough) with fluvial (here glacial, i.e., the GZW) deposits and a knickpoint (the 1.5 km depression at the head of Hecla & Griper Trough).

Therefore, an ice flow switching was first invoked to explain the recent stagnation of the Kamb Ice Stream—previously known as Ice Stream C—in West Antarctica Ice Sheet (Conway et al., 2002). Following this discovery, episodes of ice stream switching were also inferred to have occurred throughout the Pleistocene and in various palaeo-ice sheet settings (e.g., Dowdeswell et al., 2006; Vaughan et al., 2008; Winsborrow et al., 2012). Several driving mechanisms were proposed to explain the switching of ice streams: i) sediment accumulation causing a topographical change downstream (Dowdeswell et al., 2006); ii) local variations in bathymetry coupled with relative sea-level change (Stokes et al., 2009); iii) spatial and temporal variations in basal thermal regime (Ó Cofaigh et al., 2010); iv) presence of sticky spots, subglacial meltwater rerouting and ice thickness variations (Alley et al., 1994; Anandakrishnan et al., 2001; Anandakrishnan and Alley, 1997); v) competition for ice discharge and drainage basins (Greenwood and Clark, 2009; Payne and Dongelmans, 1997); and vi) topographic focusing (Sarkar et al., 2011; Storrar et al., 2017). The wide range of possible driving mechanisms outlines the fact that ice stream switching is a complex process that requires further assessment in order to model accurately the future behavior of modern ice sheets. Empirical data from the palaeo-ice sheet record is therefore needed to better constrain the mechanism of flow-switching. Networks of glacial troughs on continental shelves may offer such insights for identifying and understanding the flow-switching mechanism as they were overdeepened by past ice streams. These networks generally consist of cross-shelf troughs often interconnected up-ice to marginal troughs (Anderson, 1999; Batchelor and Dowdeswell, 2014; Nielsen et al., 2005). While cross-shelf troughs are broadly aligned with fiords, marginal troughs are aligned parallel-to-coast. Marginal troughs are generally located along the boundary between harder crystalline bedrock in the inner portion of the shelf and softer sedimentary rocks in the offshore portion of the shelf (Nielsen et al., 2005). They have been inferred to result from glacial erosion because they represent an up-ice extension of glacially eroded cross-shelf troughs (Nielsen et al., 2005), but no mechanism has been proposed to explain their formation. Here, high-resolution swath bathymetry imagery combined with archived seismic

1340 reflection data and International Bathymetric Chart of the Arctic Ocean bathymetric data (IBCAO; Jakobsson et al., 2012) are used to analyze the morphology and stratigraphy of a single glacial trough network on the northeastern Baffin Shelf, in Eastern Arctic Canada. These data suggest that past ice stream switching occurred due to the ice-discharge piracy from an ice stream in a deep cross-shelf trough (Scott Trough) via the lateral extension of a marginal trough (Hecla and Griper Trough), which led to the shutdown of the ice stream occupying the neighboring cross-shelf trough (Sam Ford Trough).

## 1345 **2 Regional setting and Glacial History**

The analyzed troughs are located on the northeastern Baffin Island Shelf in Western Baffin Bay, Eastern Arctic Canada. The trough system is characterized by two cross-shelf troughs—Scott and Sam Ford—interconnected by one marginal trough: Hecla & Griper Trough (Fig. 1). Scott and Sam Ford troughs are aligned with the major fiords of northeastern Baffin Island: Scott Trough extends northeast from the mouth of Clark and Gibbs fiord while Sam Ford Trough extends northeast from Sam Ford and Eglinton fiords (Fig. 1). These four fiords were eroded in Precambrian crystalline bedrock that extends eastward under the sedimentary bedrock strata. Precambrian basement is characterized under the shelf by half-grabens and grabens associated with rifting and spreading in Baffin Bay (Hosseinpour et al., 2013; Oakey and Chalmers, 2012). Post-rifting Cretaceous and Paleocene sedimentary rock strata overlay Precambrian bedrock on most of the shelf (Fig. 1) and are overlain by a relatively thin (<100 m) cover of unconsolidated Quaternary deposits (MacLean et al., 2014; Praeg et al., 2007). Previous studies have proposed that the cross-shelf troughs of Western Baffin Bay have a fluvial origin linked to a pre-Quaternary sea-level lowstand (Fortier and Morley, 1956; Pelletier, 1964) much like the troughs of the Labrador Shelf (Josehans and Zevenhuizen, 1987). However, most of the erosion associated with the overdeepening—reaching up to 350–450 m in Scott Trough—may be attributed to subsequent glacial erosion (Løken and Hodgson, 1971). The erosion of the troughs is intrinsically linked to the erosion of the deep fiords of northeastern Baffin Island, which modeling suggests were eroded to present-day depths in ~1 Myr (Kessler et al., 2008). The glacial overdeepening of the troughs probably began during the late Pliocene (~3.5 Ma; Srivastava et al., 1987) and all traces of preglacial fluvial systems were erased during the Pleistocene (Løken and Hodgson, 1971).

Not much is known on pre-Late Wisconsinan ice streams flowing through Baffin Island into Baffin Bay. To produce well-developed fiords, the position of these ice stream was probably stable throughout most of the Pleistocene, i.e., through few fiords and converging into fewer cross-shelf troughs. Glacial advances—and ice streams—of marine isotope stages (MIS) 5d/b and MIS4 were probably less extensive than during MIS2 (Ganopolski et al., 2010; Simon et al., 2014; Stokes et al., 2012); therefore, ice streams may not have reached the shelf edge between ~130 ka and 25 ka BP. The last glacial stage (MIS2) reached its maximum around 25 cal. ka BP in Western Baffin Bay, with the LIS reaching the shelf edge between Lancaster Sound and Home Bay (Fig. 1; Jenner et al., 2018). During the MIS2 (25 – 16 cal. ka BP), Scott and Hecla & Griper troughs were inundated by ice streams of the LIS (De Angelis and Kleman, 2007; Briner et al., 2006b; Brouard and Lajeunesse, 2017;

Margold et al., 2015a) that extended to reach the shelf break at the mouth of the troughs, while Sam Ford Trough was under slow-flowing ice (Brouard and Lajeunesse, 2017).

1375 Laurentide ice occupied most of the shelf until 14.1 cal. ka BP and deglaciation of the continental shelf was completed by ~15 – 12 cal. ka BP as coastal forelands emerged from the glacial ice cover (Briner et al., 2005, 2006a) and LIS outlets retreated to the fiord mouths after 14 ka cal BP (Brouard and Lajeunesse, 2017, 2019; Jenner et al., 2018). Paraglacial and postglacial sedimentation has been prevailing in the troughs from at least ~12 cal. ka BP and probably up to 14 cal. ka BP, which marks a minimum age for presence of outlets at the fiord mouths (Jenner et al., 2018; Osterman and Nelson, 1989; Praeg et al., 2007). Outlet glaciers of the LIS occupied the entire fiords until ~11.4 cal ka BP (Dyke, 2004) before rapidly retreating inland towards the fiord heads (Briner et al., 2009). Finally, glacial scouring observed inland of fiord heads indicates that (i)  
1380 fast flowing ice streams may have extended inland of fiord heads and (ii) the fiords were efficient conduits for ice flow and erosion through the coastal mountain range of Baffin Island (Briner et al., 2008).

## **2 Methods**

1385 Swath bathymetric data collected using Kongsberg Simrad EM-300 (12 kHz) and EM-302 (30 kHz) multibeam echosounders onboard the CCGS Amundsen by the Ocean Mapping Group (University of New Brunswick) and the Laboratoire de Géosciences Marines (Université Laval) during 2003–2016 ArcticNet Expedition were used to analyze the seafloor of the Scott-Sam Ford trough system. The specifics of acquisition for each expedition can be obtained from Géoindex+ (geoindex-plus.bibl.ulaval.ca) and Ocean Mapping Group websites (omg.unb.ca/Projects/Arctic/ArcticMetadata.html). The multibeam bathymetry data were processed using Caris Hips & Sips and merged using the MB-System software, in order to provide a bathymetric surface at a 10 m-grid resolution for interpretation and analyses. The 10-m gridded surface was plotted over the  
1390 International Bathymetric Chart of the Arctic Ocean data (Jakobsson et al., 2012) to provide a complete, but lower resolution, coverage of the seafloor in between multibeam tracks. The complete surface was transferred in ESRI ArcMap 10.2 software geomorphological mapping and topographic analyses. Individual landforms were digitalized on the surface in ArcMap 10.2 and interpreted based on their apparent character (width, length, orientation, etc.) and on recent literature (e.g., Dowdeswell et al., 2016b). The interpretation of landform types is detailed in the results section.

1395 We interpreted seismic reflection data from the Marine Data Holding public repository of National Resources Canada (Geogratis.gc.ca) in order to provide a subsurface view of the architecture of the shelf. Seismic reflection data were analyzed and extracted using the LizardTech GeoViewer software. Seismic reflection data were enhanced using the Brightness/Contrast tool in Adobe Photoshop CS5 for a clearer visualization. Maps and seismic reflection data were transferred to the Adobe Illustrator 2018 CC software for figure production and editing. BEDMAP2 data was used for analyzing Antarctica, in search  
1400 of morphologically similar trough pattern systems and for map production (Fretwell et al., 2013).



### **3 Results**

#### **3.1 Troughs morphology**

##### **3.1.1. Scott Trough**

1405 Scott Trough is 62 km long, 12 km wide and 850 m deep. A longitudinal profile across the trough shows that it has a general  
trend of depths increasing from the shelf edge (~720 m) to the fiord sills (~900 m), forming a typical glacial overdeepening  
(Figs. 2–3). The trough is also characterized by a Precambrian bedrock sill that forms two bathymetric highs (~488 m) at about  
15 km from the seaward extent of the trough (Figs. 1–2). The overdeepened basin between the Precambrian bedrock highs and  
the fiord sill is therefore overdeepened by at least ~360 m, when sediments are not considered. Sediment accumulations over  
1410 bedrock in Scott Trough are thin, generally <10 m except for small patches in longitudinal basins showing up to 70 m of  
hemipelagic sediments, turbidites and mass failure deposits (Fig. 3). The sediments in Scott Trough basins were interpreted as  
relict (prior to the last glaciation, i.e., pre-Late Wisconsinan) deposits that have been preserved from glacial erosion (Praeg et  
al., 2007); alternatively, they could result also from ice-proximal sedimentation of an ice margin anchored at the fiord mouths,  
similar to deposits observed in Sam Ford Fiord (Brouard and Lajeunesse, 2019). The sediments in Scott Trough are mostly  
confined within longitudinal depressions that have up to ~130 m relief to bedrock (Fig. 3). The longitudinal depressions show  
1415 erosional surfaces that indicate that they are not of structural origin. Airgun profiles on the ridges in-between the depressions  
show that although their upper portion consists of an unconsolidated unit, the basement is marked by strong reflections and  
hyperbola that are typical of bedrock. The overdeepening in Scott Trough is divided into 4 longitudinal basins separated by 3  
bedrock and sediment ridges (Fig. 3). The 2 western basins are aligned with Clark and Gibbs fiords while the 2 eastern basins  
are prolonged into Hecla & Griper Trough. Scott Trough is bounded by steep sidewalls, longitudinal bathymetric highs (Fig.  
1420 4) and, at its seaward end, by a fan-shaped bathymetric bulge interpreted as a trough-mouth fan (Fig. 1; Brouard and  
Lajeunesse, 2017). The transition from the fiords to Scott Trough is marked a steep wall and a drop of >450 m (Figs. 1–2).  
The transition from the fiords to the trough marks also the transition from the Precambrian crystalline basement to Sedimentary  
(Cretaceous and younger) bedrock (Fig. 1; Praeg et al., 2007).

##### **3.1.2. Hecla & Griper Trough**

1425 Hecla & Griper Trough is 27 km long, 9 km wide and 780 deep. A longitudinal profile through the trough shows that it has a  
general trend of depths decreasing from the junction with Scott Trough (~840 m) to Sam Ford Fiord Fiord sill (~450 m; Fig.  
1). Hecla & Griper Trough is bounded on its southwest side by a steep wall of Precambrian crystalline bedrock (Figs. 1). The  
northeastern wall is less steep than the western wall and consists of sedimentary rock. The crystalline-sedimentary contact is  
not apparent on airgun data but, however, sedimentary structures and layers (parallel inclined reflectors) are apparent below  
1430 sediments forming the seafloor of Hecla & Griper Trough, indicating that most of the rock underlying the trough is sedimentary  
(Fig. 5). Hecla & Griper Trough can be divided into 2 longitudinal basins separated by a ridge that extends into Scott Trough.  
This latter ridge is composed of sediments without any bedrock ridge underneath, implying less geologic control over the

development and position of the ridge, and is interpreted as a medial moraine (Fig. 5). Other similar ridges occur in Hecla & Griper Trough but are carved in sedimentary bedrock. The transition between Hecla & Griper Trough and Sam Ford Fiord is marked by a 12 km large and 350–400 m deep plateau to the southwest, by bedrock shoals to the northeast and a 1.5 km-wide depression in-between (Fig. 1).

### **3.1.3. Sam Ford Trough**

Sam Ford Trough is 77 km long, 13 km wide, and 370 m deep. Similarly to Scott trough, the bathymetric profile through Sam Ford Trough shows generally increasing depths landward, but only from the middle shelf. However, the middle shelf bathymetric high in Sam Ford Troughs is not of bedrock origin, but coincides with an accumulation of glacial sediments constructed during the stabilization of an ice margin (Fig. 6; Praeg et al., 2007). The bedrock excavation of Sam Ford Trough exceeds by at least 75 m modern water depths for most of its length and is overdeepened by about 200 m landward. The accumulation of glacial sediments appears on the swath bathymetry imagery as 3 distinct lobes with one broadly aligned parallel to the trough. Sam Ford Trough is bounded laterally by longitudinal ridges that extend from Sam Ford Fiord sill up to the shelf break (Figs. 1–7). The sill at the mouth of Sam Ford Fiord marks the transition where the fiord becomes the trough. This sill is characterized by a >470 m depression to the south (Fig. 1) and plateau to the north. The southern depression extends to form Sam Ford Trough. The plateau on the northern part of the sill is mainly characterized by crystalline bedrock ridges and flat sediment-filled basins.

## **3.2 Ice-flow landforms**

### **3.2.1. Crag-and-tails**

Crag-and-tails are flow-oriented positive landforms with an identifiable bedrock “crag” at the head and a drift tail (Evans and Hansom, 1996). A total of 202 crag-and-tails occur within the trough system and on Sam Ford Fiord sill (Fig. 7). The crag-and-tails have lengths ranging between 98 m and 5935 m with a mean length of ~1071 m. They occur between 254 m and 836 m depths and most of them are located seaward of fiord sills and seaward of bedrock highs in Scott Trough (Bennett et al., 2014). Crag-and-tails have been widely used in paleoglaciological reconstructions as indicators of ice-flow orientation (e.g., Brouard et al., 2016; Brouard and Lajeunesse, 2017; Hogan et al., 2010; Jansson et al., 2003; Kleman et al., 2007). In association with mega-scale glacial lineations, drumlins and grooves, the presence of crag-and-tails generally indicates fast ice-flow conditions, i.e., ice streaming. Overdeepened curvilinear depressions (crescentic scours) occur in some cases upstream of crag-and-tails (Fig. 8). The presence of crescentic scours in front of crag-and-tails probably indicates the presence of meltwater (Graham et al., 2009; Graham and Hogan, 2016).

### **3.2.2. Drumlins**

Drumlins are smooth, asymmetric, oval-shaped hills (positive landforms) with a steeper stoss side and a more gentle-sloping lee side (Clark et al., 2009). These landforms occur at depths ranging from 179 m to 755 m. The 486 mapped drumlins have length ranging between 78 m and 1856 m with a mean of ~ 357 m, and are mostly located on the sills of the fiords (Fig. 7).

1465 Drumlins have a long axis oriented parallel to ice flow and occur in clusters and in association with glacial lineations, crag-and-tails, whalebacks and meltwater channels. Grouped into flow sets, drumlins can reveal palaeo-ice-flow orientation. Patterns of elongation and convergence of drumlins (together with other ice-flow landforms such as mega-scale glacial lineations and crag-and-tails) can be used as a relative indicator of ice-flow velocity and can therefore be used to identify ice-stream tracks (Stokes and Clark, 2002a). Drumlins are formed under wet-bed glaciers (King et al., 2007) and occur in  
1470 association with meltwater-related landforms such as meltwater channels or crescentic scours (Fig. 8). Overdeepened curvilinear depressions (crescentic scours) are in some cases present upstream of drumlins (Fig. 8).

### **3.2.3. Glacial lineations or mega-scale glacial lineations (MSGL)**

Glacial lineations are highly elongated (apparent elongation ratio 1: 10) parallel ridges (positive landform) formed in glacial sediments (Clark, 1993). Most glacial lineations are observed in Scott and Hecla & Griper Trough (Fig. 7) where they have  
1475 lengths ranging from 156 m to 8664 m with a mean of ~1026. Glacial lineations occur in the troughs at depths between 218 m and 840 m. They are generally oriented parallel to the troughs. Usually observed in sets, these landforms have a soft and mostly regular texture that likely reflects a sedimentary character (Ó Cofaigh et al., 2005, 2013). In some cases, ridges have a rougher texture that may imply a bedrock character or very thin sediment cover. MSGLs are indicators of fast ice flow suggesting palaeo-ice stream activity (Clark, 1993; Stokes and Clark, 2002a). Accordingly, they also indicate ice-flow  
1480 orientation. Cross-cut by grounding-zone wedges, mega-scale glacial lineations are interpreted to reflect time-transgressive ice flows occurring during the landward retreat of an ice stream (Brouard and Lajeunesse, 2017; Dowdeswell et al., 2008).

### **3.2.4. Grooves**

Grooves are linear to curvilinear negative landforms observed both in sediments and in bedrock. Grooves usually occur in association and aligned with mega-scale glacial lineations, crag-and-tails and drumlins. Alike the lineations, the grooves were  
1485 mostly mapped in Scott and Hecla & Griper troughs (Fig. 7). The 465 mapped grooves have lengths ranging between 84 m and 5882 m, with a mean of 944 m. They occur at depths between 127 m and 838 m. Produced by keels beneath glacial ice eroding the underlying substrate, grooves record palaeo-ice flow direction (Graham et al., 2009; Livingstone et al., 2012). Their presence alongside MSGLs under present-day ice streams suggests that they are the product of fast ice flow, i.e., an ice stream (Jezek et al., 2011; King et al., 2009).

### 1490 **3.2.5. Ice stream lateral moraines (ISLMs)**

Ice stream lateral moraines are curvilinear ridges (positive landform) observed on the sides of cross-shelf troughs. Ice stream lateral moraines are characterized by a gentle slope on their trough side and a steeper shelf side (Batchelor and Dowdeswell, 2016). Ice-stream lateral moraines are present on both sides of cross shelf troughs, but are not observed on the sides of Hecla & Griper Trough, probably because of the lack of decent data (Figs. 1–7). ISLMs in the study area are up to 61 km-long and 8 km wide. Ice-stream lateral moraines are believed to be formed subglacially at the shear zone between fast-flowing ice and slower-flowing ice or ice-free terrain (Batchelor and Dowdeswell, 2016). They can therefore be used to delineate the lateral extent of an ice stream (Brouard and Lajeunesse, 2017; Margold et al., 2015b; Stokes and Clark, 2002b).

### 1495 **3.2.6. Meltwater channels**

On swath bathymetry imagery, meltwater channels take the shape of sinuous longitudinal depressions (negative landform) that are generally carved in bedrock (Lowe and Anderson, 2003; Nitsche et al., 2013; Slabon et al., 2018). The 235 mapped meltwater channels occur at depths ranging between 202 m and 718 m (Fig. 7). Their length varies from 126 m to 4.1 km. Some channels are characterized by a flat bottom that indicates sediment infill (Brouard and Lajeunesse, 2019; Smith et al., 2009). They form anastomosing networks often extending in-between ice-flow landforms (MSGs, drumlins, crag-and-tails). The presence of these channels indicates abundant meltwater that could favor ice-bed decoupling, enable basal sliding, and generate ice streaming (Anandkrishnan and Alley, 1997; Engelhardt et al., 1990; Lowe and Anderson, 2003; Reinardy et al., 2011).

### 1505 **3.2.7. Subglacial medial moraines**

Subglacial medial moraines are large curvilinear sediment ridges (positive landform) with a smooth character and are ice flow oriented. On swath bathymetry imagery, they can be overprinted by iceberg ploughmarks, MSGs and grooves. Subglacial medial moraines are thought to be formed subglacially under constraints created by coalescing glaciers (Dowdeswell et al., 2016a). They therefore reflect the downstream movement of ice and act as indicators of ice-flow direction. Subglacial medial moraines were first identified in Scott Trough (Fig. 7; Dowdeswell et al., 2016a). Subglacial medial moraines were mapped in Scott and Hecla & Griper troughs (Fig. 7), where they reach up to 55.5 km in lengths.

### 1515 **3.2.7. Whalebacks**

Whalebacks are rough, asymmetric and oval-shaped hills (positive landforms) with a steeper stoss side and a more gentle-sloping lee side (Evans and Hansom, 1996; Roberts and Long, 2005). A total 321 whalebacks were identified. They occur at depths between 170 m and 700 m and have lengths varying between 61 m and 1044 m. The whalebacks have a flow-oriented long axis and are generally observed in clusters. In the study area, they occur in association with glacial lineations, crag-and-tails, drumlins and meltwater (Fig. 7). The whalebacks, grouped into flow-sets can be used to reveal palaeo-ice-flow direction

1520 (Krabbendam et al., 2016). Eroded into bedrock they can result of multiple glacial erosion cycles and therefore record multiple ice flows. Alike for drumlins and crag-and-tails, overdeepened curvilinear depressions (crescentic scours) can also be present upstream of some whalebacks.

### **3.3 Grounding-zone wedges**

1525 Grounding-zone wedges (GZW) are asymmetric tabular bathymetric wedges (positive landform) that are perpendicularly aligned to trough or fiord orientation. GZW are characterized on swath bathymetry imagery by an extensive stoss side with low gradients and a steeper and narrower lee side. Grounding-zone wedges occur in Scott (n=4) and Sam Ford troughs (n=3), forming bathymetric mounts (Figs. 1–7). GZW are formed by the accumulation of subglacial sediments at the grounding zone of an ice stream during temporary standstills of an ice margin (Dowdeswell and Fugelli, 2012; Lajeunesse et al., 2018). They have also been associated with the presence of ice shelves (Dowdeswell and Fugelli, 2012). The presence of an ice-shelf is  
1530 believed to restrict vertical accommodation space for sediments in favor of sediment progradation, which explains the low-amplitude and horizontally extensive (up to 139 km<sup>2</sup>) character of GZWs.

## **4 Discussion**

### **4.1 Ice stream tracks**

1535 In Scott Trough, the presence of mega-scale glacial lineations (MSGs) extending to the shelf break, together with a till unit extending on the trough-mouth fan and glacial debris flows on the shelf edge, indicate that the Laurentide Ice Sheet (LIS) reached the shelf break during the Last Glacial Maximum (LGM; Brouard and Lajeunesse, 2017; Jenner et al., 2018). MSGs, crag-and-tails and drumlins mapped in this region indicate that during the LGM, a tributary ice stream of the Scott Ice Stream extended from Sam Ford Fiord to Scott Trough through Hecla & Griper Trough (Brouard and Lajeunesse, 2017). Accordingly, the medial moraine ridges are interpreted to be the product of differential ice-streaming erosion. In a same way, coalescence  
1540 of multiple ice streams probably favored the formation of subglacial medial moraines over the ridges (Dowdeswell et al., 2016a). While the glacial origin of Scott Trough is obvious from its overdeepening and numerous ice-flow landforms, the glacial origin of Sam Ford Trough is confirmed by the presence of (1) ice stream lateral moraines and (2) grounding-zone wedges in the trough and a small overdeepened basin on Sam Ford Fiord sill (Figs. 1-6-7-8). However, the absence of ice-flow landforms in Sam Ford Trough suggests that the trough was occupied by slow-flow ice during the last glacial episode. The  
1545 slow ice flow contrasts with a recent glacial reconstruction stating that in full glacial conditions, Sam Ford and Scott troughs were characterized by separate ice streams that drained approximately comparable areas from the LIS (Batchelor and Dowdeswell, 2014). The presence of ISLMs on the sides of Sam Ford Trough together with an overdeepened basin and a 75 m-thick GZW (Figs. 6-7) in the trough also indicate that an ice stream originating from Sam Ford Fiord has also been, at some point, efficient enough to excavate the trough and to flush enough subglacial sediment to construct the multiple GZWs.  
1550 However, the ice streams in Sam Ford Trough were not efficient enough to build a trough-mouth fan at the seaward end of the

trough. The general thickness of paraglacial and postglacial sediments (~40 m) in Sam Ford Trough also suggests that the GZWs are older than the last glaciation (i.e., pre-Late Wisconsinan) and confirms the occurrence of slow-flowing and less erosive ice in Sam Ford Trough during the last glaciation. In comparison, paraglacial-postglacial sediments in Scott Trough, outside of the basins, never exceeds 10 m in thickness.

1555 Glacial bedforms on the sill of Sam Ford Fiord indicate that an ice stream flowed from Sam Ford Fiord through Hecla & Griper Trough. Although Hecla & Griper Trough has a structural origin since it was eroded along the crystalline-sedimentary contact, glacial lineations, crag-and-tails and grooves within the trough and on the sill of Sam Ford Fiord indicate that it was eroded by an ice stream (Brouard and Lajeunesse, 2017). The bathymetric profile in Hecla & Griper Trough (Fig. 2) showing depths increasing towards Scott Trough implies that ice-stream erosion was the most effective at the junction between Hecla & Griper and Scott troughs.

#### **4.2 Erosion of Hecla & Griper Trough**

1560 Erosion of fiords, troughs and bedrock basin overdeepenings has been proved to be a function of topography, ice discharge, subglacial hydrology, basal thermal regime, basal ice debris and glacier size (Cook and Swift, 2012; Kessler et al., 2008; Ugelvig et al., 2018). Overall, higher velocities together with thicker ice will generate more basal melt and will accelerate basal sliding and sediment flushing (e.g., Cook and Swift, 2012; Jamieson et al., 2008). Kessler et al. (2008) also demonstrated that topographic steering along was sufficient to produce overdeepened fiords and troughs. Analyses of bedrock basins of Antarctica and Greenland also indicated a similar erosion process where ice-flow confinement leads to deeper overdeepenings (Patton et al., 2016). This suggests that if an ice stream—and the associated erosive power—originated from Sam Ford Fiord, it should be expected that at equivalent ice velocity Hecla & Griper Trough would be the deepest at its narrowest section, i.e.,

1570 in-between the shoals and the shelf. However, Hecla & Griper Trough is the deepest at its widest, i.e., at its junction with Scott Trough. The erosion of Hecla & Griper Trough was therefore more dependent on down-ice dynamics occurring in Scott Trough rather than up-ice in Sam Ford Fiord. The down-ice dependence of Hecla & Griper Trough erosion is in agreement with an inferred strong relationship in the development of interconnected marginal troughs and cross-shelf troughs (Nielsen et al., 2005). Coincident with the contact between crystalline and sedimentary bedrock, Hecla & Griper Trough is therefore

1575 interpreted to result from a tributary ice stream of Scott Ice Stream eroding sedimentary bedrock along a weakness line, resulting in a morphology that is similar to other marginal troughs (Anderson, 1999; Nielsen et al., 2005). The down-ice dependence of erosion in Hecla & Griper also indicates that most effective erosion occurred in an up-ice direction. Similarly, analyses of overdeepenings in Antarctica and Greenland showed that below sea-level, most of the erosion of overdeepening occurs by headward erosion (Patton et al., 2016). Upstream propagation of high velocities—and erosional power—in ice

1580 streams is mainly dependent of instabilities at the ice margin or at the grounding zone; i.e., an acceleration of ice flow can propagate up-ice the main trunk of the ice stream and up-ice in the tributary ice streams (De Angelis and Skvarca, 2003; Hughes, 1992; Kleman and Applegate, 2014; Payne et al., 2004; Retzlaff and Bentley, 1993). Such up-ice progression of an ice stream can create a positive ice-erosion feedback, in which erosion of the overdeepening causes the headwall to steepen

and therefore further enhances sliding velocity and erosional power up-ice the ice stream (Herman et al., 2011). Therefore, Hecla & Griper Trough as a host to a tributary ice stream can have facilitated upstream propagation of ice streaming up to Sam Ford Fiord sill, forming a mature marginal trough.

### **4.3 Ice stream switching**

The presence of ice-flow landforms on Sam Ford Fiord Sill that are oriented towards Hecla & Griper Trough implies that ice discharge through Sam Ford Fiord was not oriented towards Sam Ford Trough. Sam Ford Trough is, however, interpreted as the product of an ice stream mainly originating from Sam Ford Fiord and in a minor way from Eglington Fiord (Margold et al., 2015a). Eglington fiord is interpreted as a minor contributor to Sam Ford Ice Stream because of the presence of a GZW (medial subglacial moraine?) attached to the junction between the fiords and clearly indicating that most of the ice discharge came from Sam Ford Fiord (Fig. 7). A possible scenario for the occurrence of landforms associated with an ice stream flowing from Sam Ford Fiord to both Scott and Sam Ford troughs would be that ice flow from Sam Ford Fiord was partitioned between Scott and Sam Ford troughs. Recent research suggests that if Sam Ford and Scott troughs were both occupied by comparable ice streams during full glacial conditions, they would have had similar drainage areas (Batchelor and Dowdeswell, 2014), similar width and therefore similar ice discharge (Stokes et al., 2016). The medial moraines in Scott Trough indicate that half of the ice that eroded the trough came from Sam Ford Fiord. Therefore, ice from Sam Ford Fiord would be responsible for about half of Scott Trough excavation, while also being responsible for the excavation of Sam Ford Trough. Accordingly, ice discharge through Sam Ford Fiord would need to have been twice the ice discharge of combined neighbouring Clark and Gibbs fiords. However, a 2:1 ratio of Sam Ford ice discharge over and Scott ice discharge is not compatible with estimates of paleo-ice discharge (1.04:1) and drainage area (1:1) that can be derived from recent models (Batchelor and Dowdeswell, 2014; Stokes et al., 2016). Another possible scenario that could explain the occurrence of landforms related to an ice stream flowing from Sam Ford Fiord to both troughs would be that Sam Ford Fiord ice discharge has always been directed towards Hecla & Griper Trough and that Sam Ford Fiord is the product of most extensive glaciations. During most extensive glaciations a part of Sam Ford Fiord ice discharge could be spilled towards Sam Ford Trough to form a shallower trough. This is unlikely to be the case because the last glaciation (MIS-2) was the most extensive glaciation in North America since MIS-6 (<130 ka BP; Ganopolski et al., 2010; Simon et al., 2014; Stokes et al., 2012) and one of the most extensive throughout the Pleistocene (Ehlers and Gibbard, 2003); yet there is no evidence for an ice stream in Sam Ford Trough during the last glacial episode. Also, if ice discharge from Sam Ford Fiord has always been directed towards Hecla & Griper Trough, it is expected that ice would erode, by topographic steering, an overdeepening at the narrowest section of Hecla & Griper Trough (See section 4.2). However, it is possible that a small part of Sam Ford ice discharge could have been advected towards Hecla & Griper Trough from its very beginning and facilitated ice-piracy by promoting the up-ice propagation of high velocities into an already fast-flowing ice system.

Therefore, partitioned ice discharge from Sam Ford Fiord in both troughs is possible but it cannot account for the trough morphology and for the full-scale erosion of both Sam Ford and Scott troughs. It is easier to propose a mechanism

where ice from Sam Ford Fiord switched from one trough to the other. Sam Ford Ice Stream would have first eroded Sam Ford Trough and then switched orientation to flow trough Hecla & Griper Trough. Following this ice flow-switching, the erosion in Sam Ford Trough ceased while the erosion in Scott Trough was enhanced by increased ice discharge; the difference in erosion volume between Sam Ford and Scott troughs can thus be explained by this mechanism.

As mentioned earlier, several mechanisms have been proposed to explain the switching behavior of an ice stream. Here we propose a mechanism that incorporates some of these mechanisms but where the flow switch of Sam Ford ice stream is due long-term erosion of up-ice propagating ice streams (i.e., Scott Ice Stream). Ice streams propagating upstream and eroding Hecla & Griper Trough have eventually eroded the marginal trough up to a point where it extended up-ice to reach the Sam Ford Fiord mouth. The changes in fiord depth-to-bedrock resulting from the erosion of the marginal trough and associated with the upstream propagation of Scott Ice Stream in Sam Ford system led to the: 1) reorganization of the ice drainage system; 2) switching of Sam Ford Ice Stream from Sam Ford Trough to Scott Trough; and ultimately, 3) shutdown Sam Ford Ice Stream in Sam Ford Trough (Alley et al., 1994; Anandakrishnan and Alley, 1997; Graham et al., 2010) (Alley et al., 1994; Anandakrishnan and Alley, 1997; Graham et al., 2010). Such ice piracy through the switching of ice streaming most probably occurred early during Pliocene-Pleistocene glaciations; it could explain the absence of a trough-mouth fan at the seaward end of Sam Ford Trough and also why Sam Ford Trough is more than two-times shallower than Scott Trough. It is probable that ice-streaming in Sam Ford Trough only occurred during a short period at the beginning of early (Late-Pliocene—Early Quaternary?) glaciations, before its ice discharge was captured by the Scott Ice Stream. As this process repeated itself throughout glacial cycles, it accentuated the depth of Hecla & Griper Trough, which in turn facilitated the capture of Sam Ford Ice Stream by Scott Ice Stream during subsequent glaciations. The changes in depth-to-bedrock associated with the upstream propagation of Scott Ice Stream in Hecla & Griper also led to a point in time when the Sam Ford Fiord ice discharge switched to be topographically diverted towards Hecla & Griper (i.e., the 1.5 km-wide depression). From that point on, ice-streaming conditions were unlikely to occur in Sam Ford Trough. Taken together, these observations suggest that the erosion and the morphology of the troughs of northeastern Baffin Shelf is a function of a competition for ice drainage basins. This process shares striking similarities with fluvial drainage-basin reorganizations linked to river captures (Bishop, 1995): where in the northeastern Baffin Island case, a dry valley (Sam Ford Trough) with fluvial deposits (here glacial, i.e., the GZW) and a knickpoint (the 1.5 km-wide depression at the head of Hecla & Griper Trough).

An ice-drainage piracy mechanism similar to river captures in fluvial systems can ~~also~~ probably not explain the occurrence of all the other abandoned cross-shelf troughs that do not extend up-ice to the coast or to fjords, mainly because each have different geological, glaciological and climatic contexts. However, the presence of morphologically similar systems can be observed on ~~most high latitude~~ many formerly glaciated continental shelves; e.g., small troughs along the Antarctic Peninsula (Fig. 4A9a) and Pennell Trough on West Antarctica shelf, Shelf; Unnamed Trough on Disko Bank on West Greenland Shelf (Fig. 4B); 9b); Okoa Bay on the Baffin Shelf (Fig. 4C); 9c); small cross-shelf troughs off the coast of Labrador and Newfoundland (Canada; Fig. 4D); 9d); or Angmagssalik Trough on East Greenland Shelf. Much alike Sam Ford Trough, these cross-shelf troughs are shallow and oriented towards a fjord fiord that probably fed an ice stream during full glaciation.



However, these shallower troughs do not reach the fjord mouth because they are all intersected by the marginal trough of a deeper adjacent cross-shelf trough reaching the shelf break, suggesting that (i) they were cut-off from their glacial ice supply and (ii) their ice stream was probably shutdown, as with the Sam Ford Ice Stream. The presence of the such abandoned and less eroded cross-shelf troughs—which are also intersected by marginal troughs—on most formerly glaciated continental shelves of the ~~World~~ world possibly result from a similar mechanism to Scott-Sam Ford system. However, further investigations are most probably the product of a race needed to confirm that competition between adjacent ice streams for ice discharge stream played a role in the development of these trough systems.

#### **4.4 Competition for drainage basins and ice sheet stability in marine environments**

~~Although competition for ice drainage basins between ice streams has long been recognized as a driver for changes in ice sheet geometry (Greenwood and Clark, 2009; Payne and Dongelmans, 1997) it has not been given much attention compared to other hypotheses for switching as this idea has only been derived from modelling studies. However, the geomorphology and glacial trough assemblages in the Scott-Sam Ford system provides for the first time empirical evidence that adjacent ice streams interplayed in a competition for ice discharge during the Pliocene-Pleistocene. The geomorphology of Hecla & Griper Trough outlines that this competition was dependent of dynamics occurring at the down-ice and indicates that the upstream propagation of instabilities occurring at the ice margin play a fundamental role in organizing ice flow routes within ice sheets. The hypothesis of instability waves propagating upstream in ice streams and outlet glaciers has been mentioned in a series of recent papers (e.g., (Felikson et al., 2017; Nick et al., 2009; Price et al., 2011; Reese et al., 2018). The erosion of the Hecla & Griper marginal trough is in accordance with such a wave theory; the presence of a marginal trough along the transition between sedimentary and crystalline bedrock indicates that the instability wave, travelling up-ice, was redirected along the sedimentary-crystalline contact, which enabled the formation of a tributary ice stream that eroded the trough. Redirection of the instability wave was probably due to: i) differential erosion; and ii) the competition between advection and diffusion of the wave (Felikson et al., 2017). Differences in bedrock lithologies generated differential erosion at the transition between sedimentary and crystalline bedrock. This differential erosion most likely led to the overdeepening of the cross-shelf trough which created a topographic step (steep bed profile) at the transition between crystalline and sedimentary bedrock. This topographic step favored relatively thin ice and a steep ice profile where down-glacier advection dominated and thus limited up-ice diffusion of ice streaming from that location. Conversely, the sedimentary continental shelf represents a relatively flat bed and therefore flat ice profiles where diffusion of the wave could have dominated. Hence, the diffusion of the wave was redirected on the shelf along the transition between crystalline and sedimentary bedrock where the bed profile was the flattest. Long-term erosion along the bedrock contact could then have led to the erosion of a marginal trough. The formation of a marginal trough was a key structural element to produce a positive feedback that facilitated redirection and diffusion of up-ice acceleration. The competition between the adjacent ice streams on the continental shelf was therefore «won» by the ice stream that was the most efficient at diffusing its fast flow, up-ice, through its tributaries, i.e., through marginal troughs.~~

The competition between ice streams and their switching on and off imply important configuration changes in ice stream and ice sheet geometries. As inland thinning of ice sheet can be controlled by ice margin geometry (Felikson et al., 2017), the competition for ice drainage basin represents a major driver in ice sheet growth and decay. Accordingly, abrupt changes in ice stream networks are also expected to influence ice sheet stability. Where ice stream switching occurs and ice streams combine, the ice flow acceleration can propagate upstream both (Scott and Sam Ford) drainage basins. They can then affect a greater area of the ice sheet and provoke ice divide migration (Greenwood and Clark, 2009). Such flow switching of ice streams can provide more efficient and rapid pathways for continental ice to reach the ocean, possibly leading to a more rapid drawdown of ice sheets. The merging of ice streams through ice piracy should result in an increase in ice discharge in the 'winning' trough and lead to a surge or readvance phase of the ice margin and an enhanced erosion. Although the overdeepened bathymetry of Scott Trough and its extent to the shelf break cannot be unequivocally attributed as a function of ice stream switching, the overdeepened basins in Scott Trough that are related to ice flow from Sam Ford Fjord represents almost half of Scott Trough area. The presence of these basins suggests the switch could account for up to half of the erosion of Scott Trough. The mechanism of ice stream switching through marginal troughs can therefore lead to more extensive glaciations and deeper glacial troughs on high latitude continental shelves. The increasing depths in troughs behind grounding zones could also create a positive feedback during glacial retreat and result in more rapid retreat of the ice margin (Joughin and Alley, 2011; Mercer, 1978; Schoof, 2007). The particular behavior of ice stream switching within ice sheets should be the focus of further modelling studies that would include ice drainage competition between ice streams as a major control on ice sheet stability, particularly those with marine based calving margins.

Although competition for ice-drainage basins between ice streams has long been recognized as a driver for changes in ice sheet geometry (Greenwood and Clark, 2009; Payne and Dongelmans, 1997), it has not been given much attention compared to other hypotheses for switching as this idea has only been derived from modeling studies. However, the geomorphology, pattern and glacial trough assemblages in the Scott-Sam Ford system provide for the first time an empirical context where adjacent ice streams on a continental shelf could have interplayed in a competition for ice discharge during the Pliocene-Pleistocene. The erosion profile of Hecla & Griper Trough indicates that (i) this competition was dependent of glaciodynamics occurring down-ice, probably at the marine-based ice margin, and (ii) the upstream propagation of ice instabilities (or ice acceleration) occurring down-ice play a fundamental role in organizing ice-flow routes within the ice sheet. Felikson et al. (2017) modelled such up-ice propagation of a wave of thinning linked to changes in ice margin thickness. The hypothesis of instability waves propagating upstream in ice streams and outlet glaciers has also been mentioned in a series of recent papers (e.g., Felikson et al., 2017; Nick et al., 2009; Price et al., 2011; Reese et al., 2018). The erosion of the Hecla & Griper marginal trough confirms such a wave theory: instability waves traveling up-ice were redirected along the line of weakness along sedimentary-crystalline contact, which enabled the formation of a tributary ice stream that eroded Hecla & Griper Trough. Redirection of the instability wave was probably due to: i) differential erosion and ii) the competition between advection and diffusion of the wave (Felikson et al., 2017). Differences in bedrock lithologies most likely favored differential erosion rates that eventually resulted in a topographic step (steep bed profile) at the transition between crystalline and sedimentary bedrock. This topographic step

1720 1720 favored relatively thin ice and a steep ice profile, where down-ice advection dominated and thus limited up-ice diffusion of ice-streaming from that location. Conversely, the cross-shelf trough forms a relatively flat bed with flat-ice profiles where diffusion of the wave could have dominated. In this setting, the diffusion of the wave was redirected on the shelf along the transition between crystalline and sedimentary bedrock where the bed profile was the flattest. Long-term erosion along the bedrock contact could then have led to the erosion of a marginal trough. The development of a marginal trough was a key structural element to produce a positive feedback that facilitated redirection and diffusion of up-ice acceleration. The competition between adjacent ice streams on the continental shelf was therefore “won” by the ice stream that was the most efficient at diffusing up-ice its fast flow through its tributaries, i.e., through a marginal trough.

1725 1725 The competition between ice streams and their switching on and off imply important configuration changes in ice stream and ice sheet geometries. As inland thinning of ice sheets can be controlled by ice margin geometry (Felixson et al., 2017), the competition for the ice drainage basin represents a major driver in the growth and decay of an ice sheet. Accordingly, abrupt changes in ice stream networks are also expected to influence ice sheet stability. Where ice stream switching occurs and lead to the merging of two ice streams, ice-flow acceleration can propagate upstream in both glacial drainage basins (i.e.,  
1730 1730 in both Scott and Sam Ford in the study area). Merged ice streams can then affect a greater area of the ice sheet and provoke ice-divide migration (Greenwood and Clark, 2009). Such flow-switching of ice streams can provide more efficient and rapid pathways for continental ice to reach the ocean, possibly leading to a more rapid drawdown of the ice sheet. The merging of ice streams through ice piracy should result in an increase in ice discharge and erosion rates in the “winning” trough. The winning ice stream gains mass balance and thus should equilibrate by advancing its margins (if it is not already at the shelf  
1735 1735 break).

1740 1740 Although the overdeepened bedrock basin of Scott Trough and its seaward extent to the shelf break cannot be unequivocally attributed to ice stream-switching, the longitudinal basins in Scott Trough that are related to ice flow from Sam Ford Fiord represents almost half of the width of Scott Trough. The presence of these basins suggests the switching could account for up to half of the erosion of Scott Trough. The mechanism of ice stream switching through marginal troughs can therefore lead to more extensive glaciations and to the erosion of deeper glacial troughs on high latitude continental shelves: merging ice streams would allow the glacial ice to extend farther and erode deeper on these shelves. The increasing depths in troughs behind grounding zones are known to create a positive feedback during glacial retreat that result in more rapid retreat of the ice margin in progressively deeper waters (Joughin and Alley, 2011; Mercer, 1978; Schoof, 2007). Therefore, a flow-switch caused by marginal trough erosion is expected to make ice sheets occupying similar trough systems on continental  
1745 1745 shelves more sensitive to climate forcing, on both short (within a glacial cycle) and long term (over multiple glacial cycles).

## 5 Conclusions

The swath bathymetry imagery and the geophysical data collected in a simple trough network of the Northeastern Baffin Island Shelf (Arctic Canada) provide evidence for the flow switch of a ice stream that occurred during the Pliocene-Pleistocene on

1750 the northeastern Baffin Island shelf (Arctic Canada) through glacial erosion and overdeepening of a marginal trough. The glacial geomorphology of the seabed and the erosion profiles of the troughs network provides for the first time an empirical context where adjacent ice streams could have interplayed in a competition for ice discharge. This competition for ice discharge between ice streams was dependent of dynamics occurring at the marine-based ice margin (i.e., the grounding zone), indicating that the upstream propagation of high glacial velocities plays a fundamental role in organizing ice-flow routes and catchments within ice sheets. Such a union of glacial ice catchments by switching provides more efficient and rapid pathways for  
1755 continental glacial ice to reach the ocean, enhancing the extent and erosive action of ice streams on high latitude continental shelves. These results suggest that the up-ice propagation of high ice velocities is a major driver of changes in the geometry of ice sheets during their growth and decay; it can therefore affect ice sheet stability. The hypothesis that the ice stream switching mechanism plays a major role on the geological evolution of formerly glaciated continental shelves through the extension of marginal troughs is supported by other examples from continental shelves located at the former margins of the Laurentide, the  
1760 Greenland and the West Antarctica ice sheets. These trough systems show striking morphological similarities with the through networks described in the study area and could also result from a competition between adjacent ice streams. As Laurentide Ice Sheet palaeo-dynamics inferred from Canadian Arctic continental shelves can be used as an analogue to understand how modern marine-based ice-sheets will respond to future climate change and sea-level fluctuations, these results highlight the  
1765 need for further investigations and further modeling studies that should include ice-drainage competition between ice streams and the resulting flow capture as a major control on ice sheet stability.

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1770 data in the region between 2003 and 2013. We thank 2 anonymous reviewers for providing valuable comments that improved the quality of the manuscript. This project was funded by ArcticNet Network Centres of Excellence and NSERC Discovery grants to P.L.

## **7 Authors contribution**

1775 E.B. and P.L. developed the study. E.B. interpreted the geophysical data sets/datasets, wrote the paper, and prepared the figures. P.L. helped with the interpretation and analysis, and contributed to the writing and editing of the paper.

## **8 Competing Interests**

The authors declare that they have no competing interests.

## **9 Data availability**

1780 The multibeam bathymetry dataset can be visualized and requested on the Université Laval Géoindex+ website (geoindex-plus.bibl.ulaval.ca). The seismic reflection data along with the acquisition specifics are available on the Geological Survey of Canada website (ftp.maps.canada.ca/pub/nrcan\_rncan/raster/marine\_geoscience/Seismic\_Reflection\_Scanned/).

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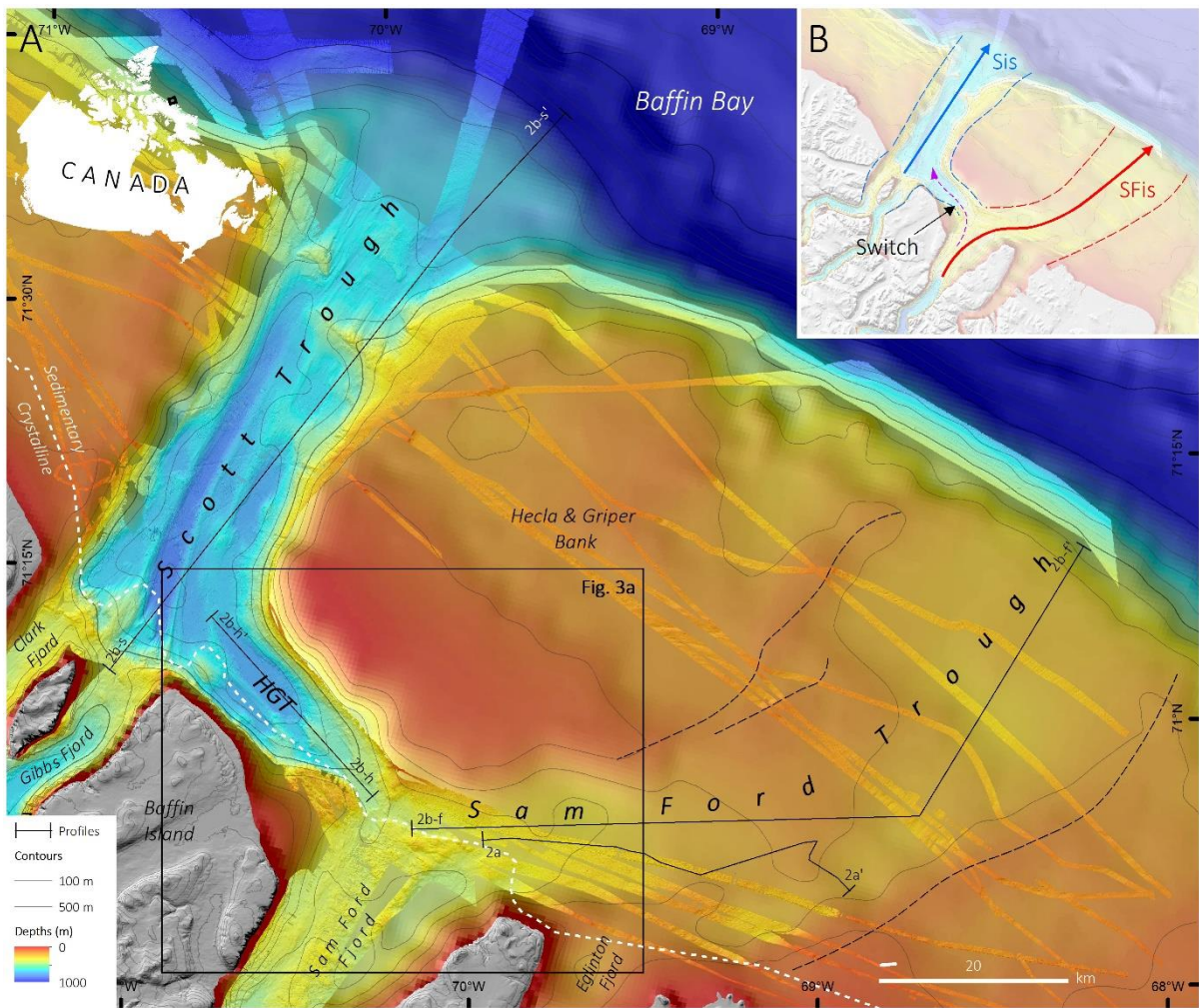
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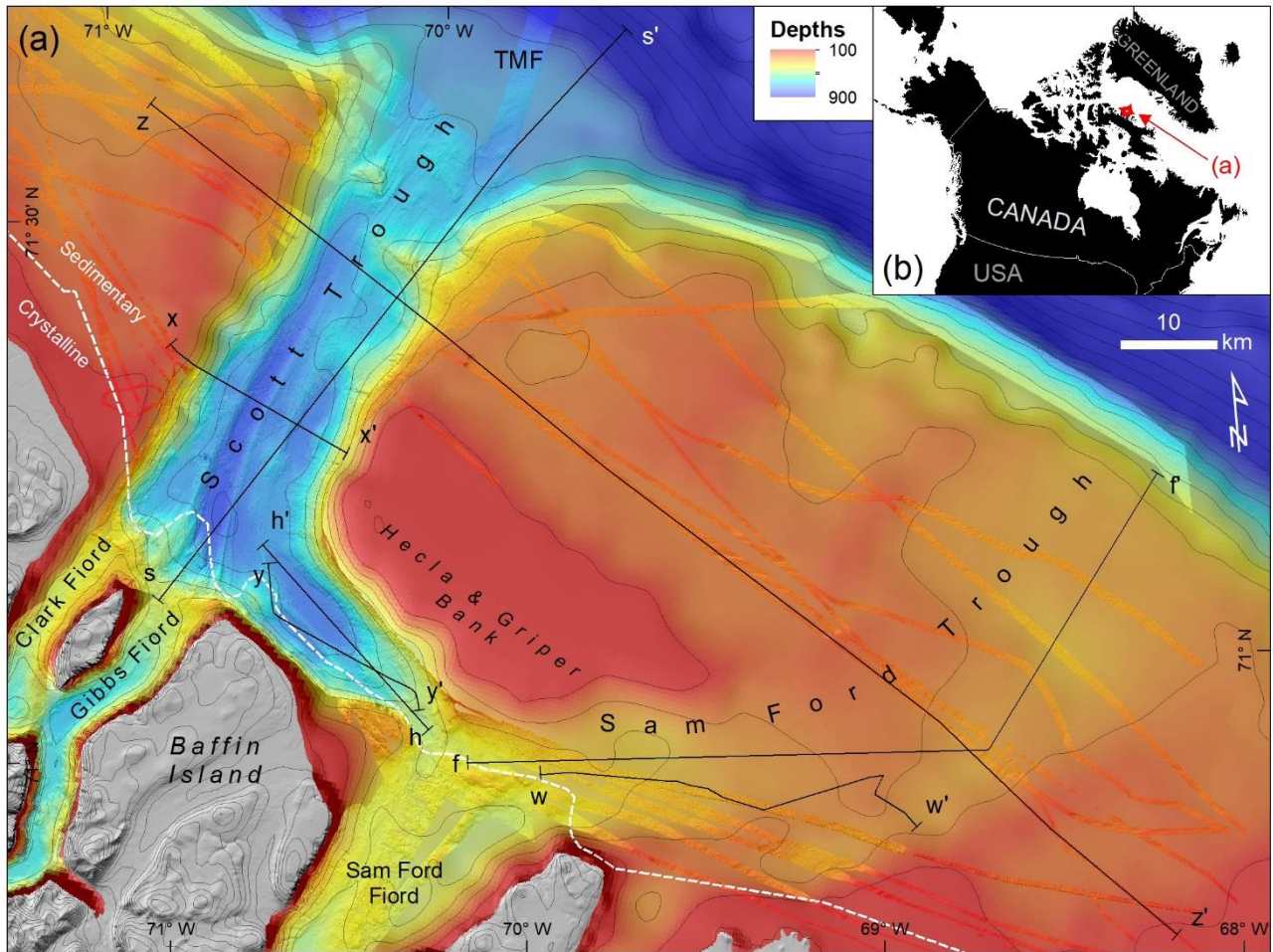
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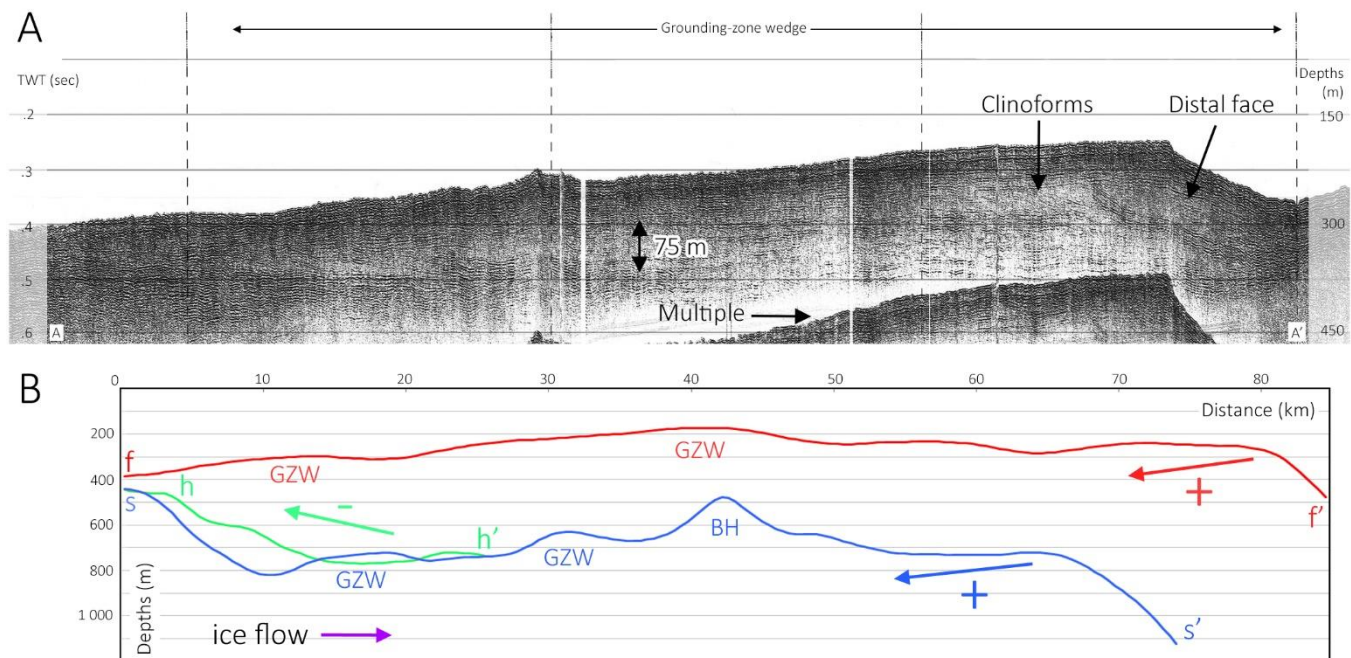
## 11 Figures



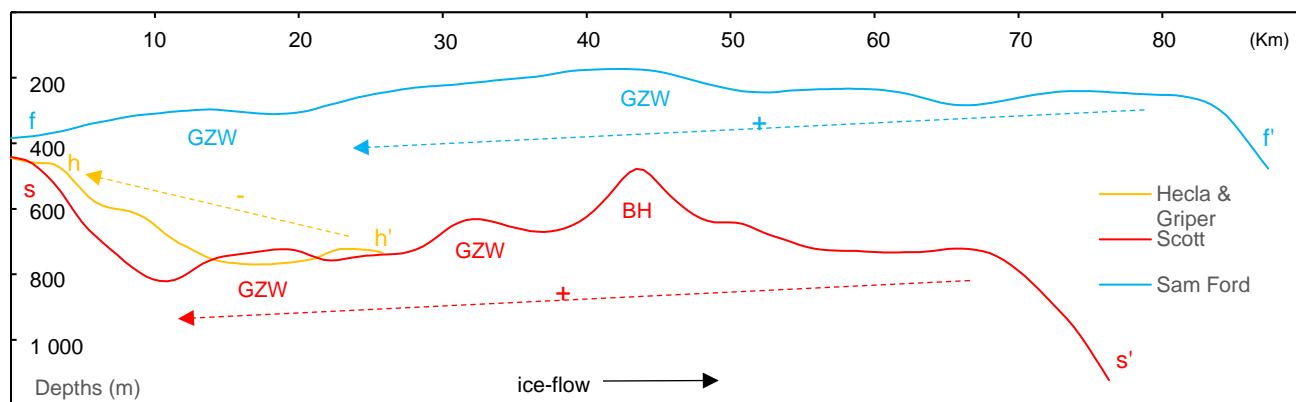
1905

Figure 1 A. Map showing the high-resolution bathymetric data collected by ArcticNet program (2003–2016) draped on the International Bathymetric Chart of the Arctic Ocean data (IBCAO; Jakobsson et al., 2012) map on the northeastern Baffin Island shelf. The black dashed-line shows the approximate limit between sedimentary and crystalline bedrock. HGT: Hecla & Griper Trough. Light-gray lines: 100 m contours. Dashed black lines: Ice-stream lateral moraines on the sides of Sam Ford Trough. **Inset:** Location of the study area. **B.** Schematic representation of ice streams that existed in the study area and the location of the ice stream switch. **Sis:** Scott Ice Stream. **SFis:** Sam Ford Ice Stream **B.** Location of the study area.

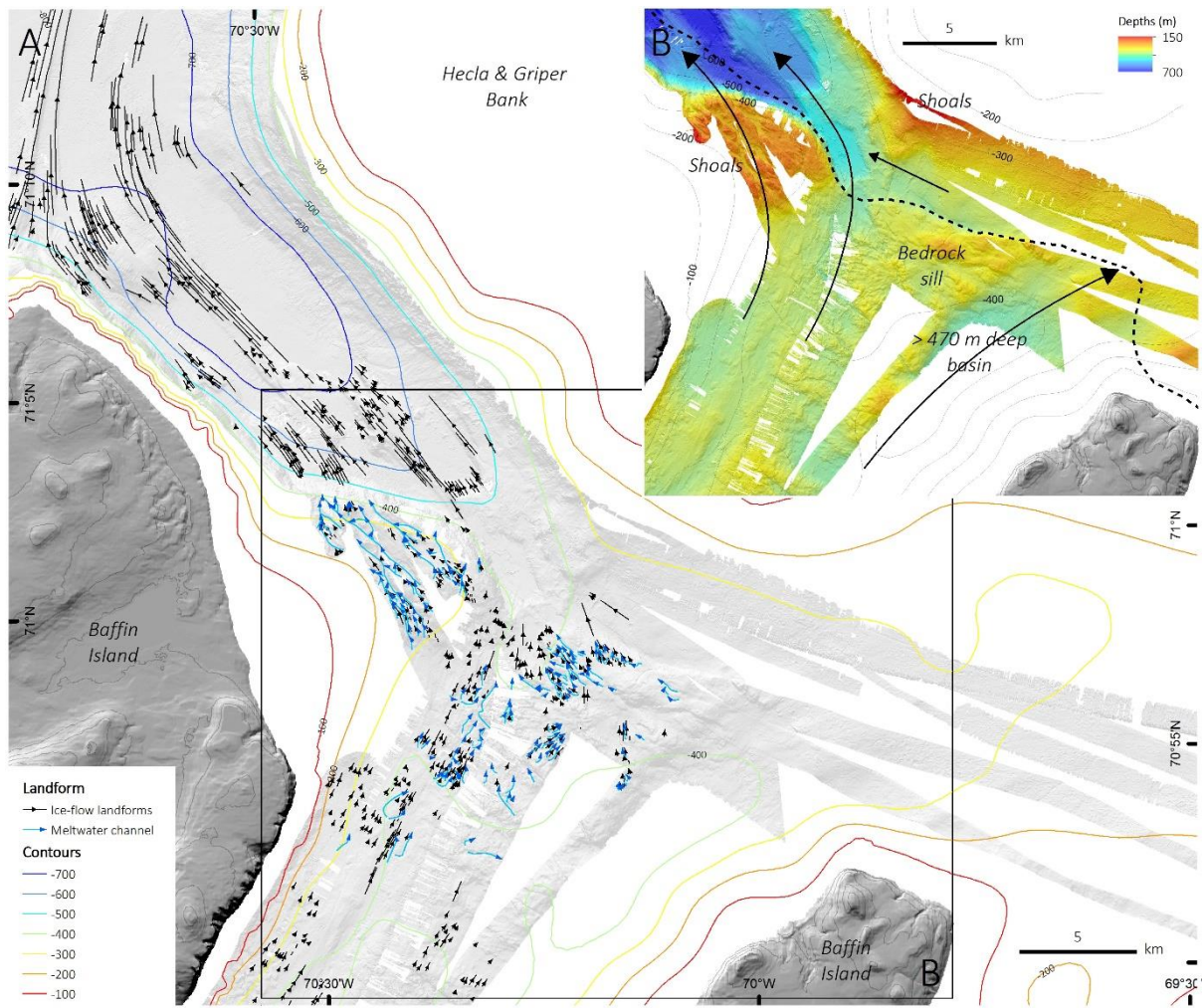
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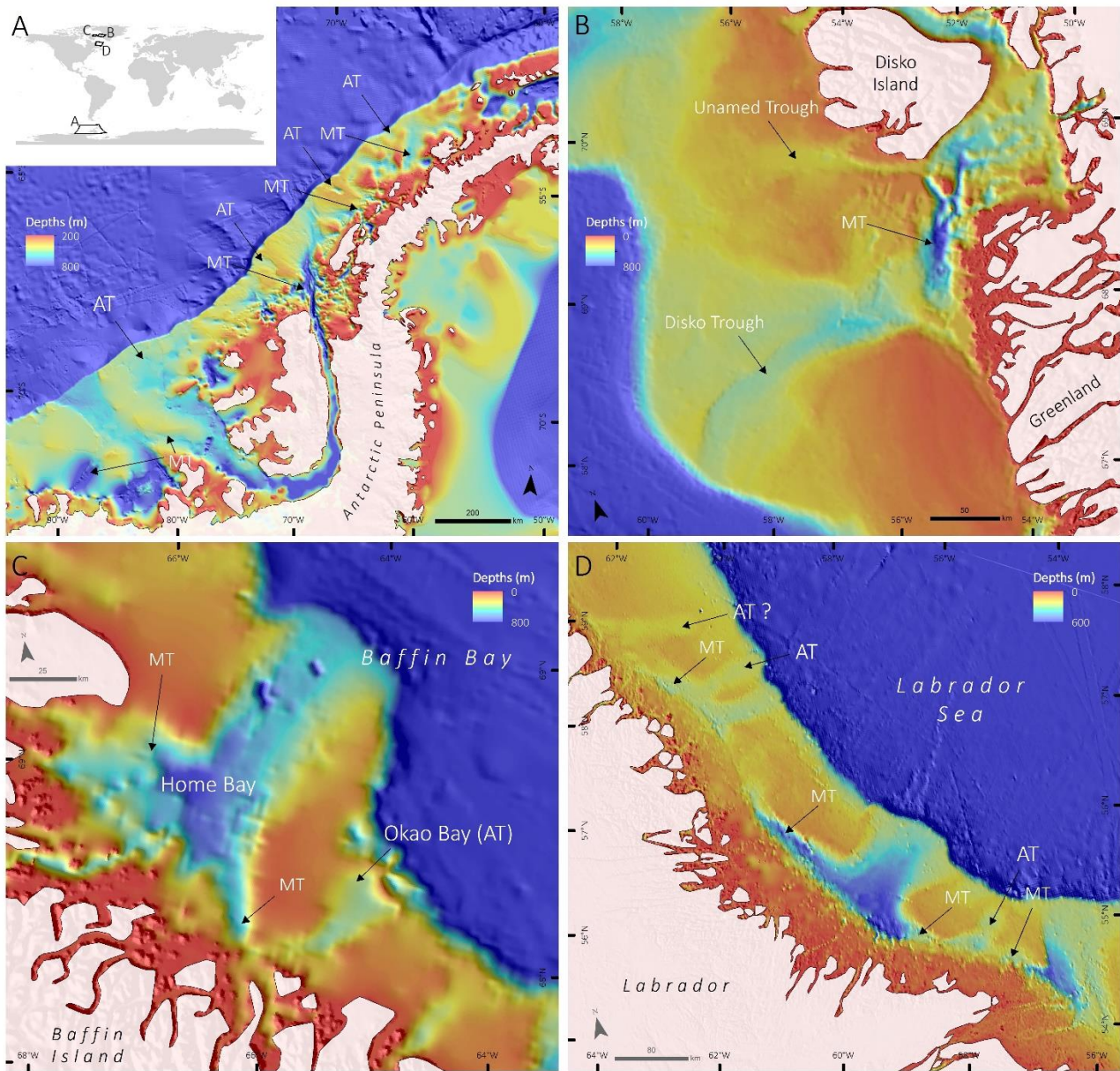
1915 **Figure 2 A.** Seismo-stratigraphic (Airgun) profile showing a major 75m-thick grounding-zone wedge (red) in inner-middle Sam Ford Trough (Profile 80028\_AG\_RAYT\_257\_0200; NRCan). **B**



1920 **Figure 2. A.** Longitudinal depths profile along ice-flow route for each trough. Arrow with minus (-) symbol indicates a general up-ice decreasing profile of depths. Arrows with plus (+) symbol indicate a general up-ice increasing profile of depths (glacial overdeepening landward). BH: Bedrock high; GZW: Grounding-zone wedge.

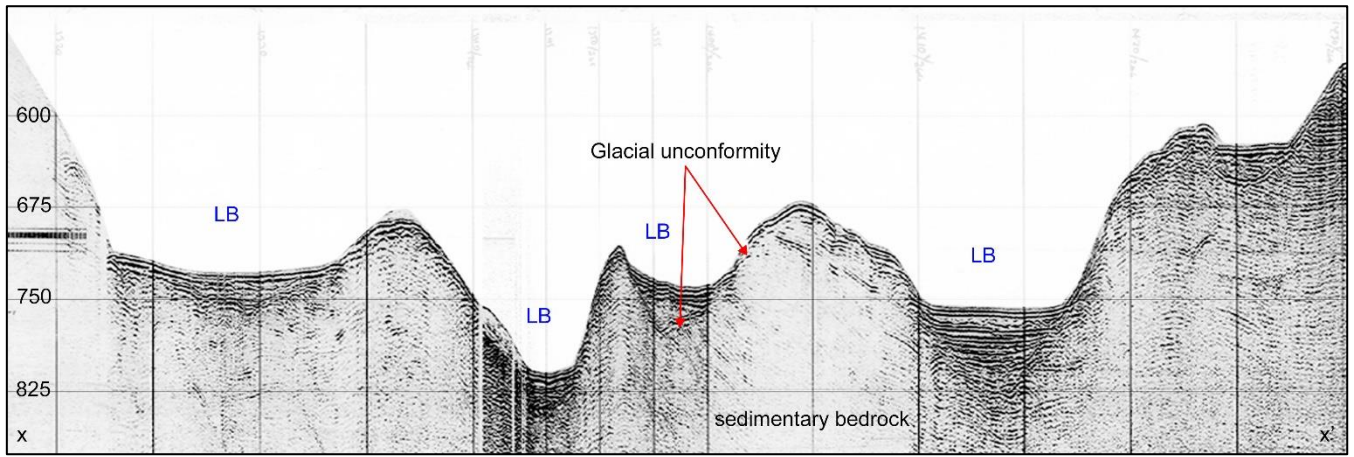


**Figure 3 A. Ice-flow landforms (lineations, crag-and-tails, drumlins, grooves) and meltwater channels interpreted from bathymetric data. SFS: Sam Ford Fjord sill. B. Close up on bathymetry showing the direction change in both ice-flow landforms and meltwater channels. Black arrows show general direction of the landforms.**



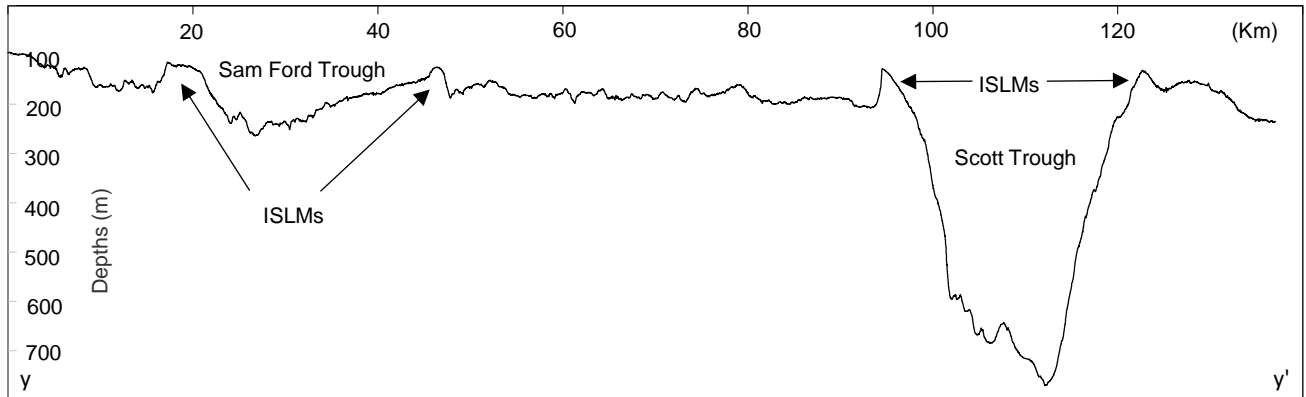
**Figure 4** A. Bathymetry (BEDMAP2; (Fretwell et al., 2013)) of the western continental shelf of the Antarctic Peninsula. MT: Marginal trough. AT: Abandoned trough. Inset: Location of figures A–D. B. Bathymetry (International Bathymetric Chart of the Arctic Ocean data; (Jakobsson et al., 2012)) of Unnamed and Disko troughs off West Greenland. MT: Marginal trough. C. Bathymetry (IBCAO) of Okoa Bay, Home Bay and marginal troughs off eastern Baffin Island. D. Bathymetry (IBCAO) of Labrador Shelf troughs off Labrador, Canada.

1935

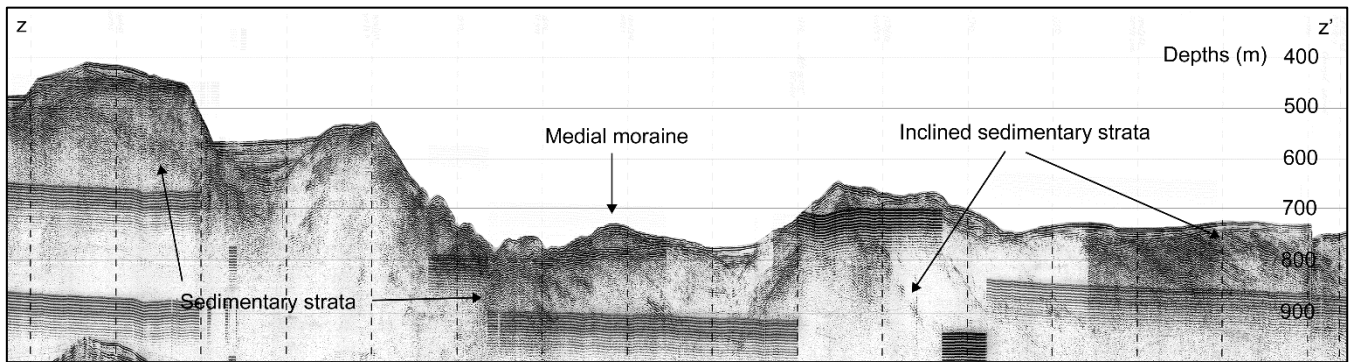


**Figure 3. Airgun profile across Scott Trough showing glacially-eroded basins filled with sediments (LB) and residual bedrock ridges (Profile 78029 AG 266 0758; NRCan).**

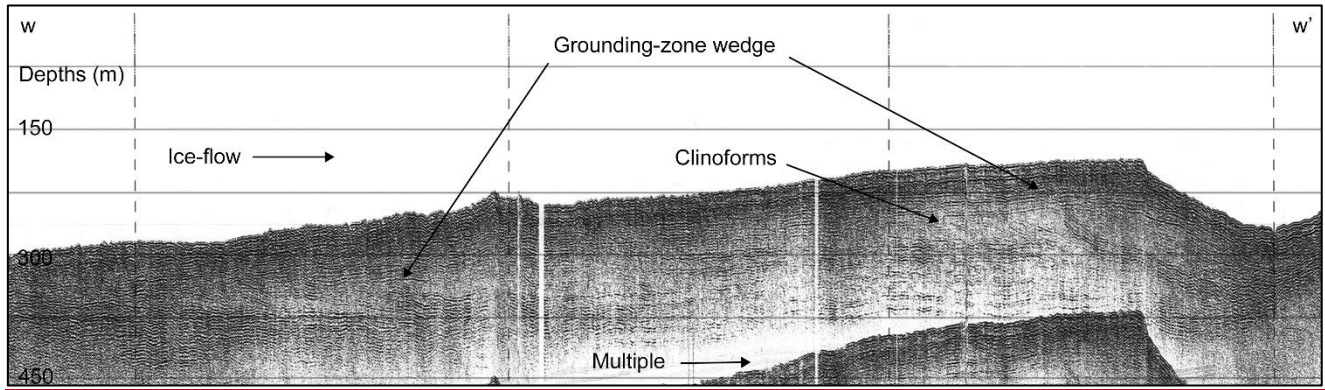
1940



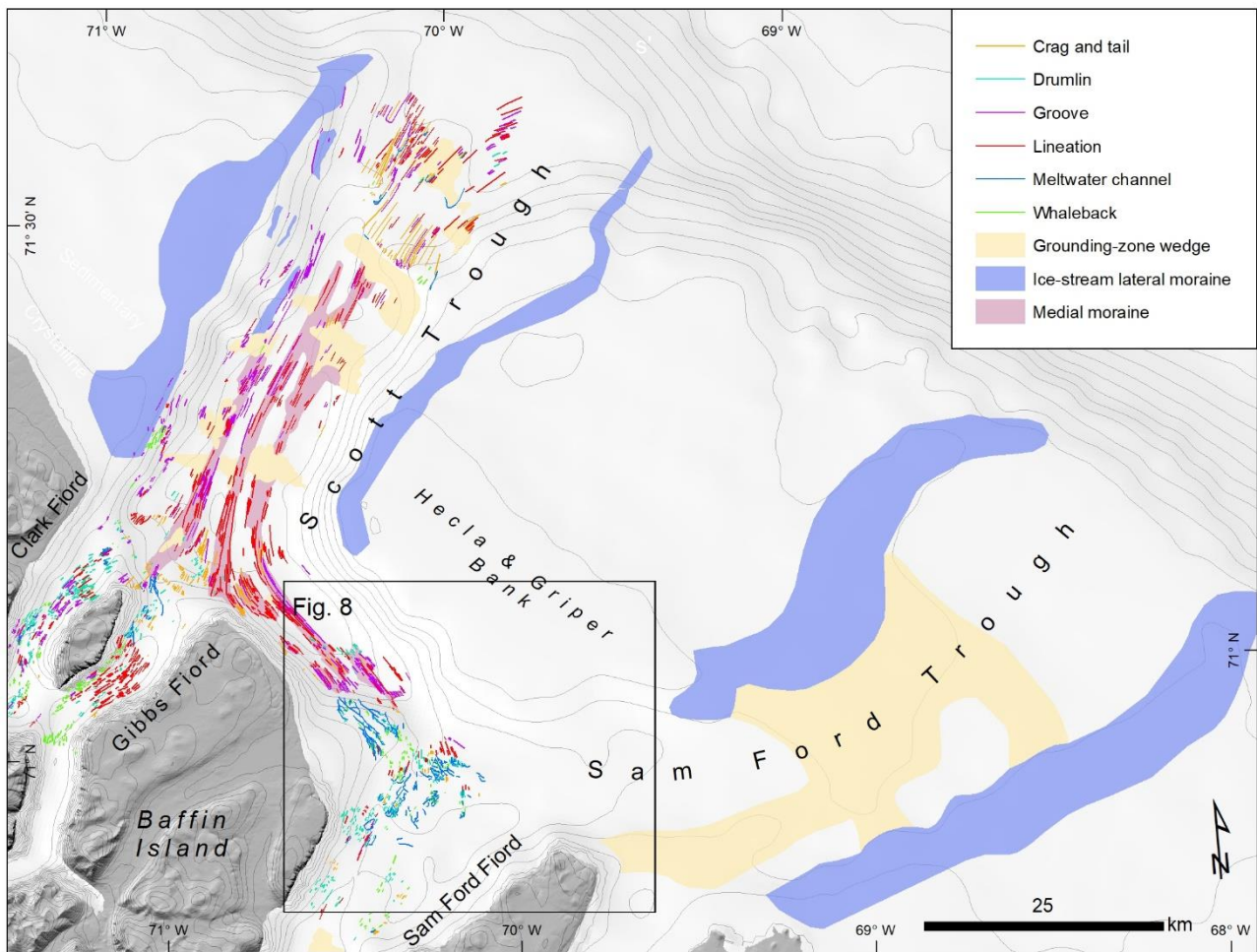
**Figure 4. Bathymetric profile across the northeastern Baffin Island Shelf showing Sam Ford and Scott troughs. The profile also shows the ice-stream lateral moraines on both sides of each trough.**



**Figure 5. Airgun profile in Hecla & Griper Trough showing both sediment and bedrock ridges molded by glacial erosion (Profile 78029 AG 268 0110; NRCan). The profile also shows inclined sedimentary strata that were eroded by glacial ice.**



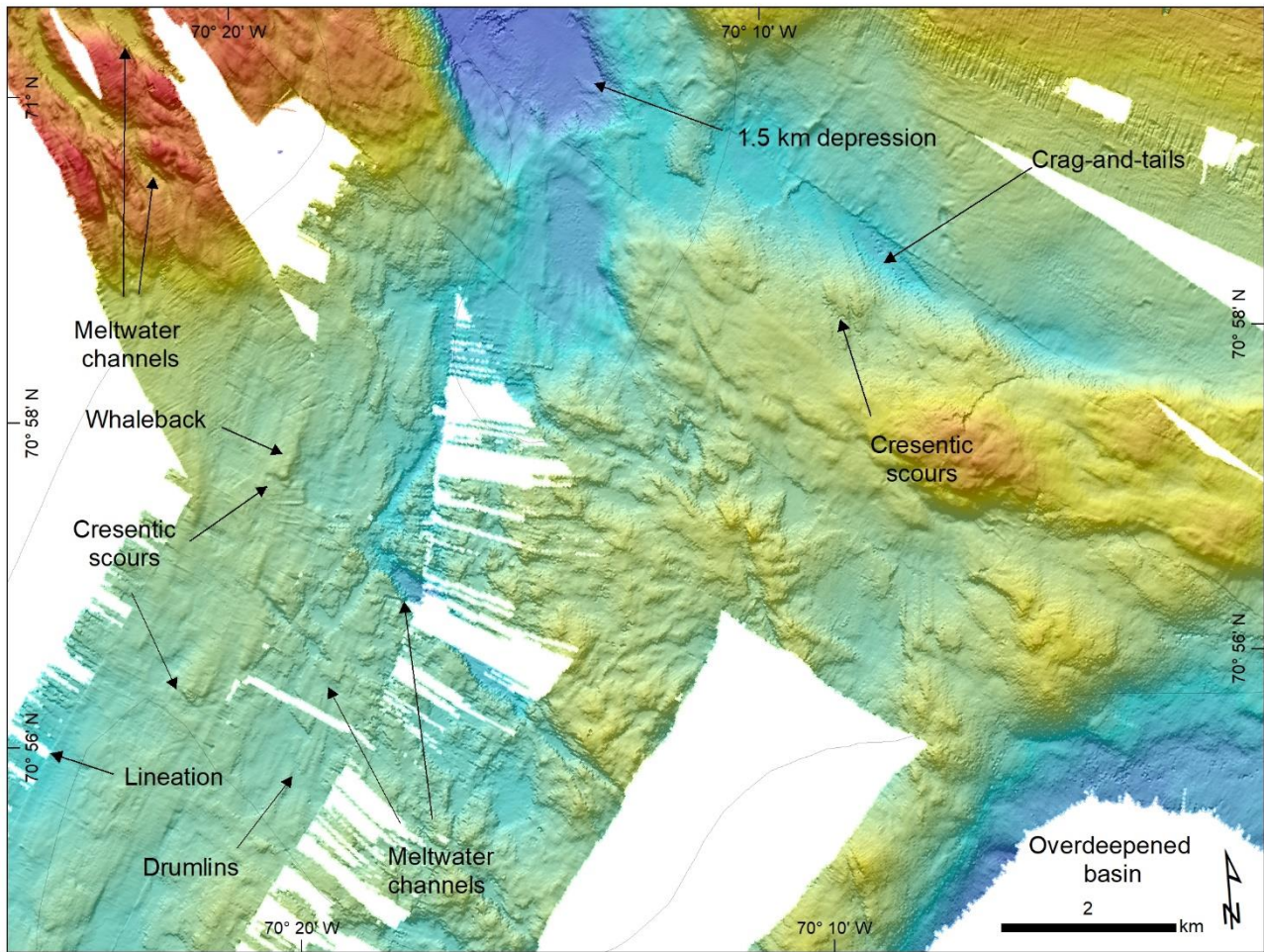
**Figure 6. Seismo-stratigraphic (Airgun) profile showing a major 75 m-thick grounding-zone wedge (red) in inner-middle Sam Ford Trough (Profile 80028 AG RAYT 257 0200; NRCan).**



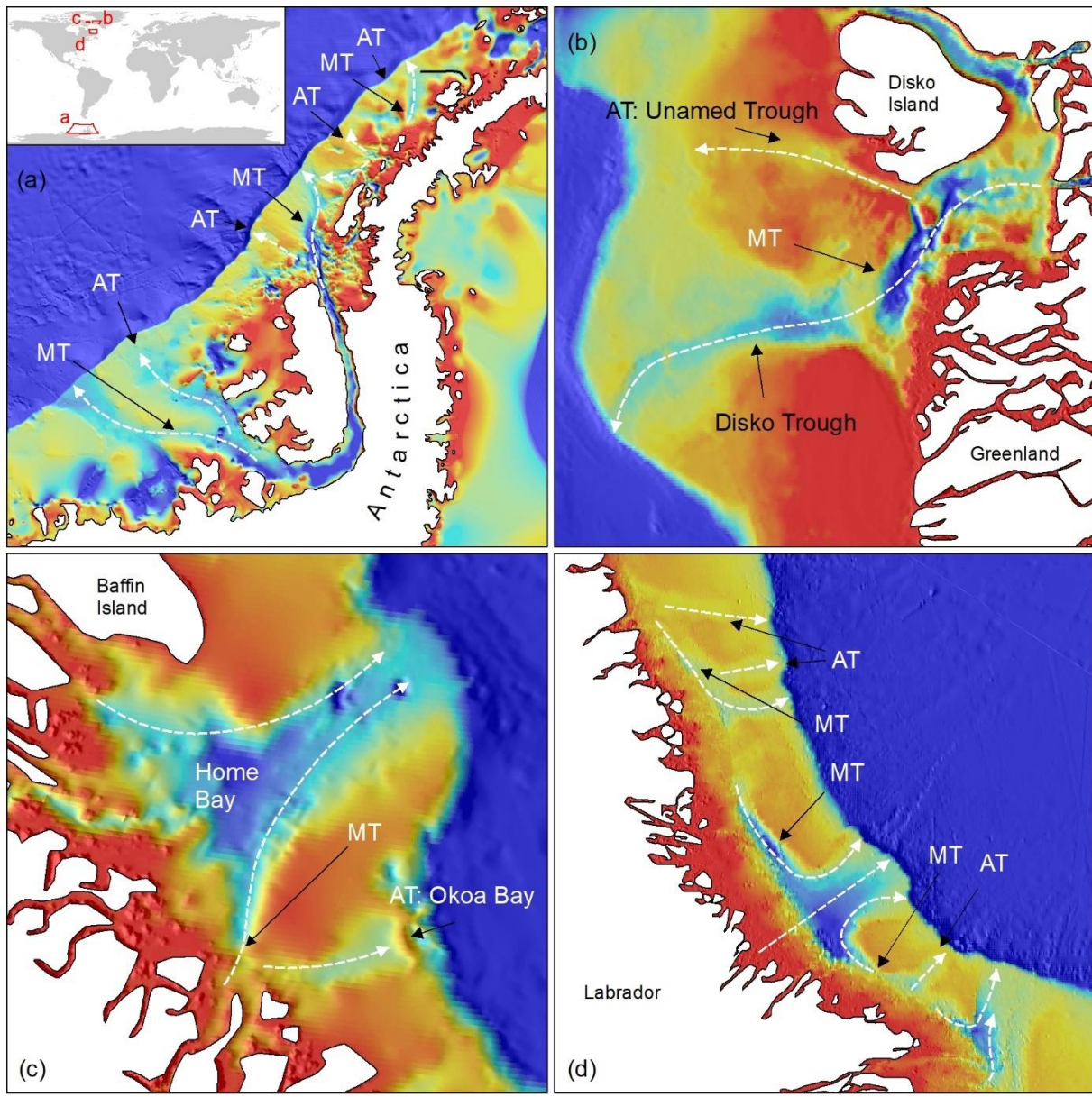
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**Figure 7. Distribution of landforms related to ice-flow and to ice margin stabilization on the continental shelf and fiords of the study area, in northeastern Baffin Island, Eastern Arctic Canada.**





**Figure 8. Examples of ice-flow landforms on Sam Ford sill that are oriented towards Hecla & Griper Trough, Eastern Arctic Canada.**



**Figure 9. A. Bathymetry (BEDMAP2; Fretwell et al., 2013) of the western continental shelf of the Antarctic Peninsula. MT: Marginal trough. AT: Abandoned trough. White dashed lines: Interpreted ice stream tracks. Inset: Location of figures A-D. B. Bathymetry (IBCAO) of Unnamed and Disko troughs off West Greenland. MT: Marginal trough. C. Bathymetry (IBCAO) of Okoa Bay, Home Bay and marginal troughs off eastern Baffin Island. D. Bathymetry (IBCAO) of Labrador Shelf troughs off Labrador, Canada.**

1955

1960