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A Race for Ice Discharge between Ice Streams on Glaciated Continental Shelves

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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 major impact on ice sheet mass balance and global sea level. However, the mechanisms controlling ice stream switching remain poorly understood. Here, we report 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. 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

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); 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 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 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 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 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 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 Steam 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 Steam 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-drainage piracy mechanism similar to river captures in fluvial systems can also explain the occurrence of other abandoned cross-shelf troughs that do not extend up the coast or to fjords on most high-latitude continental shelves; e.g., small troughs along the Antarctic Peninsula (Fig. 4A) and Pennell Trough on West Antarctica shelf, Unnamed Trough on Disko Bank on West Greenland Shelf (Fig. 4B), Okoa Bay on the Baffin Shelf (Fig. 4C), small cross-shelf troughs off the coast of Labrador and Newfoundland (Canada; Fig. 4D), or Angmagssalik Trough on East Greenland Shelf. Much alike Sam Ford Trough, these cross-shelf troughs are shallow and oriented towards a fjord 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 they were cut-off from their glacial ice supply and 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 are most probably the product of a race between adjacent ice streams for ice discharge.

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.

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Authors contribution

E.B. and P.L. developed the study. E.B. interpreted the geophysical data sets, 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.

Competing Interests

The authors declare that they have no competing interests.

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 Canada website (ftp.maps.canada.ca/pub/nrcan_rncan/raster/marine_geoscience/Seismic_Reflection_Scanned/).

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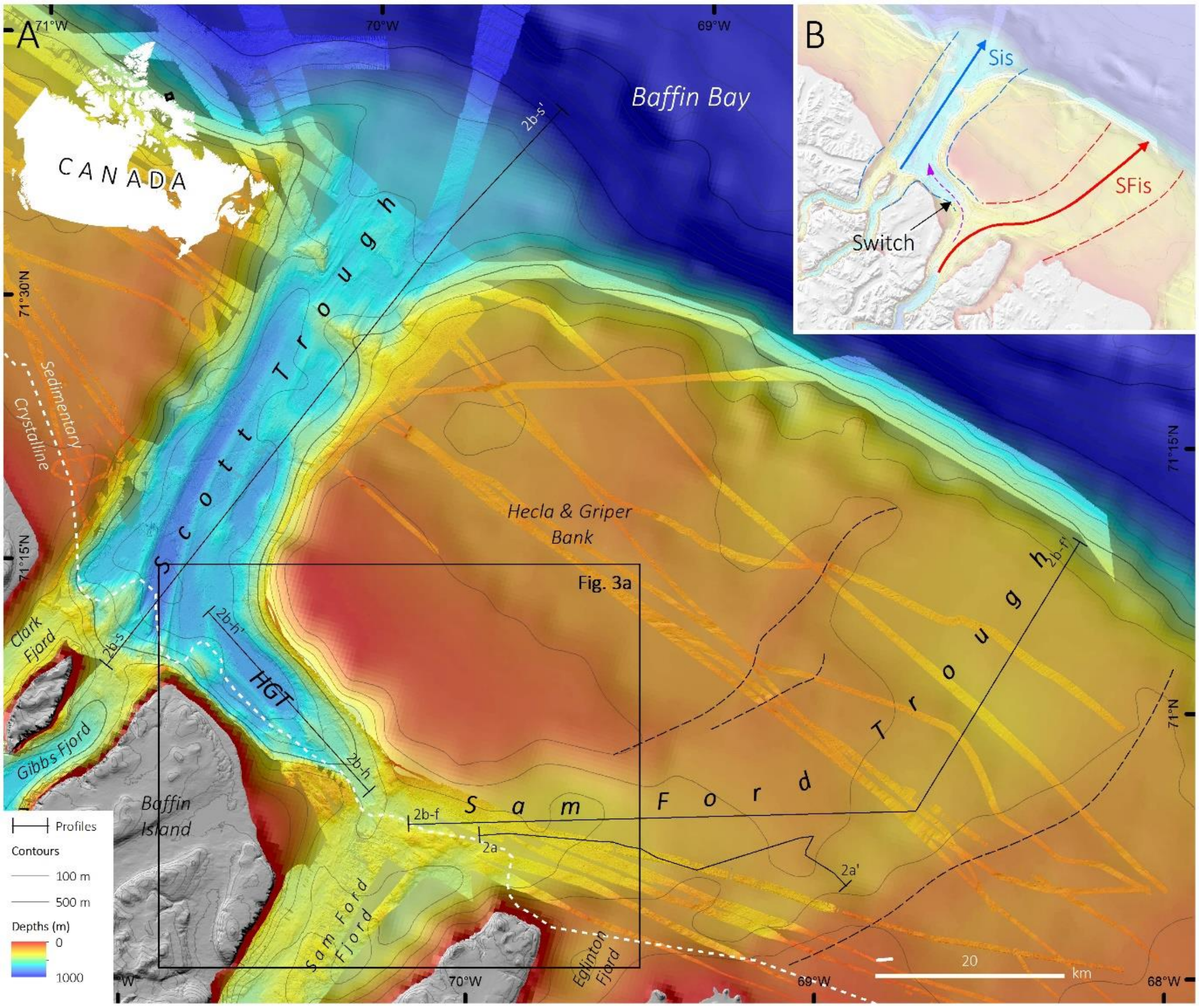

Figure 1 A. Map showing the high-resolution bathymetric data collected by ArcticNet program (2003-2016) draped on the International Bathymetric Chart of the Arctic Ocean data (IBCAO; Jakobsson et al., 2012) map on the northeastern Baffin Island shelf. The black dashed-line shows the approximate limit 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. 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.

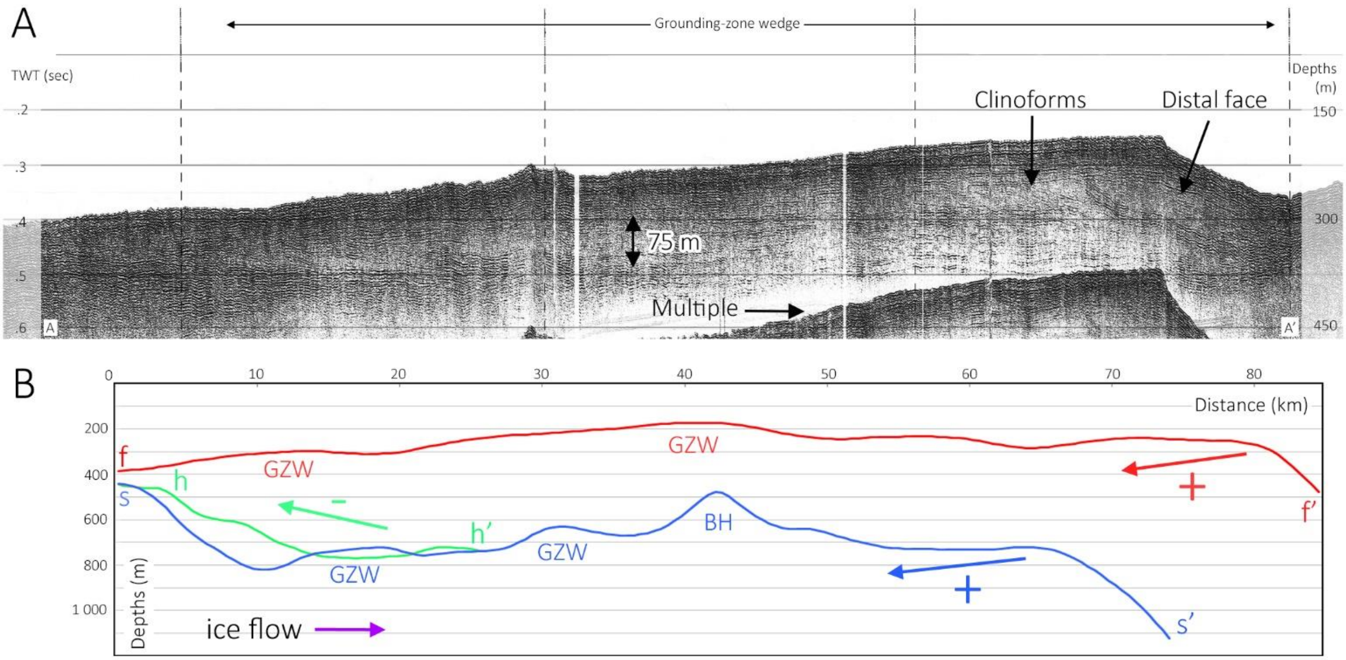

Figure 2 A. Seismo-stratigraphic (Airgun) profile showing a major 75m-thick grounding-zone wedge (red) in inner-middle Sam Ford Trough (Profile 80028_AG_RAYT_257_0200; NRCan). B. Longitudinal depths profile along ice-flow route for each trough. Arrow with minus (-) symbol indicates a general up-ice decreasing 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.

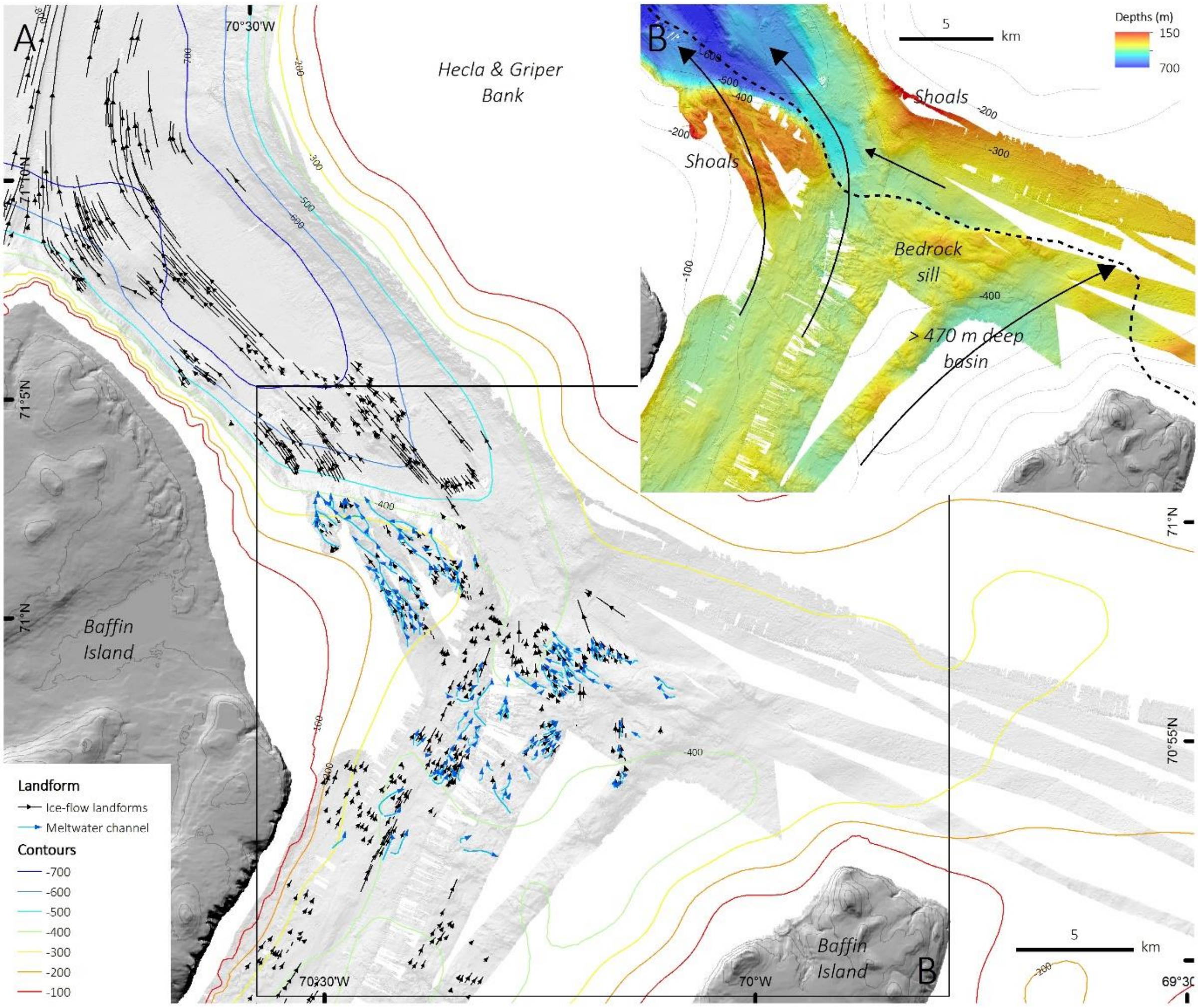

Figure 3 A. Ice-flow landforms (lineations, crag-and-tails, drumlins, grooves) and meltwater channels interpreted from bathymetric data. SFS: Sam Ford Fjord sill. B. Close-up on bathymetry showing the direction change in both ice-flow landforms and meltwater channels. Black arrows show general direction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

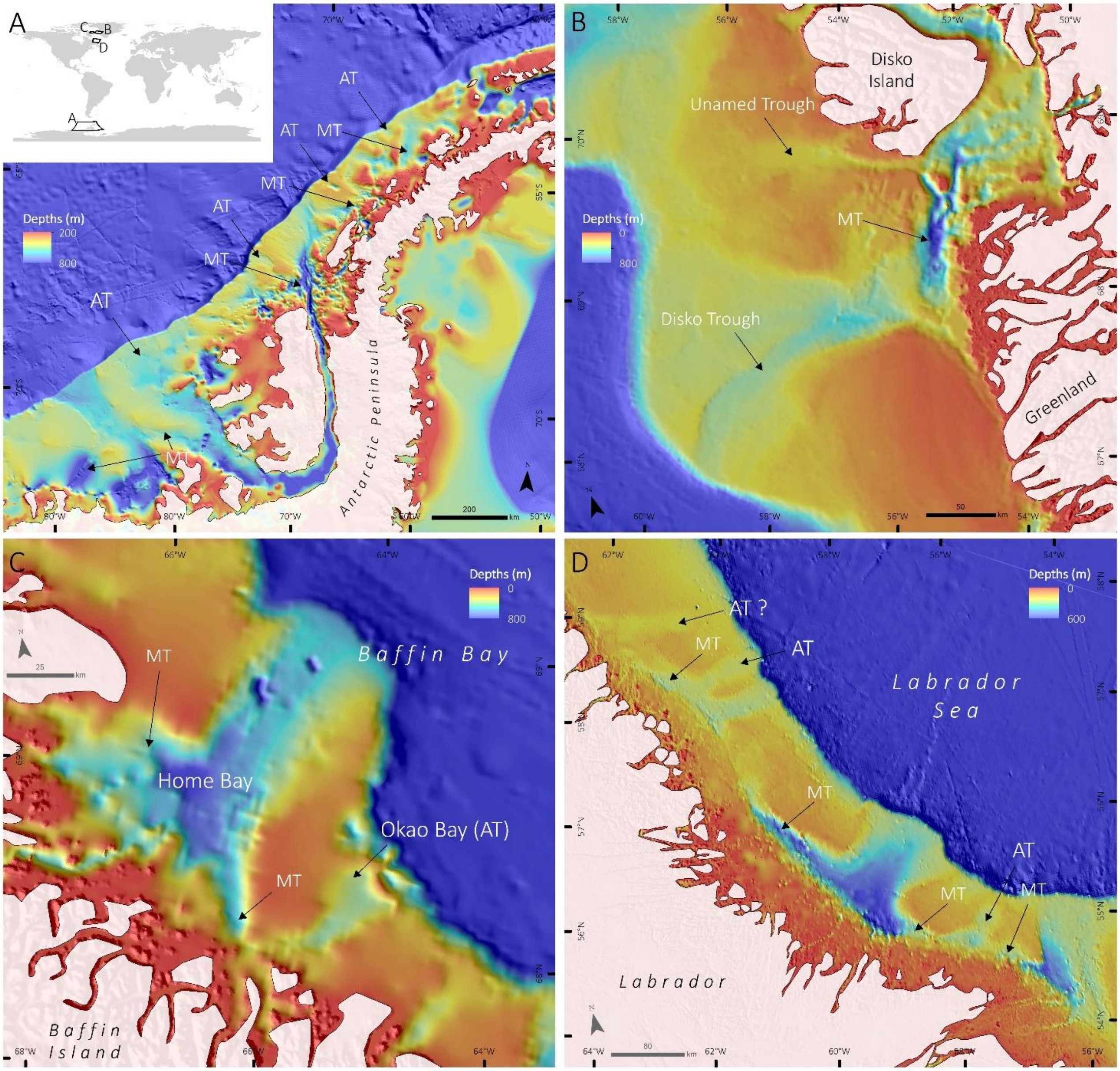

Figure 4 A. Bathymetry (BEDMAP2; (Fretwell et al., 2013)) of the western continental shelf of the Antarctic Peninsula. MT: Marginal trough. AT: Abandoned trough. Inset: Location of figures A-D. B. Bathymetry (International Bathymetric Chart of the Arctic Ocean data; (Jakobsson et al., 2012)) of Unnamed 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.