Submarine geomorphology of the northeastern Baffin Island fiords and cross-shelf troughs

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ABSTRACT
This paper presents a series of 50 geomorphological maps of the seabed of northeastern Baffin Island fiords and cross-shelf troughs, in eastern Arctic Canada. The mapping was produced using swath bathymetry imagery from multiple bathymetry datasets. A total of 24 types of landform were systematically mapped (>55,000 landforms) and reflect processes linked to subglacial, ice-marginal or paraglacial to postglacial environments. The landforms record the transition of the seabed from being covered by a marine-terminating ice sheet to the establishment of postglacial conditions. The landform assemblages allow the distinction of ice-flows orientation and ice-stream pathways along fiords and cross-shelf troughs. The multiple moraines and grounding-zone wedges indicate that the ice margin stabilized during retreat and that the overall deglaciation occurred by steps. These maps provide a framework for future investigations in northeastern Baffin Island fiords and shelf and can also provide a template for future seabed geomorphological studies in Arctic Canada.

1. Introduction
Fiords and troughs are common geomorphological systems on high-latitude coasts and continental shelves where they embody the most obvious expression of the erosional power of glaciers and ice sheets. Fiords and troughs of the present-day Greenland and Antarctic ice sheets host fast-flowing ice streams and outlet glaciers. Ice streaming is one of the most efficient mechanisms through which ice can be exported from the interior of ice sheets to the ocean; ice streams account for ~50% of Greenland (Van Den Broeke et al., 2009) and ~90% of Antarctica recent ice mass loss (Bamber, Vaughan, & Joughin, 2000). The future stability or instability of marine-based glaciers and ice sheets is intrinsically linked to the activity of their ice stream networks, which lie for the most part in fiord or cross-shelf trough settings. Accordingly, concerns have been raised over the response of Antarctic and Greenland ice streams to climate change, global sea-level rise and to warm-water incursions, especially with the presence of overdeepened fiords and troughs basins behind present-day grounding lines (Joughin & Alley, 2011; Joughin, Alley, & Holland, 2012; Mercer, 1978; Morlighem et al., 2017; Pritchard et al., 2012). As melting of Greenland and Antarctic ice sheets has the potential to raise global sea level by ~70 m (Alley, Clark, Huybrechts, & Joughin, 2005), there is a need to better constrain the dynamics of glacial retreat in crucial settings such as troughs and fiords.

While recent satellite data have brought insights on how ice sheet dynamics have evolved on a decadal time scale, they do not provide a long-term overview (centennial to millennial scale) that is consequent with a long-term evolution of climate. Centennial-to-millennial data on the long-term evolution of ice sheets can, however, be provided by investigating the geomorphology of deglaciated systems such as fiords and cross-shelf troughs. Fiords and cross-shelf troughs of deglaciated high-latitude coasts and continental shelves have the potential to provide crucial information on deglacial dynamics from a complete marine-terminating ice sheet to a full terrestrial-based ice sheet.

The advent of high-resolution swath bathymetry mapping systems in the last decades has shed a new light on landforms of glacial and postglacial origin present in fiords and troughs of previously glaciated high latitudes, such as Antarctica, Greenland, Svalbard, Norway, and Great Britain (see Dowdeswell, Canals et al., 2016). However, in Arctic Canada, systematic geomorphological mapping has been mainly limited to the terrestrial environment, which reflects the sparse swath bathymetry data available across the Canadian Archipelago. However, some sectors have been the focus multidisciplinary studies of the ArcticNet program (2003–2017) on board the CCGS Amundsen, which enabled gathering enough high-resolution swath bathymetry imagery to cover some cross-shelf troughs and fiords. The most complete sector where
troughs and fiords have been mapped is the northeastern Baffin Island shelf and fiords (Figure 1; Main Map). This sector is characterized by four major cross-shelf troughs, one marginal trough and 11 fiords where bathymetric coverage is available.

The Northeastern Baffin Island shelf and fiords are also of interest as they were inundated by the Laurentide Ice Sheet (LIS) during the Last glacial episode (29–14 ka BP) and were subsequently deglaciated by 6 ka BP (Andrews & Ives, 1978; Dyke, 2004; Briner, Bini, & Anderson, 2009; Brouard & Lajeunesse, 2017, 2019a; Jenner, Campbell, & Piper, 2018). Not much is known on pre-Late Wisconsinan ice sheets flowing through Baffin Island into the Baffin Bay. Glacial advances – and ice streams – of marine isotope stages (MIS) 5d/b and MIS4 were probably less extensive than during MIS2 (Ganopolski, Calov, & Claussen, 2010; Simon, Hillaire-Marcel, St-Onge, & Andrews, 2014; Stokes, Tarasov, & Dyke, 2012); therefore, glacial ice may not have reached the shelf edge between ∼130 and 25 ka BP. The last glacial stage (MIS2) reached its maximum around 25 ka BP in Western Baffin Bay, with the LIS reaching the shelf edge between Lancaster Sound and Home Bay (Figure 1; Jenner et al., 2018). During the MIS2 (25–16 ka BP), Scott and Hecla & Griper troughs were inundated by ice streams of the LIS (Briner, Miller, Davis, & Finkel, 2006; Brouard & Lajeunesse, 2017; Brouard & Lajeunesse, 2019b; De Angelis & Kleman, 2007; Margold, Stokes, Clark, & Kleman, 2015) that extended to reach the shelf break at the mouth of the troughs, while Sam Ford Trough was under slow-flowing ice (Brouard & Lajeunesse, 2017).

The LIS occupied most of the shelf until ∼14.1 ka BP and the deglaciation of the continental shelf was completed by ∼15–12 ka BP as coastal forelands emerged from the glacial ice cover (Briner et al., 2006; Briner, Miller, Davis, & Finkel, 2005) and its outlets retreated to the fiord mouths after 14 ka BP (Jenner et al., 2018). Paraglacial and postglacial sedimentation have been prevailing in the troughs from at least ∼12 ka BP and probably since 14 ka BP, which marks a minimum age for presence of outlets at the fiord mouths (Jenner et al., 2018; Osterman & Nelson, 1989; Praeg, Maclean, & Sonnichsen, 2007). Outlet glaciers probably stayed grounded at the fiords mouth until the onset of the Holocene (Dyke, 2004) before rapidly retreating inland towards the fiord heads (Briner et al., 2009). Cosmogenic and radiocarbon ages in Sam Ford Fiord indicate that the fiord was mostly deglaciated by 9.3–9.1 ka BP, but only completely deglaciated by ∼7 ka BP (Briner et al., 2009). This rapid deglaciation roughly corresponds to the early Holocene (10–8.5 ka BP) peak in temperature (linked to summer insolation) recorded in nearby lakes (Briner et al., 2006; Miller, Wolfe, Briner, Sauer, & Nesje, 2005) and across Baffin Bay (Briner et al., 2016). The outlet glaciers retreat was halted during the 9.5–8 ka BP interval which led to the construction of

Figure 1. Multibeam bathymetric coverage and high-resolution bathymetry on the northeastern Baffin Island shelf and in the fiords. Contours were extracted from the IBCAO data (Jakobsson et al., 2012). The left-corner inset shows the location of study area.
the extensive (>1000 km long) Cockburn moraine complex, which is apparent across most of Baffin Island (Andrews & Ives, 1978). Following the Cockburn Substage (9.5–8 ka BP), retreat of the LIS outlets from the fiords were completed by 7 ka BP (Briner et al., 2009; Dyke, 2000; Dyke, 2004). All fiords described here, except for Milne Inlet, are today under the influence of small glaciers from local ice caps present on the high summits (Figure 1). A recent study in Ayr Lake Valley, just south of Sam Ford Fiord, indicates that glaciers that drained local ice caps were more extensive during the Cockburn Substage than during the Younger Dryas (Young, Briner, Rood, & Finkel, 2012). These glaciers did not readvance further than their positions reached during the 8.2 ka cold event. These glaciers, however, readvanced during the Little Ice Age and then retreated slowly to their present-day position (Briner et al., 2009).

2. Data and methods

The analysed multibeam bathymetry database is a compilation of the ArcticNet and the Canadian Hydrographic Service (CHS) bathymetry databases (Figure 1). For the ArcticNet database, swath bathymetry data were collected over 13 years using Kongsberg Simrad EM-300 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). The specifics of acquisition for each expedition can be obtained at geoindex-plus.bibl.ulaval.ca and on the Ocean Mapping Group Website (www.omg.unb.ca/Projects/Arctic/ArcticMetadata.html). The multibeam bathymetry data were processed using Caris Hips & Sips (www.caris.com/products/hips-sips/) and MB-System (www.ldeo.columbia.edu/res/pi/MB-System/) softwares. ArcticNet data were gridded 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 swath bathymetry data from the Canadian Hydrographic Survey comprise surfaces (.csar files) for Milne Inlet and Erik Harbour at a 5 m-grid resolution. The specifics of acquisition can be obtained via a Canadian Hydrographic Survey Info request (CHSInfo@dfo-mpo.gc.ca). Data visualization and geomorphological mapping were realized using ESRI ArcGIS 10.5.1 software (www.esri.com). In ArcGIS, multiple shaded-relief rasters with different illuminations and slope rasters were used to minimize azimuth bias during analyses (Smith & Clark, 2005).

Here we present a series of 50 maps at a 1: 60,000 scale using CSRS 1983 North American Datum UTM-17 to 20 coordinate systems. The map extent, names, and numbers follow the Canadian National Topographic System grid (http://www.nrcan.gc.ca/earth-sciences/geography/topographic-information/maps/9765). Maps were transferred to the Adobe Illustrator CS5 software (www.adobe.com/illustrator) for figure production and editing. Topographic, hydrographic, and toponymic data were collected from the Canadian Geospatial database (maps.canada.ca/css/index-en.html). Geological data were collected from the National Resources Canada data website (geocan.nrcan.gc.ca; Behnia et al., 2013).

3. Submarine landforms

A total of 55,647 landforms were mapped; they are here grouped under 24 main landform types that are presented in alphabetical order (Table 1). Enhanced geomorphological maps with topography, hydrography, and regional geology are also included in order to provide further geological or topographical context.

3.1. Bedrock scarps

Bedrock scarps are longitudinal landforms, with rough character, that form an escarpment in a bedrock wall or a bedrock outcrop. They can be the product of multiple processes, including glacial and/or meltwater-related erosion in bedrock. A total of 4508 bedrock scarps were mapped, mainly within fiords but also along the trough sidewalls. These escarpments can reach over 6 km long. Bedrock scarps occur in shallow depths (<10 m) as well as in deeper waters (>1000 m).

3.2. Block debris

Block debris consist of sediment or rock blocks that have slid downslope without disintegrating. They occur on lower slopes in areas where mass movements occurred. Block debris are all in Hecla & Griper Trough and appear to be related to bedrock scarps along the north wall of the trough. They occur at depths ranging between 448 and 611 m.

3.3. Compression ridges

Compression ridges are longitudinal landforms forming steps that are usually observed on the delta, moraine, or fan faces. These ridges are transverse to slope and are generally evenly distributed on the delta, fan, or moraine faces. Similar landforms have been observed on fans or deltas in fiords and have been attributed to retrogressive slides or gravity-induced sediment creep (Eilertsen, Longva, & Corner, 2016; Hill, 2012). These mass movements probably result from high rates of sedimentation and overloading of sediment on ice-contact or ice-proximal fans or deltas.
Table 1. Landforms count, mapping style and statistics.

| Landform                        | Count | Mapping style                                                                 | Min. length (m) or area (km²) | Max. length (m) or area (km²) | Mean length (m) or area (km²) | Min. water depth (m) | Max. water depth (m) |
|---------------------------------|-------|-------------------------------------------------------------------------------|-------------------------------|-------------------------------|-------------------------------|---------------------|---------------------|
| Bedrock scarp                   | 4,508 | Line, long the break in slope.                                                | 15                            | 6,386                         | 399                           | 3                   | 1,045               |
| Block debris                    | 47    | Line, along the long axis of the block.                                       | 31                            | 631                           | 157                           | 448                 | 611                 |
| Compression ridge               | 1,643 | Line, along the break/crest-line of the landform.                             | 27                            | 3,523                         | 257                           | 22                  | 780                 |
| Crag-and-tail                   | 98    | Line, along the crest-line of the sediment tail beginning at the bedrock crag.| 98                            | 5,935                         | 937                           | 17                  | 947                 |
| Crescent-shaped bedform         | 460   | Line, along the break/crest-line of the landform.                             | 16                            | 1,465                         | 209                           | 19                  | 719                 |
| Cross-shelf trough              | 4     | Polygon, Delimited by the fiord sill, the walls along the trough and the shelf break. | 1,184                         | 1,684                         | 1,527                         | –                   | 845                 |
| De Geer moraine                 | 363   | Line, along the crest-line of the ridge.                                     | 17                            | 536                           | 108                           | 12                  | 67                  |
| Drumlin                         | 1,469 | Line, along the long axis of the landform.                                    | 54                            | 4,081                         | 378                           | 94                  | 869                 |
| Glacioluvial or fluvial fans    | 63    | Polygon, delimited by the apparent character of the fan (cone).              | 0.01                          | 10                            | 0.86                          | 0                   | 866                 |
| Groove and mega-groove          | 718   | Line, baseline of individual landform.                                        | 84                            | 5,882                         | 969                           | 121                 | 894                 |
| Grounding-zone wedge (GZW)      | 41    | Polygon, delimited by the apparent character of the wedge.                  | 0.01                          | 139                           | 18                            | 17                  | 842                 |
| Gullies                         | 20,536| Line, baseline of individual landform.                                       | 7                             | 2,951                         | 199                           | 1                   | 1,577               |
| Iceberg ploughmark              | 13,482| Line, baseline of individual landforms following the long axis.              | 1                             | 4,311                         | 223                           | 9                   | 972                 |
| Ice-stream lateral moraine      | 10    | Polygon, delimited by the apparent character of the ridge.                  | 1                             | 175                           | 60                            | 16                  | 863                 |
| Lineation and mega-scale glacial lineation | 2,445 | Line, along the crest-line of the ridge.                                    | 91                            | 17,190                        | 1,156                         | 78                  | 1,162               |
| Marginal trough                 | 1     | Polygon, delimited by the walls along the trough and by the cross-shelf trough. | 236                           | 236                           | 236                           | –                   | 769                 |
| Meltwater channel               | 938   | Line, baseline of individual landform.                                       | 66                            | 5,698                         | 801                           | 149                 | 899                 |
| Moraine                         | 2,634 | Line, along the crest-line of the ridge.                                     | 24                            | 11,220                        | 450                           | 4                   | 1,034               |
| Ridge (unresolved origin)       | 444   | Line, along the crest-line of the ridge.                                     | 36                            | 20,020                        | 756                           | 36                  | 945                 |
| Sedimentary scarp               | 4,527 | Line, along the break in slope.                                              | 22                            | 7,027                         | 462                           | 4                   | 1,082               |
| Subglacial medial moraine       | 41    | Polygon, delimited by the apparent character of the ridge.                  | 1                             | 182                           | 17                            | 404                 | 821                 |
| Trough-mouth fan                | 2     | Polygon, delimited by the apparent character of the fan (cone).              | 859                           | 1,663                         | 961                           | 396                 | 1639                |
| Turbidity channel               | 76    | Line, baseline of individual landforms.                                      | 319                           | 7,304                         | 1,490                         | 59                  | 975                 |
| Whalebacks                      | 780   | Line, along the long axis of the landform.                                    | 61                            | 3,169                         | 350                           | 5                   | 929                 |

Note: Areas are in italic.
The vast majority of compression ridges occur in fiords but some occur in Scott Trough (Figure 2).

### 3.4. Crag-and-tails

Crag-and-tails are flow-oriented positive landforms with an identifiable bedrock ‘crag’ at the head and a drift tail (Evans & Hansom, 1996). Crag-and-tails have been widely used in paleoglaciological reconstructions as indicators of ice-flow orientation (e.g. Brouard & Lajeunesse, 2019a; De Angelis & Kleman, 2007; Jansson, Stroeven, & Kleman, 2003; Hogan et al., 2010; Brouard, Lajeunesse, Cousineau, Govare, & Locat, 2016). In association with MSGL, drumlins and grooves, crag-and-tails generally indicates relatively fast ice-flow conditions, i.e. ice streaming. Overdeepened curvilinear depressions (crescentic scours) can occur upstream of crag-and-tails (Figure 3(A)). Crescentic scours in front of crag-and-tails suggests the presence of meltwater (Graham et al., 2009; Graham & Hogan, 2016). Crag-and-tails were distinguished from drumlins or whalebacks as being two-part landforms (i.e. rough head and a distinctive sediment tail), while drumlins and whalebacks have a mostly homogenous character.

### 3.5. Crescent-shaped bedforms

Crescent-shaped bedforms (CSB) are usually observed in series in turbidity-current channels or on delta or fan faces. Crescent-shaped bedforms are landforms that have been associated with gravity-flow events (Clarke, 2016; Clarke, Marques, & Pratomo, 2014; Normandeau et al., 2014; Paull et al., 2010) and which have been associated with the melting of retreating glaciers (Normandeau et al., in press). Here, CSBs occur in turbidity-current channels and on the south wall of Scott Trough (Figure 2(B)). They occur at depths down to 719 m.

### 3.6. Cross-shelf troughs

Cross-shelf troughs are large flow-oriented bathymetric depressions located on the shelf and that usually widen towards the shelf break (Anderson, 1999; Batchelor & Dowdeswell, 2014; Nielsen et al., 2005). They are the most extensive landforms (≤1648 km²) in the study area. The bottom of a trough can be characterized by glacial lineations, grounding-zone wedges, subglacial medial moraines, and iceberg ploughmarks. Cross-shelf troughs are usually overdeepened landward and shallower at the shelf break where they can coincide with a trough-mouth fan. These depressions were glacially excavated and overdeepened (≤ 845 m; Løken & Hodgson, 1971), and represent corridors for preferential ice flow and are usually associated with the presence of ice streams. Cross-shelf troughs have therefore been used as evidence for ice-sheet advance onto the shelf during Quaternary glaciations.

### 3.7. De Geer moraines

De Geer moraines are series of low-amplitude parallel ridges with regular spacing that are perpendicularly...
aligned to ice flow (Lindén & Möller, 2005; Todd, Valentine, Longva, & Shaw, 2007). De Geer moraines are generally interpreted as being constructed during winter standstills or readvance of the ice margin (Bouvier, Johnson, & Påsse, 2015). They are associated with slow retreat of an ice margin in contact with relatively shallow bodies of water (Todd et al., 2007). The De Geer moraine ridges—all in Erik Harbour—are spaced ~25–60 m apart, in a regular fashion and at depths <68 m (Figure 4(A)).

3.8. Drumlins

Drumlins are smooth, asymmetric, oval-shaped hills with a steeper stoss side and a more gentle-sloping lee side (Clark, Hughes, Greenwood, Spagnolo, & Ng, 2009). Drumlins can form in sediment or in bedrock and generally have a long axis oriented parallel to ice flow. They 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
3.9. Fans (glaciofluvial or fluvial)

On swath bathymetry imagery, submarine fans form semicircular mound-like bulge observed along fiord walls and downstream of glaciers, rivers, or streams. Fans are generally eroded by gullies (forming small channels) and some by turbidity-current channels (Figure 4(B)). Fans can form where sediment-rich water flow enters a calmer environment leading to the rapid deposition of the sediment load (Dowdeswell et al., 2015; Mugford & Dowdeswell, 2011; Powell, 1990; Svytitski, 1989). Accordingly, the fans present in the region are all related to a tidewater glacier or a river.

3.10. Glacial lineations or mega-scale glacial lineations

Glacial lineations are highly elongated (apparent elongation ratio 1: 10) parallel ridges, usually in sets and formed in glaciogenic sediments (Clark, 1993; Spagnolo et al., 2014; Stokes et al., 2013; Stokes & Clark, 2002a). Mega-scale glacial lineations (MSGL) in the study area are differentiated from glacial lineations when they are >1 km in overall length. MSGL are indicators of fast ice flow suggesting palaeo-ice stream activity (Clark, 1993; Stokes & Clark, 2002a). Accordingly, they also indicate ice-flow orientation. MSGL may be covered by grounding-zone wedges and are therefore interpreted to reflect time-transgressive ice flows occurring during the landward retreat of an ice stream (Brouard & Lajeunesse, 2017; Dowdeswell, Ottesen, Evans, Cofaigh, & Anderson, 2008). Glacial lineation and MSGLs have lengths ranging between 91 and 17,190 m, and occur to depths of 1162 m.

3.11. Groove or mega-grooves

Grooves are linear to curvilinear negative landforms observed both in sediments and in bedrock (Bradwell, Stoker, & Krabbendam, 2008). Grooves usually occur in association and aligned with mega-scale glacial lineations, crag-and-tails and drumlins. Grooves with an overall length of >1 km are here classified as mega-grooves. The occurrence of grooves 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, Hindmarsh, & Stokes, 2009). Produced beneath glacial ice by debris transport causing abrasion and plucking of the underlying substrate, grooves record palaeo-ice flow orientation (Graham et al., 2009; Krabbendam, Eyles, Putkinen, Bradwell, & Arbelaez-Moreno, 2016).

3.12. Grounding-zone wedges (GZW)

Grounding-zone wedges are asymmetric tabular bathymetric wedges that are perpendicularly aligned to the orientation of the trough or of the fiord. GZW are identified on the swath bathymetry imagery by an extensive stoss side with low gradients and a steeper and shorter lee side. GZW in Baffin Island troughs are identified on seismic reflection data as acoustically semi-transparent chaotic units that are interpreted as glaciogenic sediments (Brouard & Lajeunesse, 2017; Praeg et al., 2007). In many cases they are overprinted by iceberg ploughmarks and pits, glacial lineations and grooves (Figure 5(A)). 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 & Fugelli, 2012; Lajeunesse, 2016). Generally, GZW have been associated with the presence of former ice shelves (Batchelor & Dowdeswell, 2015; Dowdeswell & 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 km²) character of GZW. While GZW occur mostly within cross-shelf troughs, some are present within fiords (Batchelor, Dowdeswell, & Rignot, 2018; Brouard & Lajeunesse, 2019a). Grounding-zone wedges occur in the fiords of Erik Harbour and Milne Inlet at depths ranging between 17 and 241 m.

3.13. Gullies

Gullies are small V-shaped linear depressions that form straight to sinuous channels in sediment. Gullies generally occur where slopes are higher than 10°. On slopes, multiple gullies can coalesce at their lower end to form a turbidity-current channel (Figure 5(B)). Gullies are formed under the erosional stress caused by the downslope movement of sediments (O’Brien et al., 2015). The downslope movement of sediment can be due to overloading of sediment on steep or unstable slope (Batchelor et al., 2018), or, to local seismicity (Bennett, Campbell, & Furze, 2014). Gullies are the most common landforms mapped in the northeastern Baffin Island troughs and fiords; the vast majority being confined to fiord walls between 2 and 1577 m depths.
3.14. Iceberg ploughmarks or pits

On swath bathymetry imagery, iceberg ploughmarks take the shape of linear, curvilinear, to almost circular depressions with an overall ‘random’ orientation. These depressions are produced when the keel of an iceberg is dragged along the seafloor or is grounded on the seafloor (e.g. Dowdeswell & Ottesen, 2016; Hill, 2016). In the study area, iceberg ploughmarks can reach lengths of >4 km and occur at depths down to 972 m. Present-day glaciers in the fiords are unlikely to produce icebergs with drafts >100 m and modern-day drafts of icebergs flowing through the Baffin Bay rarely exceed 300 m (Praeg et al., 2007). Therefore, present-day icebergs cannot account for the deep keel scours. The location of deep iceberg ploughmarks (>300 m deep) is likely to reflect the calving episodes during ice retreat. They were not mapped on the shelf outside the troughs.

3.15. Ice-stream lateral moraines

Ice-stream lateral moraines are curvilinear ridges 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 & Dowdeswell, 2016). Generally, the ice-stream lateral moraines are overprinted by iceberg ploughmarks and grooves (Figure 6(A)). 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 & Dowdeswell, 2016). Therefore, they can be used to delineate the lateral extent of an ice stream (Brouard & Lajeunesse, 2017; Margold, Stokes, & Clark, 2015; Stokes & Clark, 2002b). Ice-stream lateral moraines occur on both sides of each trough, except for Pond Trough.

3.16. Marginal troughs

A marginal trough is a deep, parallel-to-coast bedrock moat located up-ice of a cross-shelf trough (Anderson, 1999; Batchelor & Dowdeswell, 2014; Brouard & Lajeunesse, 2019b; 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 (Grant, 1970; 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). Alike cross-shelf troughs, marginal trough beds can be characterized by the presence of glacial lineations, crag-and-tails and grooves. The presence of MSGL, crag-and-tails and grooves on their bed indicates they were occupied and eroded by ice streams. Marginal troughs have also been interpreted as the product of upstream progradation of ice streams along the crystalline-sedimentary faulting (Brouard & Lajeunesse, 2019b). There is one marginal trough in the study area: Hecla & Griper Trough, which extends between Scott Trough and Sam Ford Trough (Figure 1). Hecla & Griper Trough reaches a depth of 770 m, is ~25 km long and oriented southeasterly, parallel to the coast.
3.17. Meltwater channels

On swath bathymetry imagery, meltwater channels take the shape of sinuous longitudinal depressions (negative landform) that are generally carved in bedrock (Lowe & Anderson, 2003; Nitsche et al., 2013; Slabon, Dorschel, Jokat, & Freire, 2018). Some channels are characterized by a flat bottom which indicates sediment infill (Brouard & Lajeunesse, 2019a; Smith, Hillenbrand, Larter, Graham, & Kuhn, 2009). These channels form anastomosing networks often extending in-between ice-flow landforms (MSGLs, drumlins, crag-and-tails). The channels indicate abundant meltwater which could favor ice-bed decoupling, enable basal sliding, and generate ice streaming (Anandakrishnan & Alley, 1997; Engelhardt, Humphrey, Kamb, & Fahnestock, 1990; Lowe & Anderson, 2003; Reinardy et al., 2011). Meltwater channels occur at depths ranging between 150 and 900 m. Their length varies from 67 to 5.7 km.

3.18. Moraines

Moraines are sediment ridges forming elongated, arcuate and transverse-to-ice-flow bathymetric highs that were deposited during stillstands or re-advance of outlet tidewater glaciers. Moraines are vertically-developed landforms (Figure 6(B)) which indicates vertical accommodation space, i.e. the absence of an ice shelf, as opposed to the horizontally-developed GZW. They generally have a steeper stoss side and a more gentle-sloping lee side (Benn & Evans, 2014). Moraines have lengths up to 11.2 km and occur at depths down to 1034 m. Moraines mostly occur in fiords but few moraines also occur in the troughs (Figure 7(A)). Moraines at the edge of Scott Trough, on the trough-mouth fan, are similar to lift-off moraines detailed on the Norwegian shelf and could suggest a tidally-influenced ice margin (Figure 7(B); Elvenes & Dowdeswell, 2016). Also, some fiord-head moraines coincide with the general outline of the Cockburn moraine complex (Figure 7(A); Andrews & Ives, 1978) which was constructed during the re-advance of the LIS during the 9–8.5 ka interval (Briner et al., 2009).

3.19. Ridges (unresolved origin)

These ridges are linear to curvilinear positive landforms that occur in sediment deposits or in bedrock and which the origin could not be resolved by the bathymetric morphology analysis.

3.20. Sedimentary scarps

Sedimentary scarps are longitudinal landforms forming an escarpment into sediment that likely imply erosion in sediment. The erosion result from sediment transport through the turbidity channels and/or to mass movements (Brouard & Lajeunesse, 2019a). They occur at depths ranging between 4 and 1082 m, and can extend over 7 km.

3.21. Subglacial medial moraines

Subglacial medial moraines are flow-oriented, large curvilinear sediment ridges (Figure 8). On swath bathymetry imagery, they are generally overprinted by iceberg ploughmarks, MSGL, and grooves. Subglacial
Figure 7. A. Distribution of moraines, grounding-zone wedges and ice-stream lateral moraines in the study area. Moraines at the fiord heads are generally coincident with the Cockburn moraine complex. B. Probable ‘lift-off’ moraine ridges located at the shelf break on the Scott trough-mouth fan (Brouard & Lajeunesse, 2017).

Figure 8. Examples of subglacial medial moraine in Scott Trough. These moraines originate at the junction between Clark and Gibbs fiords and at the junction between Hecla & Griper Trough and Gibbs Fiord (Dowdeswell, Todd, & Dowdeswell, 2016).
medial moraines are interpreted to be formed subglacially under constraints created by coalescing glaciers (Dowdeswell, Todd et al., 2016). Therefore, they reflect the downstream movement of ice and represent indicators of ice-flow orientation. Subglacial medial moraines were first identified in Scott Trough (Dowdeswell, Todd et al., 2016), but also occur in Buchan, Pond and Hecla & Griper troughs (Figure 7(A)), where they reach 55.5 km in lengths.

3.22. Trough-mouth fans

Trough-mouth fans take the shape of fan-shaped bathymetric bulges at the seaward end of cross-shelf troughs. They are located at the shelf break and extend to the bottom of the shelf slope. Trough-mouth fans generally consist of stacked glacigenic-debris flows separated by suspension-settling sediments, turbidites and/or contourites (Laberg & Vorren, 1995). Glaciogenic debris flows are mostly the product of slope instabilities at the grounding zone during the occupation of the trough by an ice stream. Therefore, trough-mouth fans record episodes of ice occupying the troughs during the Quaternary glaciations. These fans are generally eroded by numerous gullies. Trough-mouth fans occur at the edge of Scott and Buchan troughs (Brouard & Lajeunesse, 2017).

3.23. Turbidity-current channels

Turbidity-current channels are elongated and sinuous depressions eroded in sediment, extending downslope in flat and sediment-filled basins. These channels are formed by underflows or currents transporting sediment downslope and have been reported on other high-latitude shelves and in fiords (Dowdeswell & Vázquez, 2013; Syvitski & Shaw, 1995; Syvitski, Burrell, & Skei, 1987). Turbidity-current channels occur on delta, fan or moraine faces and, in some cases, aligned with fiord-head rivers. Channels can originate as minor gullies and converge to form a main collective channel (Figure 5(B)). Channels are delimited laterally by sedimentary scarps and may bear crescent-shaped bedforms (cyclic steps; Normandieu et al., in press). Channels here have lengths ranging from 320 to 7.3 km and occur at depths between 50 and 976 m.

3.24. Whalebacks

Whalebacks are asymmetric and oval-shaped hills of bedrock (positive landform; Roberts & Long, 2005). Generally, whalebacks have a flow-oriented long axis and are observed in clusters. In the study area, they occur in association with glacial lineations, crag-and-tails, drumlins, and meltwater channels. Whalebacks can be characterized by the presence of overdeepened curvilinear depressions (crescentic scours) upstream of their stoss side. Grouped into flow-sets, they can be used to reveal palaeo-ice-flow orientation (Krabben-dam et al., 2016). Whalebacks can be the result of multiple glacial erosion cycles and therefore record multiple ice flows that eroded into bedrock.

4. Discussion and conclusions

The maps presented in this paper contain >55,000 landforms that reflect a wide variety of processes linked to erosion and deposition during the Pleistocene and the Holocene. The most noticeable landform assemblages are those linked to paleo-ice streams: MSGLs, crag-and-tails, drumlins, whalebacks and meltwater channels all reflect ice flows in Scott, Buchan and Pond troughs, as well as in Eclipse Sound. Therefore, the ice stream tracks indicate high ice velocities along the fiords and the troughs (Brouard & Lajeunesse, 2017). The distribution of Ice-stream related landforms shows that ice-streaming occurred on both crystalline and sedimentary bedrock, which is consistent with doubt raised over a geological setting control on ice streaming location (Roberts & Long, 2005; Stokes & Clark, 2003).

Moraines and GZW both suggest that ice streams on the shelf and outlet glaciers in the fiords experienced episodes of ice-margin and/or grounding-zone stability during glacial retreat (Figure 7; Brouard & Lajeunesse, 2017, 2019). Therefore, the glacial retreat over the northeastern Baffin Island shelf and fiords has been episodic rather than catastrophic (Briner et al., 2009), or slow and steady (Brouard & Lajeunesse, 2017; Dowdeswell et al., 2008). Moraines at the fiord heads that coincide with the general outline of the Cockburn moraine complex show that both terrestrial and marine-terminating glaciers probably underwent stability and readvance during the 9.5–8 ka interval.

Meltwater channel networks on the seabed indicates that meltwater was abundant under the ice streams and outlet glaciers, and even in overdeepened basins. While the interconnectivity (or age) between sets of channels cannot be ascertained, the presence of such networks raises questions on the subglacial hydrology under this part of the Laurentide Ice Sheet: Were these networks fed by subglacial lakes or did they supplied subglacial lakes similar to those associated with ice streams in Antarctica (e.g. Bell, Studinger, Shuman, Fahnestock, & Joughin, 2007)?; Did their path vary overtime and influence ice-stream routing? These questions highlight the need for further analysis in order to define the precise nature of meltwater drainage in this area and its role in promoting ice-streaming conditions.

Numerous landforms are associated with the downslope movement of sediments (e.g. gullies, sedimentary scarps, turbidity-current channels). These erosional landforms indicate that remobilization of sediment might still be an active process both in fiords and on
the shelf. The presence of crescent-shaped bedforms in turbidity-current channels that appear to be the link to present-day rivers suggest that they might be active (migrating). Sediment scarps that are linked to mass movements may also result from recent slope activity. The initiation of the mass movements could result of local seismicity (Halchuk, 2009) and therefore could reflect a potential hazard (Bennett et al., 2014).

The geomorphological mapping carried out on the northeastern Baffin Island Coast and Shelf provides a useful dataset for further detailed quantitative analysis and modeling of paleo-ice streams and outlet glaciers dynamics. These maps and database should also provide a framework for further geomorphological and geological investigations on paleoglaciology, palaeohydrology, palaeoseismicity, and for studies on more recent sedimentary dynamics linked to natural hazards or climate change. The systematic mapping of submarine landforms in sparsely mapped areas such as the Canadian Arctic Archipelago should be the focus of future studies in order to provide robust databases for analyzing and understanding the past history dynamics of marine-based ice sheets.

Software

Caris Hips & Sips was used to process the bathymetric data. MB-System was used to grid the bathymetric data collected on the research cruises. Relief-shaded visualizations of the bathymetry data and on-screen digitization of the landforms were produced using ESRI ArcGIS 10.2. Map production was undertaken in ESRI ArcGIS 10.2 and then in Adobe Illustrator CS5.

Data

The authors will supply data (as ESRI Shapefiles) used in the production of the accompanying maps. These will be available as Supplementary Materials. The multibeam bathymetry dataset acquired by ArcticNet can be visualized and acquired on the Université Laval Géoindex+ website (geoindex-plus.bibl.ulaval.ca). The multibeam bathymetry data from the Canadian Hydrographic Survey and the acquisition specifics can be obtained via request at the website of the Canadian Hydrographic Survey (CHSInfo@dfo-mpo.gc.ca).

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