Submarine landforms reveal varying rates and styles of deglaciation in North-West Greenland fjords

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ABSTRACT

An understanding of the former configuration and dynamics of the Greenland Ice Sheet is needed to provide a context for modern observations, to constrain numerical models and to predict the likely future ice-sheet response to climatic change. Whereas previous geophysical investigations of the North-West Greenland margin have focused on the mapping of full-glacial and deglacial landforms on the mid to outer shelf, relatively little is known about more recent ice-sheet dynamics on the inner shelf and in the fjords. We present swath-bathymetric data from the inner shelf and fjords of North-West Greenland. Streamlined subglacial landforms, including ice-sculpted bedrock and mega-scale glacial lineations, reveal the direction of Late Quaternary ice flow through fjords and across the inner shelf. Landforms that are transverse to the former ice-flow direction, including small recessional moraines, major moraine ridges and grounding-zone wedges, show the locations of former still-stands in the grounding zone during regional deglaciation and terminus readvances linked to the Little Ice Age. The distribution of submarine glacial landforms in the inner fjords suggests that the outlet glaciers of North-West Greenland experienced varying rates and styles of ice retreat during the late Holocene, which was probably controlled mainly by fjord water depth.

Inner fjords that have contemporary water depths of less than 350 m contain series of small recessional moraines, which indicate the slow retreat of a grounded ice margin. Small recessional moraines are generally absent from inner fjords with water depths of more than 350 m, which are interpreted to have experienced more rapid ice retreat during the late Holocene.

Keywords: North-West Greenland; bathymetry; Late Quaternary; ice sheet dynamics; submarine landforms; moraines; turbidity-current channels.

1. INTRODUCTION

Up to 50% of Greenland's ice mass loss is related to ice discharge from marine-terminating outlet glaciers, as opposed to through surface melt (van den Broeke et al., 2009; Rignot et al., 2011; Enderlin et al., 2014). Many of Greenland's outlet glaciers have accelerated, thinned and retreated during the past few decades (Rignot and Kanagaratnam, 2006; Moon et al., 2012). Acceleration, thinning and retreat at the termini of outlet glaciers is suggested to be caused by intensification of subaqueous melting of the glacier fronts due to an increase in subsurface water temperature (Holland et al., 2008; Murray et al., 2010; Straneo et al., 2010; Christoffersen et al., 2011; Rignot et al., 2010, 2012). Of particular concern is an increase in the temperature and vertical extent of a relatively warm (0 to 4 °C) subsurface water mass, termed Atlantic Water, which is present around Greenland at a depth of below ~ 250 m (Straneo and Heimbach, 2013; Rignot et al., 2016). The warmest Atlantic Water, of up to 4°C, is present on the subpolar North Atlantic and Baffin Bay margins, whereas the coldest is found within North Greenland fjords that border the Arctic Ocean (Straneo and Heimbach, 2013). Access of Atlantic Water to the glacier margin is controlled strongly by the water depth of the fjord in which the glacier terminates (Christoffersen et al., 2011; Mortensen et al., 2011; Gladish et al., 2015). This has provided the motivation for geophysical surveys of the previously poorly known Greenland fjord bathymetry beyond marine-terminating outlet glaciers (Rignot et al., 2015, 2016) and attempts to generate synthetic fjord bathymetry where depth measurements are lacking (Williams et al., 2017).

The North-West margin of the Greenland Ice Sheet (Fig. 1a) is drained by at least 80 fast-flowing outlet glaciers, a large number of which experience ice-flow velocities of greater than 1000 m/year (Fig. 1b) (Moon and Joughin, 2008). Whilst observations have shown that most of the outlet glaciers in this sector are experiencing acceleration, thinning and retreat (e.g. Krabill et al., 2004; Moon and Joughin, 2008; Moon et al., 2015), very little is known about the water depth and fjord geometry beyond the present-day glacier termini.

There is also uncertainty concerning the past configuration and dynamics of ice on the North-West Greenland margin. Whereas previous investigations of past ice flow have focused predominantly on the mapping of full-glacial and deglacial landforms on the mid to outer shelf (Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015; Slabon et al., 2016), the more recent history of ice retreat across the innermost shelf and through the fjords of North-West Greenland is relatively little known. It is in these fjords that water depth is also most poorly known and yet is a first-order constraint on terminus stability and rates of ice retreat.

In this paper, we present swath-bathymetric data from the inner shelf and fjords of North-West and West Greenland (Figs. 1a-c) in order to reveal the water depth and geometry of these fjords and to map and interpret the landforms that are preserved on the seafloor. Furthermore, we develop a landform-assemblage model for the fjords and the inner shelf of North-West Greenland, and discuss the implications of these data for rates and styles of outlet-glacier retreat.

This study bridges the gap between interpretations of past ice-sheet dynamics on the mid to outer shelf, and the modern, observational record of outlet-glacier behaviour. An understanding of the former extent and dynamics of Greenland's outlet glaciers is needed to constrain numerical ice-sheet models and provide a context for present-day observations of outlet-glacier retreat.

2. BACKGROUND

2.1 Geologic and oceanographic setting

The North-West Greenland margin is underlain predominantly by Precambrian crystalline basement rocks (Henriksen, 2008). A thick sequence of plateau basalts, which were formed in connection with Paleogene volcanism during the opening of the North Atlantic between 60 and 54 Ma ago, is present in coastal regions to the south of Upernavik Isstrøm at around 73°N (Fig. 1b). Extensional faults run parallel to the coastline along the entire North-West Greenland margin (Henriksen, 2008).

Whereas the basement rock is covered by only a thin veneer of sediment close to the present-day coastline, a thick, succession of sediments is present beneath most of the continental shelf and slope (Fig. 1d) (Henriksen, 2008; Oakey and Chalmers, 2012). This sedimentary succession is composed of Pliocene and Late Miocene contourite deposits, overlain by thick sequences of glacigenic sediments of Late Pliocene and Pleistocene age (Knutz et al., 2015; Hofmann et al., 2016). The repeated expansion of grounded ice to the shelf break during the Late Plio-Pleistocene resulted in significant progradation and widening of the continental shelf and produced a succession of glacial sediment that is several hundred metres thick (Fig. 1d). The upper part of this succession has been eroded and removed by subsequent ice-sheet advances across the shelf, as shown by the truncation of some prograding clinoforms (Fig. 1d).

The present-day architecture of the North-West Greenland margin is dominated by more than thirty major fjord systems and three major cross-shelf troughs; the northern Melville Bay (NMB), Melville Bay (MB), and southern Melville Bay (SMB) troughs (Fig. 1b) (Batchelor and Dowdeswell, 2014; Slabon et al., 2016). The troughs, which are up to 100 km wide and 1100 m deep, are separated by shallower inter-trough banks that are between 100 and 400 m below the present-day sea level (Fig. 1b). The 90 km-wide Uummannaq Trough (Ó Cofaigh et al., 2013a; Dowdeswell et al., 2014, 2016a) is located around 270 km south of the SMB Trough (Fig. 1a). The fjords and cross-shelf troughs of North-West and West Greenland were probably formed initially by river systems that drained the interior of Greenland prior to the onset of cross-shelf glaciation (Funder et al., 1989; Weidick and Bennike, 2007).

Prograding sedimentary depocentres or trough-mouth fans (TMFs) exist on the continental slope beyond the major cross-shelf troughs of the North-West Greenland margin (Fig. 1d) (Batchelor and Dowdeswell, 2014). TMFs build up through the rapid delivery of glacial sediments to the shelf edge by fast-flowing ice streams over successive full-glacial periods (e.g. Vorren et al., 1998; Dowdeswell and Siegert, 1999). The TMF beyond Uummannaq Trough has been shown to be composed predominantly of glacigenic-debris flows (Ó Cofaigh et al., 2013b; Dowdeswell et al., 2014).

At present, the Baffin Current transports fresh and cold (<1°C) Arctic Water to Baffin Bay through Nares Strait and the channels of the Canadian Arctic Archipelago (Tang et al., 2004). The Arctic Water occupies the upper 100 - 300 m of the water column. The West Greenland Current, which operates below around 250 m, transports warm (0 - 4°C) and salty Atlantic Water northward along the West Greenland margin (Straneo and Heimbach, 2013).

2.2 The Last Glacial Maximum and deglaciation

The Greenland Ice Sheet has traditionally been inferred not to have crossed the West or North-West Greenland shelf during the Last Glacial Maximum (LGM) (Brett and Zarudzki, 1979; Funder et al., 1994, 2011; Wilken and Mienert, 2006). However, marine geophysical and geological data acquired from the mid and outer shelf have now provided evidence for grounded ice streams reaching the shelf break within NMB, MB, SMB and Uummannaq troughs during the LGM (Ó Cofaigh et al., 2013a, b; Dowdeswell et al., 2014; Hogan et al., 2016a; Slabon et al., 2016). Streamlined sedimentary landforms, interpreted as mega-scale glacial lineations (MSGLs), have been identified on the outer-shelf seafloor within MB, SMB and Uummannaq troughs, whilst ridges, interpreted as terminal moraines, have been identified at the shelf break beyond NMB, MB, SMB and Uummannaq troughs (e.g. Fig. 1d) (Dowdeswell et al., 2014; Slabon et al., 2016). Grounding-zone wedges (GZWs) also provide evidence of the presence of ice in cross-shelf troughs on the 250 km-wide shelf (Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015).

Radiocarbon dates indicate that the Late Quaternary ice stream that occupied Uummannaq Trough on the West Greenland margin (Figs. 1a and c) had started to retreat from the shelf break by 14.8 ka (Ó Cofaigh et al., 2013a). It is uncertain whether the ice sheet remained grounded on the mid to outer shelf during the Younger Dryas cold period, or whether it had retreated to an outer-fjord position at this time (Bennike and Bjork, 2002; McCarthy, 2011; Jennings et al., 2014; Ó Cofaigh et al., 2013a, Roberts et al., 2013; Dowdeswell et al., 2014). It has, furthermore, been assumed that the ice sheet stabilised close to the fjord mouths in West Greenland during the early Holocene, before retreating into the fjords (Weidick and Bennike, 2007; Roberts et al., 2013).

Terrestrial evidence and numerical ice-sheet models suggest that the western margin of the Greenland Ice Sheet retreated inland of its modern position during the early-middle

Holocene, around 5 to 4 ka ago (Weidick, 1968; Long et al., 2009; Simpson et al., 2009), before advancing beyond its present-day position during the Little Ice Age (LIA) (Weidick and Bennike, 2007). A prominent series of historical terrestrial moraines, which are generally associated with the maximum extent of the LIA readvance, have been mapped up to several tens of kilometres beyond the present-day ice margin of West Greenland (Kaplan et al., 2002; Weidick et al., 2004, 2012; Weidick and Bennike, 2007; Briner et al., 2010, 2011; Larsen et al., 2011; Young et al., 2011).

Comparatively little is known about the pattern and timing of full-glacial, deglacial and Holocene ice-sheet behaviour on the North-West Greenland margin (Fig. 1b). The presence of several GZWs within NMB, MB and SMB troughs (Fig. 1b) (Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015; Slabon et al., 2016) suggests that the ice sheet may have readvanced to, or at least stabilised at, a mid to outer shelf position during the Younger Dryas, after retreating from the shelf break during the LGM. The ice sheet had retreated to an inner-shelf to outer-fjord position by the early Holocene (Bennike and Bjork, 2002; Bennike, 2008; Briner et al., 2013; Slabon et al., 2016). Similarly to the West Greenland margin, the North-West Greenland Ice Sheet is suggested to have retreated landward of its present-day margin during the mid Holocene, before it subsequently re-advanced during the LIA (Weidick, 1958; Briner et al., 2013). A series of historical terrestrial moraines, which probably date from the LIA, represent the maximum late Holocene extent of the ice sheet beyond Upernavik Isstrøm (Fig. 1b) (Weidick, 1968; Briner et al., 2013).

2.3 The modern observational record

Ice dynamics are particularly important on the North-West Greenland margin, where there is very little exposed land and an extensive contact between the ice sheet and the ocean (Kjær et al., 2012; Khan et al., 2015). The North-West Greenland margin has exhibited a strongly negative mass balance in the early 21st Century (Rignot et al., 2008; Khan et al., 2010). Several of the major marine-terminating outlet glaciers on this margin, including Upernavik Isstrøm, Døcker Smith Glacier, Kong Oscar Glacier and Gades Glacier (Fig. 1b), are inferred to be losing mass (Rignot and Kanagaratnam, 2006).

The outlet glaciers of North-West Greenland have also experienced particularly high rates of thinning (Krabill et al., 2000, 2004) and an increase in the rate of ice-front retreat, especially since the beginning of the 21st Century (Moon and Joughin, 2008; Carr et al., 2013; Moon et al., 2015). Two main modes of terminus retreat have been observed, which are 1) large, isolated, stepwise retreat that is associated with topographic changes such as the glacier losing contact with a pinning point, and 2) slower, gradual retreat (Carr et al., 2013; Moon et al., 2015). Subglacial topography has been inferred to be an important control on outlet-glacier dynamics, with glaciers grounded in deep water tending to be closer to flotation and more prone to larger, unstable retreat after a perturbation (Pfeffer, 2007; Enderlin and Howat, 2013).

The outlet glaciers of North-West Greenland have experienced both periods of increased velocity and periods of relatively stable velocity during the past few decades. Observations show that the outlet glaciers did not exhibit any significant ice-flow acceleration between 1996 and 2005 (Rignot and Kanagaratnam, 2006), yet they experienced a pronounced speed-up in 2005, before a slow-down from 2006 to 2009 (Khan et al., 2015). The glaciers in this sector were probably already flowing faster than their balance-flux conditions in 1996, and, in some cases, in 1957 (Rignot and Kanagaratnam, 2006). This indicates that the glaciers had experienced ice-flow acceleration in response to climatic trends that took place prior to the widespread application of remote sensing techniques.

3. DATA AND METHODS

The main bathymetric database used in this study (Fig. 1b and c) was acquired by NASA's Oceans Melting Greenland (OMG) project (http://dx.doi.org/10.5067/OMGEV-BTYSS; Fenty et al., 2016). This bathymetric survey was conducted using a Teledyne Reson SeaBat 7160 Multibeam Echo Sounder, which has a system frequency of 44 kHz and 512 beams. The OMG data are supplemented by bathymetric data from the Rink Fjord and the inner shelf of Uummannaq Trough (Fig. 1b), which were collected during the JR175 cruise of the RRS *James Clark Ross* in September 2009 (Ó Cofaigh et al., 2013a; Dowdeswell et al., 2014). The JR175 cruise used a Kongsberg-Simrad EM120 system operating at 12 kHz with 191 beams. We have also used the International Bathymetric Chart of the Arctic Ocean (IBCAO) bathymetric data (v. 3.0; Jakobsson et al., 2012), which has a 500 m grid resolution, to show the broad-scale architecture of the continental shelf and slope (Fig. 1b and c).

The OMG data were acquired using the QINSy software and processed using the CARIS HIPS software by Terrasond Ltd. Data visualisation and interpretation were performed using a combination of Fledermaus (QPS; v. 7.7) and ArcMap (v. 10) software. The OMG and JT175 bathymetric data are generally of good quality, with only a few data gaps and track-line artefacts (e.g. Figs. 2a and 6f). The OMG and JR175 data are gridded with a cell-size of 25 m, which is suitable for identifying and mapping glacial landforms. However, it is possible that some fine-scale features are not identified at this resolution. No sub-bottom profiles or sediment cores have been available for this study as none were collected during the OMG project.

Landsat 8 satellite imagery is used to show the modern ice sheet margin. The satellite images were acquired in August 2014, July 2015, and June and October 2016, and were downloaded from Earth Explorer. We use data from NASA's Making Earth System Data Records for Use in Research Environments (MEaSUREs) program (Joughin et al., 2010) to produce a map of Greenland Ice Sheet average velocity between 2000 and 2009 (Fig. 1b and c). These data were compiled from five seasonal ice-sheet-wide velocity maps derived from Interferometric Synthetic Aperture Radar (InSAR) data, with the 2000 to 2008 data sourced from RADARSAT-1, and the 2008 to 2009 data constructed from the Advanced Land Observation Satellite (ALOS) and TerraSAR-X data.

4. RESULTS

4.1 Large-scale bathymetry

Fjord water depth immediately beyond the contemporary ice margin on North-West Greenland is shown to range between 100 and 600 m, with considerable variations occurring between neighbouring fjords (Fig. 1b and c). The fjords are U-shaped in cross-profile, have steep walls and are typically 2 to 6 km wide. Many of the fjords divide into two or more tributaries near their heads, where the outlet glaciers of the Greenland Ice Sheet have their marine margins (Figs. 2 to 4). The point at which the tributary fjords join the main trunk is often associated with a pronounced break in seafloor slope gradient (e.g. Figs. 2a, e, 3a and d). In long-profile, the fjords are characterised by a series of overdeepened basins that are separated by bedrock sills. These basins typically have water depths of between 600 and 1400 m. Whereas the seafloor in the inner fjords is typically rough and irregular on bathymetric data, the outer-fjord seafloor, particularly within overdeepened basins, has a relatively smooth and regular character (Figs. 2 to 4).

Our data show that the inner shelf of North-West Greenland is incised by a series of troughs that extend from the fjords and feed into the major cross-shelf troughs of the mid to outer shelf, which are up to 250 km long and 100 km wide (Fig. 1b). The inner shelf troughs are 5 to 10 km wide, up to 1000 m deep, and U-shaped in cross-profile.

The observed large-scale bathymetry of the North-West Greenland fjords is a product of glacial erosion over many successive glacial cycles. Their morphology is similar to other mid- and high-latitude fjord systems (e.g. Syvitski et al., 1987; Dowdeswell et al., 1994, 2016c; Hjelstuen et al., 2013). Variations in fjord depth probably reflect local geology, as well as differences in former ice-flow and erosion rates.

Areas of rough and irregular seafloor on the North-West Greenland margin are interpreted as exposed or near-surface bedrock. In contrast, the relatively smooth seafloor of the overdeepened basins is interpreted as the surface of sedimentary substrate. Due to a lack of sub-bottom profiles and sediment cores in this study, we do not have information about the sediments in these basins. However, the sediment-filled basins are likely to contain sequences of glacimarine and hemiplegic sediments, which are deposited predominantly by suspension settling of fine-grained material from turbid meltwater plumes, with a smaller component derived from ice-rafted debris (IRD) (e.g. Cowan and Powell, 1990; Dowdeswell et al., 1992, 1998; Ó Cofaigh and Dowdeswell, 2001; Ó Cofaigh et al., 2016). Mass-movement events, including submarine slides, turbidity currents and slope creep, are also widespread processes within many fjord systems (Syvitski et al., 1987; Hjelstuen et al., 2013). Acoustically transparent turbidite lenses are often produced by turbidity currents initiated by mass-failure events (Aarseth, 1997; Bellward et al., 2016b).

The 5 to 10 km wide, U-shaped troughs that extend seaward from the fjords to the major cross-shelf troughs (Fig. 1b) are interpreted to have been eroded by corridors of relatively fast-flowing ice as they converged towards major palaeo-ice streams. The transition from smaller, second-order troughs on the inner shelf to major cross-shelf troughs on the mid and outer shelf corresponds with a change in the nature of the seafloor, from exposed or near-surface inner-shelf bedrock, to a laterally extensive mid and outer shelf sedimentary substrate (Fig. 1d).

4.2 Submarine landforms

The fjords and inner shelf of North-West Greenland contain a variety of submarine landforms, including elongate ridges, ridges and wedges transverse to the past ice-flow direction, sinuous channels, linear to curvilinear depressions, and bedrock features that are often rough (Figs. 2 to 10). These landforms are described and interpreted in the follow section.

4.2.1 Elongate bedrock ridges

Description

Sets of parallel, elongate ridges made up of exposed or near-surface bedrock obstacles are a common feature of the fjords and inner shelf (Fig. 5b to f). These elongate ridges are asymmetric in the former ice-flow direction, with a steeper landward face that rises up to 200 m above the surrounding seafloor, and a gently-sloping seaward side (Fig. 5g and h). They are linear to curvilinear in plan-form, up to 5 km long, and up to 500 m wide (Fig. 5). They have typical elongation (length:width) ratios of between 10:1 and 30:1. Some of the elongate ridges possess semi-circular moats up to 500 m wide and 20 m deep at their landward sides (Fig. 5b, g and h).

Interpretation

Although the elongate ridges appear to be of exposed or near-surface bedrock, it is not possible to determine from bathymetric data alone whether their gently-sloping tails are composed of bedrock that has been streamlined by the action of ice (i.e. ice-sculpted bedrock), or sediment that has accumulated in the lee side of an obstacle (i.e. crag-and-tails).

Elongate ridges of similar morphology have been identified in many formerly-glaciated environments, including the fjords of Norway and the channels of the Canadian Arctic Archipelago (e.g. Ottesen et al., 2008; Dowdeswell et al., 2016d).

The moats that are present at the landward side of some of the elongate ridges have similar dimensions and geometry to crescentic scours that have been described from Uummannaq Trough (Fig. 1a), as well as other formerly-glaciated margins (Graham et al., 2009; Graham and Hogan, 2016; Hogan et al., 2016b). The formation of crescentic scours has been linked to meltwater erosion, erosion by a saturated till slurry, and/or the direct action of mobile basal ice (Graham et al., 2009).

4.2.2 Elongate ridges formed in sedimentary substrate

Description

Elongate ridges are also present on relatively smooth areas of the seafloor that have been interpreted as sedimentary substrate (Fig. 4a, d and f). These streamlined sedimentary features are up to 200 m wide and can be traced for up to 6 km. They have elongation ratios of up to 50:1.

Interpretation

The observed elongate ridges are interpreted as MSGLs. Such landforms have been described from a wide range of formerly-glaciated terrestrial and marine environments, where they are inferred to be indicators of fast-flowing outlet glaciers or ice streams (Stokes and Clark, 2001; Shipp et al., 1999; Canals et al., 2000; Ó Cofaigh et al., 2002, 2010, 2016). MSGLs and drumlins have previously been described within the major cross-shelf troughs of

North-West and West Greenland, where they record the former locations of fast-flowing ice streams (Dowdeswell et al., 2014; Hogan et al., 2016a; Slabon et al., 2016).

4.2.3 Small transverse ridges

Description

Sets of small ridges that have been formed transverse to the former ice-flow direction are identified in the fjords and on the inner shelf of North-West Greenland. They are between 1 and 10 m high, 50 to 200 m wide, and can be traced for lengths of up to several kilometres (Figs. 2, 3 and 6b). The ridges occur in clusters of parallel to sub-parallel features spaced 50 to 100 m apart (Figs. 2f and 6c), and are only present in water depths of less than 350 m (Fig. 11). They are particularly widespread in the shallow inner fjords along the northern part of the study area (Figs. 2, 4 and 11). Groups of small, transverse ridges are also identified on the inner shelf southwest of Upernavik Isstrøm (Figs. 1 and 11), where they occur at the northern lateral margin of a cross-shelf depression, in water depths of between 250 and 300 m (Fig. 6a).

Interpretation

The small parallel ridges (Figs. 2, 3, 6a and b) are interpreted as recessional moraines (e.g. Boulton, 1986; Shipp et al., 2002; Ottesen et al., 2005; Todd et al., 2007; Todd, 2016). These landforms, which are often referred to as De Geer moraines (Lindén and Möller, 2005), are produced by the delivery and ice pushing of sediment during short-lived still-stands or readvances of a grounded ice margin during overall retreat (Boulton et al., 1996; Nygård et al., 2004; Lindén and Möller, 2005). Small recessional moraines are often formed annually due to minor readvances of the grounding zone taking place during winter months (Boulton, 1986; Ottesen and Dowdeswell, 2006; Ó Cofaigh et al., 2008).

The presence of small recessional moraines in the geological record indicates a relatively slow retreat of a grounded ice mass (Dowdeswell et al., 2008). The recessional moraines in the inner fjords of North-West Greenland (e.g. Figs. 2, 3 and 6b) were probably formed during outlet-glacier retreat following the LIA readvance. In contrast, the recessional moraines on the inner shelf southwest of Upernavik Isstrøm (Fig. 6a) may have been produced during ice sheet retreat from a mid-shelf position during the Younger Dryas (Ó Cofaigh et al., 2013a; Dowdeswell et al., 2014; Hogan et al., 2016a; Slabon et al., 2016).

4.2.4 Large transverse ridges

Description

Two large ridges are identified in the fjords of North-West Greenland. These ridges are both located in the southern part of the study area; one is located 5 km seaward of the present-day margin of Alison Glacier (Fig. 6e and 11), and the other one is identified 12 km west of Upernavik Isstrøm (Fig. 4a, d). Both ridges are around 70 m high, 1.3 km wide in the ice-flow direction, and are roughly symmetrical in long-profile (Figs. 4e and 6d). The ridges occur in water depths of 600 - 700 m and have a relatively smooth seafloor character on bathymetric images (Figs. 4d and 6e).

Interpretation

These two large, symmetrical ridges are interpreted as major moraine ridges (e.g. Sexton et al., 1992; Seramur et al., 1997). In contrast to small recessional moraines, which build up during short-lived still-stands or readvances of the ice-margin, the major moraine ridges were formed during longer grounding-zone still-stands, probably with a duration of at least decades to centuries (Dowdeswell et al., 2008).

The position of the major moraine ridge beyond Upernavik Isstrøm coincides with the observed outlet-glacier limit of 1849 (Fig. 4a) (Weidick, 1958), which was at or close to a series of historical terrestrial moraines. These historical moraines have been interpreted to mark the maximum late Holocene ice sheet extent in the fjord (Weidick, 1968), which probably occurred during the LIA (Briner et al., 2013). The other major moraine in our study area, which is located around 5 km beyond the present-day ice margin, may also have been formed during the LIA.

4.2.5 Large asymmetric wedges

Description

Six large, asymmetric wedges are present in the northern part of the study area, north of 74°45´N, in water depths of 300 to 500 m (e.g. Figs. 3a, 6f and 11). The wedges have a steeper ice-distal slope and a gentler ice-proximal slope (Figs. 3c and 6h), and are located between 2 and 20 km seaward of the present-day ice margin (Fig. 11). With down-fjord lengths of between 5 and 7 km and heights of 60 to 80 m, the wedges have greater length to height ratios compared with higher amplitude moraine ridges.

Interpretation

The asymmetric geometry of the sedimentary wedges suggests that they are GZWs (e.g. Powell and Alley, 1997; Ó Cofaigh et al., 2005; Mosola and Anderson, 2006; Ottesen et al., 2007; Dowdeswell and Fugelli, 2012; Larter et al., 2012). GZWs have been interpreted to build up at the margins of outlet glaciers and ice streams that terminate in a floating ice shelf, which limits the vertical accommodation space that is available for sediment accumulation (Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015). In contrast, higher amplitude moraine ridges are more likely to develop at tidewater glacier margins that have unrestricted vertical accommodation space at the grounding-zone (King and Fader, 1986; King et al., 1987; Powell and Alley, 1997). Although no dates are available to constrain the age of the six GZWs in our study area, the fact that they are all located within 20 km of the present-day ice margin suggests that they may have been formed during the LIA.

4.2.6 V-shaped linear depressions

Description

V-shaped linear depressions are incised into the steeply sloping flanks of many of the fjords (Figs. 7b, c, 8a and b), but are also observed where the fjord seafloor is characterised by other prominent changes in slope gradient (Fig. 3a and 7a). These features typically comprise single, linear forms, although some features coalesce in their lower reaches. The linear depressions are between 50 and 200 m wide, up to 20 m deep and up to 2 km long. Some of the depressions appear to feed into sinuous channels (Figs. 7, 8a and b).

Interpretation

The V-shaped linear depressions (Figs. 7b, c, 8a and b) are interpreted as submarine gullies, formed by the downslope transfer of sediments (e.g. Ottesen and Dowdeswell, 2009; Forwick et al., 2010; Bellward et al., 2016b). Small-scale sediment failures are a common feature of high- and mid-latitude fjord systems and are probably caused by relatively high rates of sediment accumulation on steep slopes. The ice-proximal location of many of the gullies in our study area (Figs. 7b, c, 8a and b) suggests that they may be related to the discharge of sediment-laden meltwater from tidewater glacier margins. We do not identify any larger-scale slide scars or sediment failures in the fjords of North-West Greenland.

4.2.7 Fan complexes beyond outlet glaciers

Description

Fan-like depocentres are present beyond several of the marine-terminating outlet glaciers of the North-West Greenland Ice Sheet (e.g. Figs. 4f and 6g). These fans have an arcuate geometry, a slope gradient of between 2 and 6°, and can be traced for up to 4 km beyond the present-day ice margin. Some of these depocentres are dissected by sinuous channels that are up to 200 m wide, and which are fed from narrow gullies that extend from the contemporary ice margin and the steep fjord walls (e.g. Fig. 6i).

Interpretation

The dimensions and arcuate geometry of the fan-like depocentres, combined with their location close to the present-day ice sheet margin, suggests that these features are ice-proximal fans. Ice-proximal fans are produced by the delivery of sediment carried within subglacial meltwater streams to the tidewater glacier margin (Syvitski, 1989; Powell, 1990; Mugford and Dowdeswell, 2011; Dowdeswell et al., 2015; 2016e).

4.2.8 Fan complexes beyond glacially-fed rivers

Description

Fan-like depocentres, with slopes of 4 to 5°, are present on the continental shelf seaward of Disko Island and Nuussuaq Peninsula (Figs. 1c, 8d and i). Satellite data reveal that these fan complexes are located at the mouths of glacially-fed rivers (Fig. 8d and i). The fan complexes are associated with groups of parallel to sub-parallel channels that are at least 2.5 km long, up to 200 m wide and up to 10 m deep (Fig. 8f to h). Small ridges, up to 5 m high and 150 m wide, are present on the banks adjacent to the channels, as well as within the channels themselves (Fig. 8d, f and i).

Interpretation

The fan complexes are interpreted as glacifluvial deltas formed by the delivery of sediments to the marine environment by subaerial, proglacial streams (Prior et al., 1981; Corner et al., 1990; Storms et al., 2012). The sets of parallel to sub-parallel channels on the fans (Fig. 8d and i) are probably erosional chutes that form when bedload material deposited at the lip of the delta is transported intermittently down the delta front by channelised turbidity flows (Prior et al., 1981; Corner et al., 1990; Eilertsen et al., 2016). The small ridges that are observed adjacent to and within the chutes (Fig. 8f and g) are probably sediment waves produced by unconfined turbidity flows that transported sediment down the delta slope (Cartigny et al., 2011). The ridges could also result from sediment creep (e.g. Bellward et al., 2016a).

4.2.9 Sinuous channels

Description

Sinuous channels with lengths of between 2 and 34 km are present in several of the inner fjords of North-West Greenland (Figs. 4c, f, 6g, 7, 8a and b). Many of the channels originate close to the present-day ice sheet margin, where they are fed by networks of gullies that extend from the ice margin and the steep fjord walls (Figs. 6g, 7b, c, 8a and b). Whereas some of the channels extend only a few kilometres across the steep slope immediately beyond the glacier termini (e.g. Fig. 6g), other channels can be traced for several tens of kilometres across deeper, relatively flat and featureless regions of the seafloor (Fig. 7b and c). Some sinuous channels do not originate from the present-day ice margin itself, but are fed by gullies that extend from a prominent break in the seafloor. An example of this is the well-developed sinuous channel in the fjord beyond Carlos Glacier, which originates around 8 km seaward of the glacier terminus (Fig. 7a).

The sinuous channels consist of a single trunk that is between 100 and 300 m wide and up to 40 m deep. They have flat, U-shaped bases and are often asymmetric in cross-section (Fig. 7). The channels decrease in depth in a seaward direction, eventually losing morphological expression on the seafloor at the resolution of our bathymetric data (Fig. 7).

Interpretation

The sinuous channels are interpreted as turbidity-current channels that transport sediments from steep slopes close to the ice margin to deeper basins within the fjords (Fig. 7). Turbidity-current channels of similar dimensions have been described from Rink Fjord on the West Greenland margin (Figs. 1c and 11) (Dowdeswell et al., 2014) and Nordvestfjord on the East Greenland margin (Dowdeswell et al., 2016c), as well as several other Arctic fjords (Syvitski et al., 1989; Conway et al., 2012). Such features have also been reported from high-latitude deep marine-sedimentary basins (Ó Cofaigh et al., 2004; García et al., 2012, 2016).

The turbidity-current channels in the fjords of North-West Greenland were probably generated by the down-slope flow of dense, sediment-laden water released at the ice margin. The presence of gullies on slopes adjacent to sinuous channels (Figs. 6g, 7, 8a and b) provides evidence for the association of turbidity-current channel development with small-scale slope failure. The fresh appearance of the turbidity-current channels on bathymetric images, combined with their location close to the contemporary ice margin (Fig. 7), suggests that they have been active relatively recently or may be active at present. The asymmetric cross-sectional geometry of the channels (Fig. 7) probably reflects the presence of point-bars and levees at the channel sides, whilst the seaward reduction in channel depth is probably linked to the diminishing velocity of turbidity flows as they extend across the relatively flat fjord floor (García et al., 2012).

4.2.10 Linear to curvilinear depressions

Description

Linear to curvilinear depressions of no uniform orientation are present on the inner shelf seafloor between the SMB and Uummannaq troughs (Figs. 8c and 11). These depressions are up to 100 m wide, several kilometres long and 4 m deep (Fig. 8c and e). Small berms are often present on either side of the depression (Fig. 8e). The depressions only occur in water depths shallower than 250 m in the region southwest of Upernavik Isstrøm, but are present down to depths of 550 m at the lateral margins of Uummannaq Trough (Figs. 8c and 11).

Interpretation

The irregular, linear to curvilinear depressions (Figs. 8c and 11) are interpreted as iceberg ploughmarks that were formed by the grounding of iceberg keels in seafloor sediments (e.g. Dowdeswell et al., 1993, 2014; Syvitski et al., 2001; Evans et al., 2002, 2009; Arndt et al., 2017). The relative absence of iceberg ploughmarks from the fjords and inner shelf of North-West Greenland (Fig. 11) can be explained by relatively high rates of glacimarine sedimentation within the fjords, the prevalence of exposed or near-surface bedrock, which is more difficult to incise, and the considerable seafloor depths (down to 1400 m) of many of the fjord and inner shelf basins. Whereas some of the iceberg ploughmarks may have been formed relatively recently, it is likely that many of these features, including those that are present in water depths down to 550 m at the lateral margins of the Uummannaq Trough, were produced during the last deglaciation (Dowdeswell et al., 2014). Few icebergs with keels greater than about 500 - 600 m are calving off the outlet glaciers of the Greenland Ice Sheet today (Dowdeswell et al., 1992).

4.2.11 Bedrock features

Description

Wide regions of the fjord and the inner-shelf seafloor between around 76 and 73°N are composed of exposed or near-surface bedrock that has a rough and irregular appearance on the bathymetric images (Fig. 9). This landscape contains knolls and fault scarps up to 200 m high and linear fractures of several kilometres in length (Fig. 9a, c and d). South of around 73°N, the bedrock exhibits lower-amplitude variations in relief and has a terraced and flattened appearance (Fig. 9b).

Elongate ridges, up to several hundred metres wide, several kilometres long and aligned with the modern ice-flow direction, are also widespread within the bedrock terrain (Fig. 9d). Some of these features show evidence of streamlining, such as high elongation ratios and/or tapered lee ends. Several U-shaped depressions, up to 10 km wide and 600 m deep, traverse the inner shelf (Fig. 9b and e).

Interpretation

The bathymetry of the inner shelf is primarily controlled by bedrock structures that have been accentuated by deep weathering, and which, to a minor degree, have been modified by glacial activity. The fault scarps, knolls and linear fractures (Fig. 9a and c), are characteristic of bedrock that has been weathered, folded and faulted (e.g. Bonow et al., 2006; Krabbendam and Bradwell, 2014). Similar bedrock features have been interpreted from high-resolution bathymetry of small sections of the inner-shelf seafloor by Freire et al. (2015) and Gyllencreutz et al. (2016). The contrasting appearance of the inner shelf along the margin is probably related to variations in bedrock lithology. Whereas the northern part of the study area, which has an high-amplitude relief, is underlain by crystalline basement rocks, an extensive plateau of basalts is present south of around 73°N, in the region of lower-relief bedrock (Fig. 1b) (Henriksen, 2008).

The elongate ridges that are associated with areas of rough and irregular seafloor are interpreted as ice-sculpted bedrock. The relatively high elongation ratios of these features suggest that they were formed by erosion at the bed of warm-based, relatively fast-flowing sections of the Greenland Ice Sheet, such as outlet glaciers or ice streams, during at least one, and probably multiple glacial periods. In addition to the presence of streamlined bedrock (Fig. 9d), glacial modification of bedrock terrain is suggested by the broad, U-shaped depressions that traverse the platy basaltic rocks in the south of the study area (Fig. 9b and e). These depressions are interpreted as second-order, or tributary, troughs that were eroded by relatively fast-flowing ice, which may have occupied pre-existing faults and structures in the bedrock.

5. DISCUSSION

5.1 A landform-assemblage model for North-West Greenland

A landform-assemblage model for the fjords and inner shelf of North-West Greenland is presented in Figure 10. Gullies, turbidity-current channels and/or ice-proximal fans occur immediately seaward of some of the modern-day outlet glaciers (Figs. 4f, 7b and c). In relatively shallow (< 350 m) inner-fjord areas, streamlined bedrock features are overprinted by groups of small recessional moraines (Figs. 2b to d, 3b and 6b). Major moraine ridges and GZWs are present within 20 km of the modern ice margin in some of the fjords (Figs. 3, 4d, 6e and f). The outer fjords of North-West Greenland contain over-deepened, sediment-filled basins, with occasional outcrops of ice-sculpted bedrock (Figs. 2 to 5, 7). Deep, U-shaped troughs on the inner shelf (Figs. 9b and 10) are interpreted as tributary or second-order troughs that were excavated by corridors of relatively fast-flowing ice as it extended from the fjords and converged towards the major cross-shelf troughs of the mid and outer shelf. Beyond the lateral margins of the troughs, where dynamically inter-ice stream areas of presumably slower-flowing ice during full-glacial periods were likely present (e.g. Ottesen and Dowdeswell, 2009; Dowdeswell et al., 2016d; Klages et al., 2016), the inner shelf is characterised by irregular bedrock terrain that contains fault scarps, fractures and ice-sculpted bedrock (Figs. 9 and 10). Glacifluvial deltas, comprising steep slopes, erosional chutes and small sediment ridges, are present beyond the mouths of glacially-fed river systems on Nuussuaq Peninsula and Disko Island (Fig. 8d and i).

Glacier-influenced fjords have been suggested to lie along a continuum of environmental settings (Dowdeswell et al., 1998, 2016b). Glaciers that terminate in the cold fjords of East Greenland and West and East Antarctica are restricted to minimal surface-meltwater production and lose mass predominantly by iceberg production and the basal melting of ice shelves and frontal ice cliffs (Domack, 1988; Dowdeswell et al., 1993; Rignot et al., 2013). Sedimentation rates are therefore generally low in these environments, resulting in the pristine preservation of subglacial and ice-marginal landforms on the seafloor (Fig. 6a and b) (e.g. Canals et al., 2000; Dowdeswell et al., 2004, 2010; Mosola and Anderson, 2006). The influence of surface meltwater increases progressively towards the milder end of the environmental continuum (Dowdeswell et al., 1998, 2016b), with higher rates of predominantly meltwater-derived sedimentation taking place within the fjords of, for example, Spitsbergen (Elverhøi et al., 1980; Dowdeswell and Dowdeswell, 1989; Sexton et al., 1992; Svendsen et al., 1992). The fjords of Chile and southeast Alaska represent the warmest contemporary glacimarine settings on Earth. Streamlined lineations and subdued moraine ridges are often absent from the seafloor due to burial by high rates of meltwater-derived sedimentation (Boyd et al., 2008; Dowdeswell and Vásquez, 2013; Dowdeswell et al., 2016b).

The established landform-assemblage model in this study contains many features that are typical for relatively cold climatic and oceanographic settings, such as Antarctica and other regions of Greenland. These features include streamlined glacial lineations, major moraine ridges and GZWs, groups of recessional moraines, and iceberg ploughmarks on shallow banks (Figs. 10 and 11) (Canals et al., 2000; Dowdeswell et al., 2004, 2010; Ó Cofaigh et al., 2005; Mosola and Anderson, 2006).

However, the fjords of North-West Greenland also possess some features, including ice-proximal fans (Figs. 4f and 6g) and turbidity-current channels (Fig. 7), that are characteristic of fjords that are located in a warmer climatic regime with relatively high rates of glacier melt and meltwater-derived sedimentation. The ice-proximal location of the turbidity-current channels, combined with their fresh appearance on bathymetric images (Fig. 7), suggests that these channels are at least partially active today. Active turbidity-current channels of similar dimensions and geometry have been described from Alaskan, British Columbian and Chilean fjords (Syvitski et al., 1987; Dowdeswell and Vásquez, 2013).

The distribution of turbidity-current channels on the North-West Greenland margin (Fig. 11) probably reflects the gradient and stability of the slope immediately beyond the glacier terminus, as well as the volume of meltwater that is released from the ice margin, derived from both ice-cliff and ice-surface melting and delivery from a subglacial drainage system. Turbidity-current channels are present within a greater proportion of the fjords that were surveyed in the southern part of the study area (Fig. 11). This pattern may reflect higher rates of glacier melt and the increased importance of meltwater delivery to fjords at lower latitudes.

5.2 The former pattern of ice-flow on the North-West Greenland margin

By combining the distribution and orientation of streamlined glacial landforms, including ice-sculpted bedrock and MSGLs, we can show that ice flowed through the fjords and tributary troughs and converged into the major cross-shelf troughs of the mid and outer shelf (Fig. 11).

The distribution of submarine landforms also reveals the pattern of past ice flow on the relatively shallow continental shelf between SMB and Uummannaq troughs (Fig. 11a and d). Streamlined glacial landforms suggest that fast-flowing ice converged into Uummannaq Trough from a source on southern Svartenhuk Peninsula (Fig. 11e). Over-deepened tributary troughs, streamlined glacial lineations with a convergent flow pattern, and a cross-shelf depression of up to 300 m in depth, provide evidence for a palaeo-ice stream within a broad trough to the north-west of Svartenhuk Peninsula (Fig. 11d). This trough has not been included in previous inventories of cross-shelf troughs (e.g. Batchelor and Dowdeswell, 2014) due to its subdued bathymetric expression and uncertainty about its seaward extent. Although the fresh appearance of submarine landforms on bathymetric images (e.g. Fig. 6a) indicates that an ice stream occupied this trough sometime during the last glacial cycle, the geometry of the continental slope beyond the trough, which lacks the progradational architecture and convex shape that is typical of high-latitude TMFs (Figs. 1 and 11a) (Batchelor and Dowdeswell, 2014), suggests that an ice stream was not active in this location during many successive glacial periods. It is possible that an ice stream existed in the trough beyond Svartenhuk Peninsular during only the last glacial period or during regional deglaciation.

The inner shelf seafloor to the south-west of Gades Glacier also displays an interesting pattern of past ice-flow directions (Fig. 11b). The large-scale bathymetry of this region shows a broad bathymetric high separating the deep basins of NMB and MB troughs (Fig. 11b). However, the orientations of ice-sculpted bedrock and MSGLs in this area (Fig. 5b) indicate that ice from the fjord beyond Døcker Smith Glacier, and possibly even further to the east, flowed in a westerly direction across this topographic high into NMB Trough during the last glacial cycle, rather than into the MB Trough (Fig. 11b) (Slabon et al., 2016). The fact that the bathymetric high between the two troughs has not been eroded by the action of fast-flowing ice suggests that this ice-flow configuration is unlikely to have existed throughout multiple glacial cycles.

These two examples of potential spatial and temporal variability in palaeo-ice stream flow contribute to a growing body of evidence of dynamic palaeo-ice sheet behaviour. Short-lived ice-streaming events during deglaciation have been identified previously in the Canadian Arctic, where they have been inferred to have occurred in response to ice break-up in adjacent marine areas or when thinning ice became increasingly influenced by underlying topography (Kleman et al., 2006; Stokes et al., 2009). Palaeo-ice streams on the Norwegian-Svalbard margin are inferred to have exhibited on-off switching in sediment and ice delivery (Hooke and Elverhøi, 1996; Nygård et al., 2007), and to have had the potential to trigger the large-scale collapse of ice sheets (Sejrup et al., 2016). Palaeo-ice streams have also been interpreted to have switched flow direction between successive glacial periods, possibly in response to sediment deposition and the filling of available accommodation space (Dowdeswell et al., 2006; Sarkar et al., 2011; Montelli et al., 2016).

5.3 Variable rates and styles of ice-sheet retreat through North-West Greenland fjords

The major submarine moraine that is identified beyond the present-day margin of Upernavik Isstrøm (Fig. 4a) coincides with the position of historical terrestrial moraines (Weidick, 1958, 1968), interpreted to have been formed around 1850 during the maximum extent of the LIA readvance (Briner et al., 2013). Although no dates are available to constrain the age of the other major moraines and GZWs in the fjords of North-West Greenland (Fig. 11), the fact that they are all located within 20 km of the present-day ice margin suggests that they also may mark the maximum ice-sheet extent during the LIA. Submarine moraines that have been interpreted to have been formed during the LIA have been identified up to several tens of kilometres beyond the present-day ice margin in many other high- and mid-latitude fjord systems (e.g. Sexton et al., 1992; Mangerud and Landvik, 2007; Dowdeswell and Vásquez, 2013). It is interesting to note that GZWs are only present in the northern part of the study area, north of 74°45′N, whereas major moraine ridges are located south of this latitude (Fig. 11). If the moraines and GZWs are assumed to have formed at the same time, this pattern could be a consequence of cooler ocean water at higher latitudes enabling the formation of floating ice shelves during deglaciation and, consequently, the development of subdued GZWs rather than high-amplitude moraine ridges. Similarly, the very recent satellite-observed breakup of floating ice shelves, sometimes known as ice tongues, in several Greenland fjords, such as Jakobshavn Isfjord and Kangerdlussuaq Fjord, is also likely a product of the incursion of relatively warm Atlantic Water (e.g. Joughin et al., 2004; Holland et al., 2008; Straneo and Heimbach, 2013).

We do not identify geomorphological evidence of any major Late Quaternary still-stands or readvances of the Greenland Ice Sheet in the fjords of North-West Greenland prior to the LIA. Early Holocene ice sheet retreat is therefore suggested to have been relatively uninterrupted. Continuous and rapid early Holocene retreat has been inferred for other regions of the Greenland Ice Sheet (e.g. Young et al., 2011; Hughes et al., 2012). High mean rates of early Holocene ice sheet retreat through fjords, of 240 – 340 m/year, have also been documented for the former outlet glaciers of the South-West Scandinavian Ice Sheet (Mangerud et al., 2013). Ice sheet retreat through the Norwegian fjords was driven by climate warming but controlled by calving of the floating ice front (Mangerud et al., 2013).

The small recessional moraines that are a common feature in many North-West Greenland fjords (Figs. 2, 4, 7a, b and 11) are interpreted to have formed during outlet-glacier retreat subsequent to the LIA. Some of the recessional moraines may have been produced in the past few decades, during the period of contemporary outlet-glacier retreat that has been observed from satellite imagery (Krabill et al., 2000; Moon and Joughin, 2008; Carr et al., 2013; Moon et al., 2015). The distribution of recessional moraines in the inner fjords of North-West Greenland reveals varying rates and styles of ice retreat since the LIA (Figs. 10 and 11). Recessional moraines, which are interpreted to indicate the slow retreat of a grounded ice margin (Dowdeswell et al., 2008), are present only in inner fjords that have contemporary water depths of shallower than 350 m (Fig. 11). In contrast, inner fjords with water depths of greater than 350 m, in which small recessional moraines are lacking (Fig. 11), are interpreted to have experienced more rapid ice retreat linked in part to buoyancy effects in deep water. There is no significant relationship between fjord widths and the presence or absence of small recessional moraines. We therefore infer that fjord depth was a major control on the rate and style of late-Holocene ice retreat through the inner fjords of North-West Greenland. A strong bathymetric control on the rate and style of marine-terminating outlet-glacier retreat has been inferred for other formerly-glaciated margins, including the fjords of Baffin Island and Norway (Briner et al., 2009; Mangerud et al., 2013).

Shallower fjords promote a slower rate of ice retreat by reducing the rate of iceberg calving from marine-terminating outlet glaciers (Echelmeyer et al., 1991; Joughin et al., 2004; Schoof, 2007; Gudmundsson et al., 2012). Shallower fjords on the North-West Greenland margin probably also reduce glacier retreat rates by preventing the incursion of relatively warm Atlantic Water, which is present around Greenland at a depth of below 250 m, to the glacier terminus (Holland et al., 2008; Murray et al., 2010; Straneo et al., 2010; Christoffersen et al., 2011; Rignot et al., 2010, 2016).

The observation that recessional moraines are a more common feature of fjords in the northern part of the North-West Greenland margin, probably relates to the prevalence of relatively shallow (<350 m) inner fjords in this region (Fig. 11). Rates of erosion and over-deepening by palaeo-ice streams may have been lower on the shallower northern North-West Greenland margin compared with rates of erosion to the south, where the palaeo-ice streams had larger drainage-basin areas (Batchelor and Dowdeswell, 2014). In addition, slower rates of outlet-glacier retreat in more northerly fjords could reflect differences in past ocean water temperature along the margin, with cooler water at higher latitudes resulting in less melting of the glacier terminus compared with relatively warmer water to the south.

The water depth immediately beyond the present-day outlet-glacier termini, which ranges from 100 to 600 m (Fig. 1b and c), has implications for contemporary glaciology as well as palaeo-glaciological reconstructions. Our bathymetry data show that around half of North-West Greenland's outlet glaciers terminate in fjords that have water depths greater than 250 m (e.g. Døcker Smith Glacier in Fig. 3); these glaciers may therefore be vulnerable to frontal melting resulting from the incursion of Atlantic Water to their margins (Rignot et al., 2015, 2016). In contrast, around half of the glaciers in this sector of the ice sheet terminate in fjords that are shallower than 250 m, which may prevent the incursion of Atlantic Water to the glacier termini (e.g. Morell Glacier in Fig. 3, and the glaciers that terminate in De Dødes Fjord in Fig. 2). It should be noted that several additional factors, including fjord width, the shape of the calving front and the presence of floating termini, can influence patterns of glacier retreat. Consequently, there is no straightforward relationship between water depth at the terminus and glacier retreat rates (Fried et al., 2015; Rignot et al., 2015).

6. CONCLUSIONS

- In this study, we analysed bathymetric data from the inner shelf and fjords of North-West Greenland. Fjord water depth immediately beyond the contemporary ice margin ranges from 100 - 600 m, with considerable variations occurring between neighbouring fjords.
- We identify a variety of submarine glacial landforms, including MSGLs, moraine ridges, GZWs, glacifluvial deltas, turbidity-current channels and iceberg ploughmarks. The interpretation of these landforms provides an important link between the record of past ice-sheet dynamics on the continental shelf and the modern, observational record of outlet-glacier behaviour.
- Streamlined glacial landforms reveal the former ice-flow direction across the margin (Fig. 11). The inner shelf contains a number of tributary troughs that are interpreted to have been excavated by corridors of relatively fast-flowing ice as they converged towards the major ice streams of the mid and outer shelf.
- The identified major moraine ridges, GZWs and small recessional moraines show that the North-West Greenland Ice Sheet experienced grounding-zone still-stands during regional deglaciation and terminus readvances linked to the LIA.

- Our data reveal the presence of a major moraine ridge in the fjord beyond Upernavik Isstrøm, which we suggest to have been formed during the LIA. Several other major moraine ridges and GZWs (Fig. 11) may mark the maximum extent of the LIA readvance through the fjords.
- Inner-fjord areas that have water depths of less than 350 m are characterised by groups of small recessional moraines (Fig. 11), which indicate the slow retreat of grounded ice. In contrast, recessional moraines are absent from inner fjords that have water depths of greater than 350 m, in which retreat is interpreted to have been more rapid.
- We infer water depth to be a major control on the rate and style of late Holocene outlet-glacier retreat on the North-West Greenland margin, with shallower fjords probably reducing glacier retreat rates by preventing the incursion of relatively warm Atlantic Water to the glacier terminus.
- Although neighbouring fjords are shown to have exhibited varying styles of ice retreat, the northern part of the margin, which has shallower fjords, generally experienced a slower rate of outlet-glacier retreat (Fig. 11), probably related to climatic latitudinal gradients along the Greenland margin, as well as variations in fjord depth.

7. ACKNOWLEDGEMENTS

We thank NASA's Oceans Melting Greenland (OMG) project for access to the bathymetric data from North-West and West Greenland, and TGS-NOPEC Geophysical Company ASA for permission to reproduce the 2-D seismic-reflection profile shown in Figure 1d. We thank Berit Hjelstuen, Johann Klages and an anonymous reviewer for their helpful reviews of this paper. During this work, C.L. Batchelor was in receipt of a Junior Research Fellowship at

Newnham College, Cambridge. The bathymetric data that was collected during JR175 of the RRS *James Clark Ross* to West Greenland in 2009 was funded by Natural Environment Research Council (NERC) grant NE/D001951/1 to C. Ó Cofaigh.

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9. FIGURE CAPTIONS

Figure 1. (a) Location map of the areas in (b) and (c). DBT = Disko Bay Trough; GIS = Greenland Ice Sheet; UT = Uummannaq Trough. (b) and (c) Maps of the swath-bathymetric data on the North-West Greenland and West Greenland margins, respectively. Bathymetric data of Rink Fjord and Uummannaq Trough were collected during the JR175 cruise of the

RRS *James Clark Ross* in September 2009 (Ó Cofaigh et al., 2013a; Dowdeswell et al., 2014). Background is greyscale IBCAO bathymetry (Jakobsson et al., 2012) with 100 m contours. The average ice velocity of the Greenland Ice Sheet between 2000 and 2009 is from NASA's Making Earth System Data Records for Use in Research Environments (MEaSUREs) program (Joughin et al., 2010). Yellow circles are published deglacial dates (Bennike and Bjork, 2002; Bennike, 2008; McCarthy, 2011; Briner et al., 2013; Kelley et al., 2013; Roberts et al., 2013; Lane et al., 2014; Rinterknecht et al., 2014; Slabon et al., 2016). Pink dashed lines are approximate locations of mid shelf grounding-zone wedges (GZWs) from Slabon et al. (2016). Red dashed line shows approximate geological boundary between crystalline bedrock in the north and a basalt plateau to the south (Henriksen, 2008). MBT = Melville Bay Trough; NMBT = Northern Melville Bay Trough; SMBT = Southern Melville Bay Trough; TMF = trough-mouth fan. (d) Seismic-reflection dip profile of the Melville Bay Trough and adjacent continental slope (located in panel b), provided by TGS.

Figure 2. (a) Bathymetric data for De Dødes Fjord and associated tributary fjords on the North-West Greenland margin. Location is shown in Fig. 1b. Background is Landsat 8 satellite imagery acquired in June 2016. (b) The mapped distribution of submarine landforms in the area shown in (a). Key is the same as in Fig. 3b. (c) and (d) Details showing streamlined lineations and moraine ridges close to the present-day ice margin. (e) Seafloor depth along a transect from the ice margin to the main trunk of De Dødes fjord. (f) Long profile showing the dimensions of the recessional moraine ridges shown in (d).

Figure 3. (a) Bathymetric data of the fjord beyond Døcker Smith Glacier and Morell Glacier on the North-West Greenland margin. Location is shown in Fig. 1b. Background is Landsat 8 satellite imagery acquired in June 2016. White dashed lines show ice-sheet position in June

2016. (b) The mapped distribution of submarine landforms in the area shown in (a), with explanatory key. DSG = Døcker Smith Glacier; MG = Morell Glacier. (c) Long-profile of an asymmetric wedge within the fjord. (d) Long-profile of the shallow fjord and bedrock sill beyond Morell glacier. (e) Detail of elongate ridges overprinted by small recessional moraines. (f) Detail of ice-sculpted bedrock in a relatively deep region of the fjord.

Figure 4. (a) Bathymetric data of the fjord beyond Upernavik Isstrøm, North-West Greenland margin. Location is shown in Fig. 1b. White dashed lines show ice-sheet position in 1849 and 1985 (from Briner et al., 2013). Background is Landsat 8 satellite imagery acquired in July 2015. (b) The mapped distribution of submarine landforms in the area shown in (a). Key is the same as in Fig. 3b. (c) Detail of turbidity-current channel beyond the present-day ice margin. (d) Detail of the major moraine ridge. (e) Long-profile of the relatively deep fjord beyond Upernavik Isstrøm. (f) Detail of an ice-proximal fan and turbidity-current channel beyond the present-day ice margin.

Figure 5. (a) Map showing the locations of panels in Figs. 5 to 10. Green outline shows extent of OMG bathymetry. DI = Disko Island; MBT = Melville Bay Trough; NMBT = Northern Melville Bay Trough; SMBT = Southern Melville Bay Trough; UT = Uummannaq Trough. (b) to (f) Examples of streamlined lineations and ice-sculpted bedrock on the North-West and West Greenland margin. (g) and (h) Long-profiles showing the height of outcrops of exposed or near-surface bedrock.

Figure 6. Examples of transverse-to-flow landforms on the North-West Greenland margin. Locations are shown in Fig. 5a. (a) and (b) Small, recessional moraines in a fjord and on the inner shelf, respectively. (c) Long-profile showing the dimensions of the recessional

moraines shown in (b). (d) Long-profile of the large moraine ridge shown in (e). (e) Large moraine ridge in a fjord beyond Alison Glacier. (f) Asymmetric sedimentary wedge beyond Dietrichson Glacier. (g) Ice-proximal fan and turbidity-current channels close to the margin of Igdlugdlip Sermia. (h) Long-profile of the asymmetric wedge shown in (f). (i) Long-profile of the ice-proximal fan and channel shown in (g).

Figure 7. (a) to (c) Examples of turbidity-current channels in the fjords of North-West Greenland. Locations are shown in Fig. 5a. Background is Landsat 8 satellite imagery acquired in August 2014 and June 2016.

Figure 8. Examples of linear to curvilinear landforms in the fjords and on the inner shelf of West and North-West Greenland. Locations are shown in Fig. 5a. (a) and (b) Gullies and turbidity-current channels close to present-day ice margins. (c) Iceberg ploughmarks on the inner-shelf seafloor. (d) Groups of parallel to subparallel chutes on a glacifluvial delta beyond Nuussuaq Peninsula. (e) Cross-profile of an iceberg ploughmark and associated berms. (f) and (g) Details of chutes and sediment waves on glacifluvial deltas beyond Nuussuaq Peninsula. (h) Cross-profile of a chute on a glacifluvial delta. (i) Groups of parallel to subparallel chutes on a glacifluvial delta beyond Nuussuaq Peninsula. Background is Landsat 8 satellite imagery acquired in October 2016.

Figure 9. (a) to (d) Examples of linear fractures, fault scarps, U-shaped depressions and ice-sculpted bedrock on the inner shelf of the North-West Greenland margin. Locations are shown in Fig. 5a. (e) and (f) Cross-profiles of the U-shaped depressions shown in (a) and (b).

Figure 10. Schematic landform-assemblage model for the fjords and inner shelf of North-West Greenland.

Figure 11. (a) The pattern of Late Quaternary ice flow on the North-West and West Greenland margins, as revealed by the orientation of ice-sculpted bedrock and MSGLs. (b) to (e) The distribution of submarine glacigenic landforms on the North-West and West Greenland margin. Bathymetric data covering Rink Fjord and Uummannaq Trough were collected during the JR175 cruise of the RRS *James Clark Ross* in September 2009 (Ó Cofaigh et al., 2013a; Dowdeswell et al., 2014).

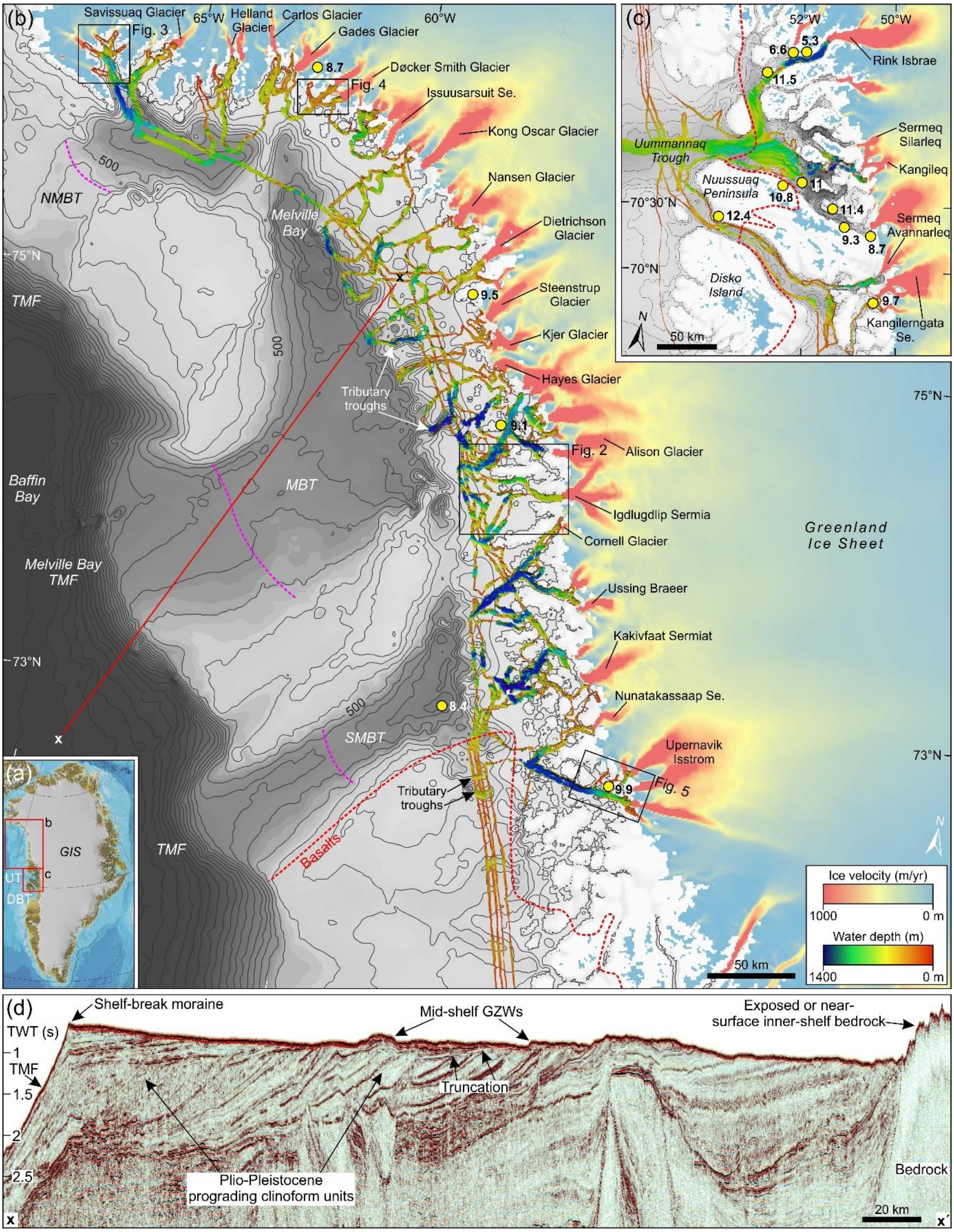

(b)
Savissuaq Glacier
Fig. 3
65°W
Helland Glacier
Carlos Glacier
Gades Glacier
60°W
8.7
Døcker Smith Glacier
Fig. 4
Issuusarsuit Se.
Kong Oscar Glacier
500
NMBT
Nansen Glacier
Melville Bay
Dietrichson Glacier
75°N
TMF
9.5
Steenstrup Glacier
Kjer Glacier
500
Tributary troughs
Hayes Glacier
9.1
Fig. 2
Alison Glacier
Baffin Bay
MBT
Igdlugdlip Sermia
Cornell Glacier
Melville Bay TMF
Greenland Ice Sheet
Ussing Braeer
Kakivfaat Sermiat
73°N
500
8.4
Nunatakassaap Se.
SMBT
Upernavik Isstrom
9.9
Fig. 5
Tributary troughs
Basalts
TMF
(a)
b
GIS
UT
c
DBT
50 km
Ice velocity (m/yr)
1000
0 m
Water depth (m)
1400
0 m
(c)
52°W
50°W
5.3
6.6
Rink Isbrae
11.5
Uummannaq Trough
Sermeq Silarleq
Kangileq
Nuussuaq Peninsula
11
10.8
70°30'N
11.4
12.4
Sermeq Avannarleq
9.3
8.7
70°N
Disko Island
9.7
Kangilerngata Se.
50 km
75°N
73°N
(d)
Shelf-break moraine
Mid-shelf GZWs
Exposed or near-surface inner-shelf bedrock
TWT (s)
1
TMF
1.5
Truncation
2
2.5
Plio-Pleistocene prograding clinoform units
Bedrock
20 km
x
x´

Figure 1

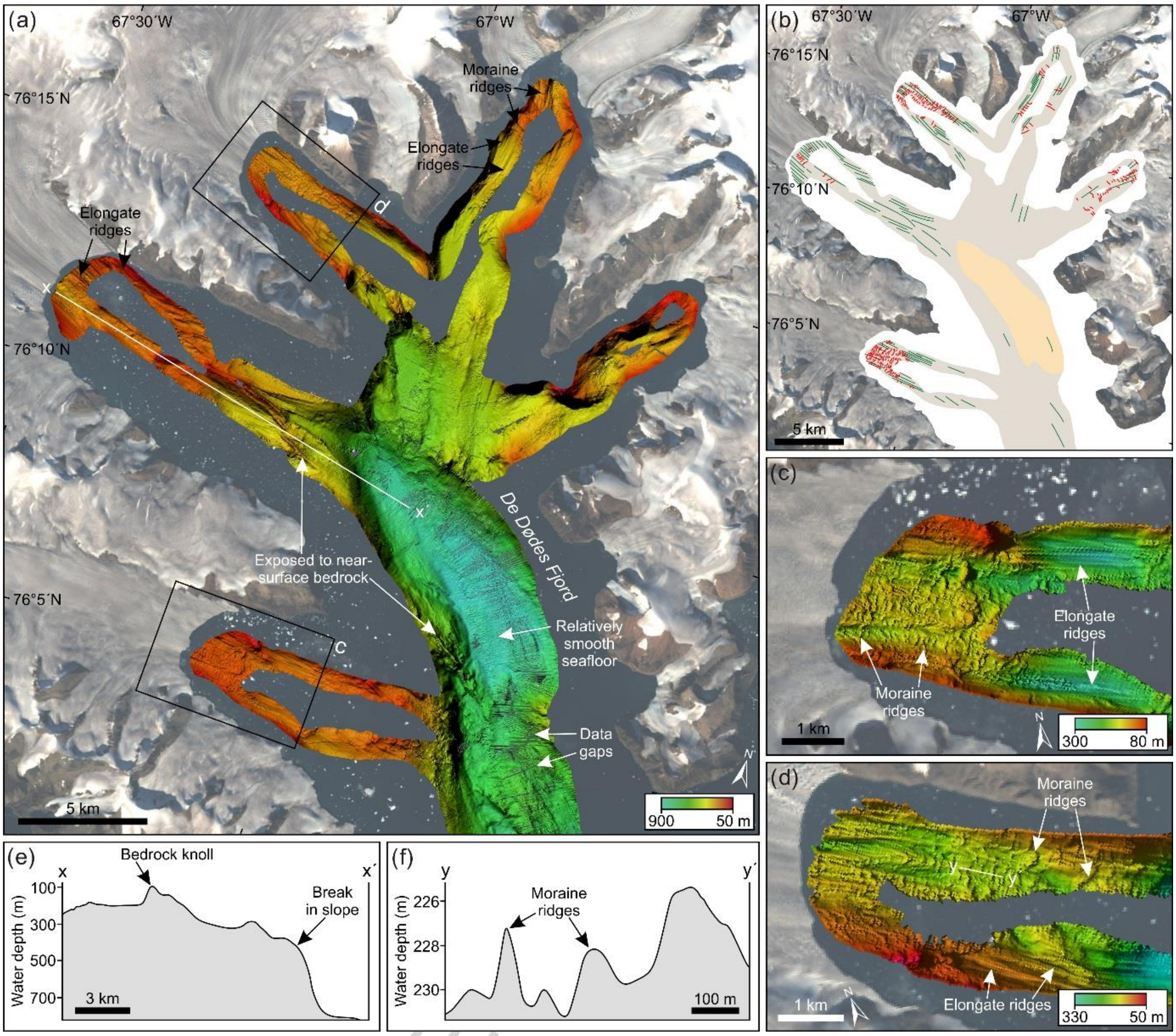

(a)
67°30´W
67°W
76°15´N
76°10´N
76°5´N
Moraine ridges
Elongate ridges
Elongate ridges
d
x
x´
Exposed to near-surface bedrock
De Dødes Fjord
Relatively smooth seafloor
c
Data gaps
5 km
900
50 m
(b)
67°30´W
67°W
76°15´N
76°10´N
76°5´N
5 km
(c)
Elongate ridges
Moraine ridges
1 km
300
80 m
(d)
Moraine ridges
y
y´
1 km
Elongate ridges
330
50 m
(e)
x
x´
Bedrock knoll
Break in slope
Water depth (m)
100
300
500
700
3 km
(f)
y
y´
Moraine ridges
Water depth (m)
226
228
230
100 m

Figure 2

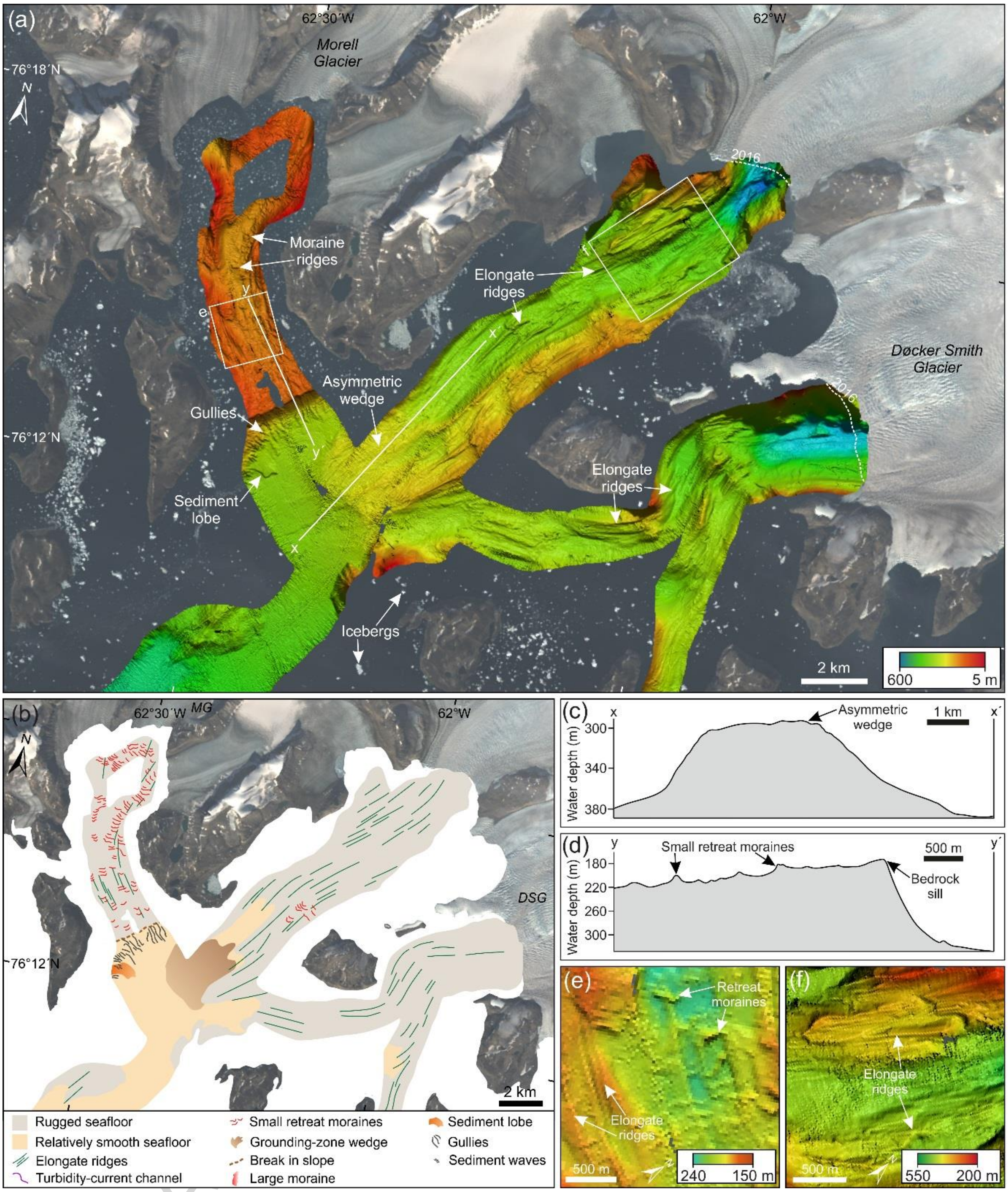
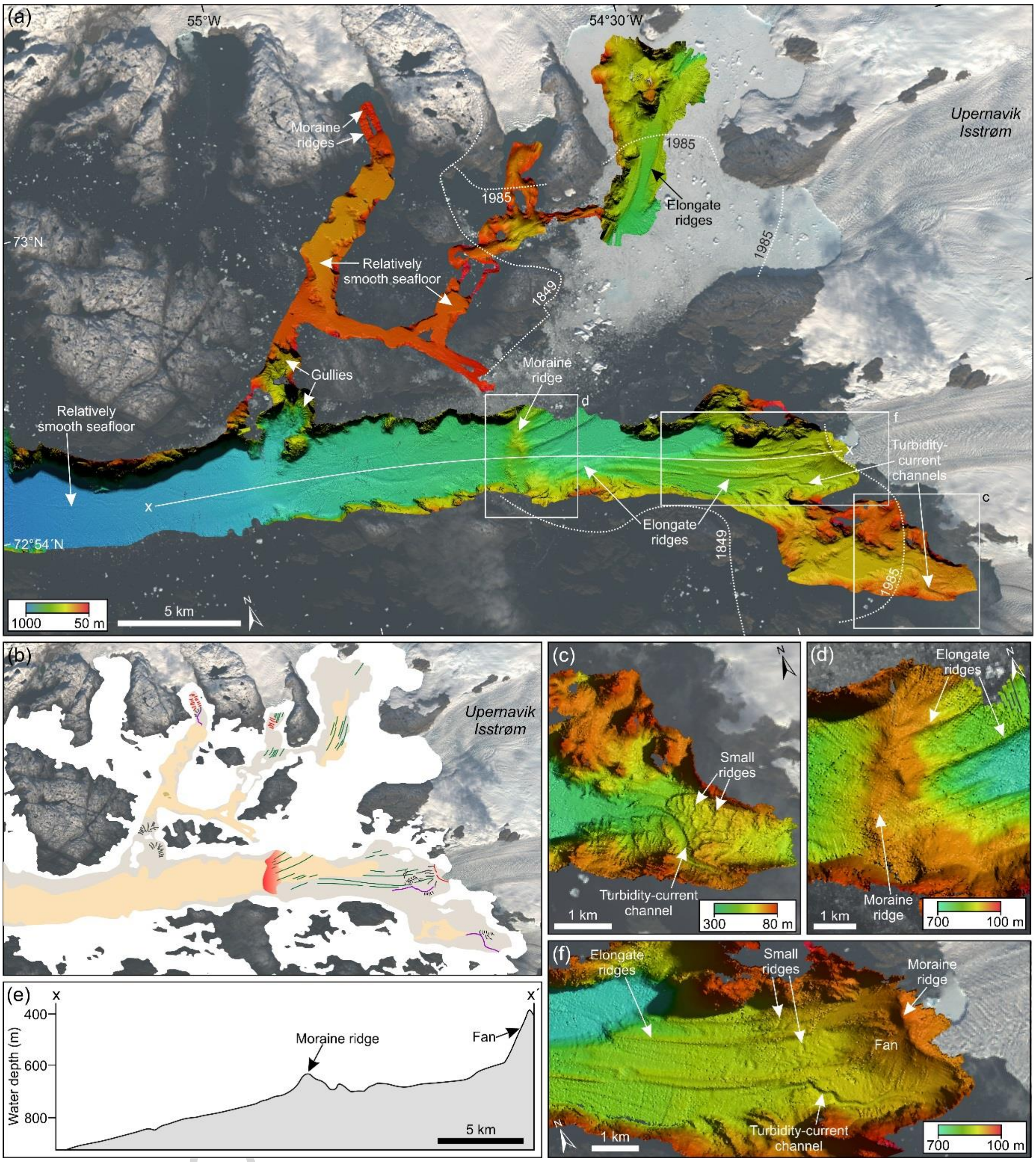
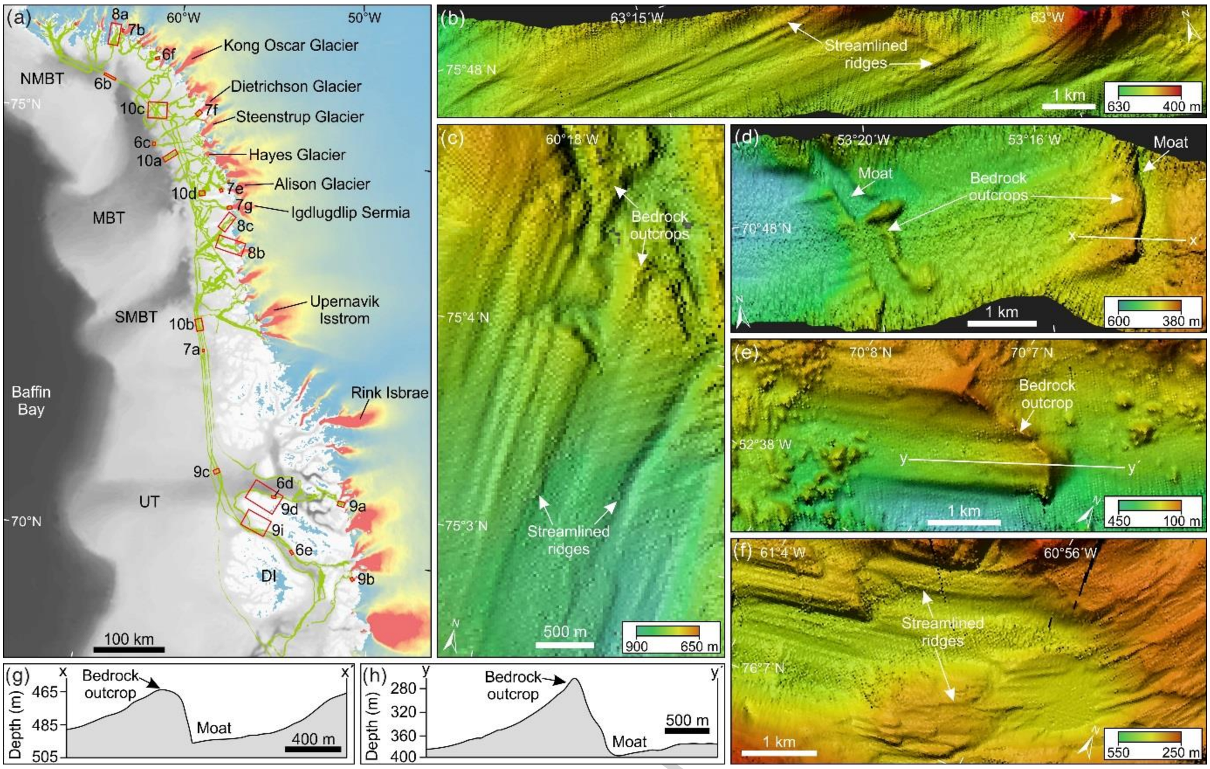

(a)
62°30´W
62°W
Morell Glacier
76°18´N
N
2016
Moraine ridges
Elongate ridges
Døcker Smith Glacier
Asymmetric wedge
Gullies
76°12´N
Sediment lobe
Elongate ridges
Icebergs
2 km
600
5 m
(b)
62°30´W
MG
62°W
DSG
76°12´N
2 km
Rugged seafloor
Relatively smooth seafloor
Elongate ridges
Turbidity-current channel
Small retreat moraines
Grounding-zone wedge
Break in slope
Large moraine
Sediment lobe
Gullies
Sediment waves
(c)
Asymmetric wedge
1 km
Water depth (m)
300
340
380
(d)
Small retreat moraines
500 m
Bedrock sill
Water depth (m)
180
220
260
300
(e)
Retreat moraines
Elongate ridges
500 m
240
150 m
(f)
Elongate ridges
500 m
550
200 m

Figure 3



(a)
55°W
54°30´W
Moraine ridges
1985
Elongate ridges
Upernavik Isstrøm
73°N
Relatively smooth seafloor
1849
Gullies
Moraine ridge
Relatively smooth seafloor
d
f
Turbidity-current channels
x
x´
c
Elongate ridges
72°54´N
1000
50 m
5 km
(b)
Upernavik Isstrøm
(c)
Small ridges
Turbidity-current channel
1 km
300
80 m
(d)
Elongate ridges
Moraine ridge
1 km
700
100 m
(e)
400
600
800
Water depth (m)
Moraine ridge
Fan
5 km
(f)
Elongate ridges
Small ridges
Moraine ridge
Fan
Turbidity-current channel
1 km
700
100 m

Figure 4



(a)
8a
7b
60°W
50°W
6f
Kong Oscar Glacier
NMBT
6b
Dietrichson Glacier
75°N
10c
7f
Steenstrup Glacier
6c
10a
Hayes Glacier
10d
7e
Alison Glacier
7g
Igdlugdlip Sermia
MBT
8c
8b
Upernavik Isstrom
SMBT
10b
7a
Baffin Bay
Rink Isbrae
9c
6d
UT
9d
9a
70°N
9i
6e
DI
9b
100 km
(b)
63°15'W
63°W
Streamlined ridges
75°48'N
1 km
630
400 m
(c)
60°18'W
Bedrock outcrops
75°4'N
75°3'N
Streamlined ridges
500 m
900
650 m
(d)
53°20'W
53°16'W
Moat
Moat
Bedrock outcrops
70°48'N
x
x'
1 km
600
380 m
(e)
70°8'N
70°7'N
Bedrock outcrop
52°38'W
y
y'
1 km
450
100 m
(f)
61°4'W
60°56'W
Streamlined ridges
76°7'N
1 km
550
250 m
(g)
x
x'
Bedrock outcrop
Depth (m)
465
485
505
Moat
400 m
(h)
y
y'
Bedrock outcrop
Depth (m)
280
320
360
400
500 m
Moat

Figure 5

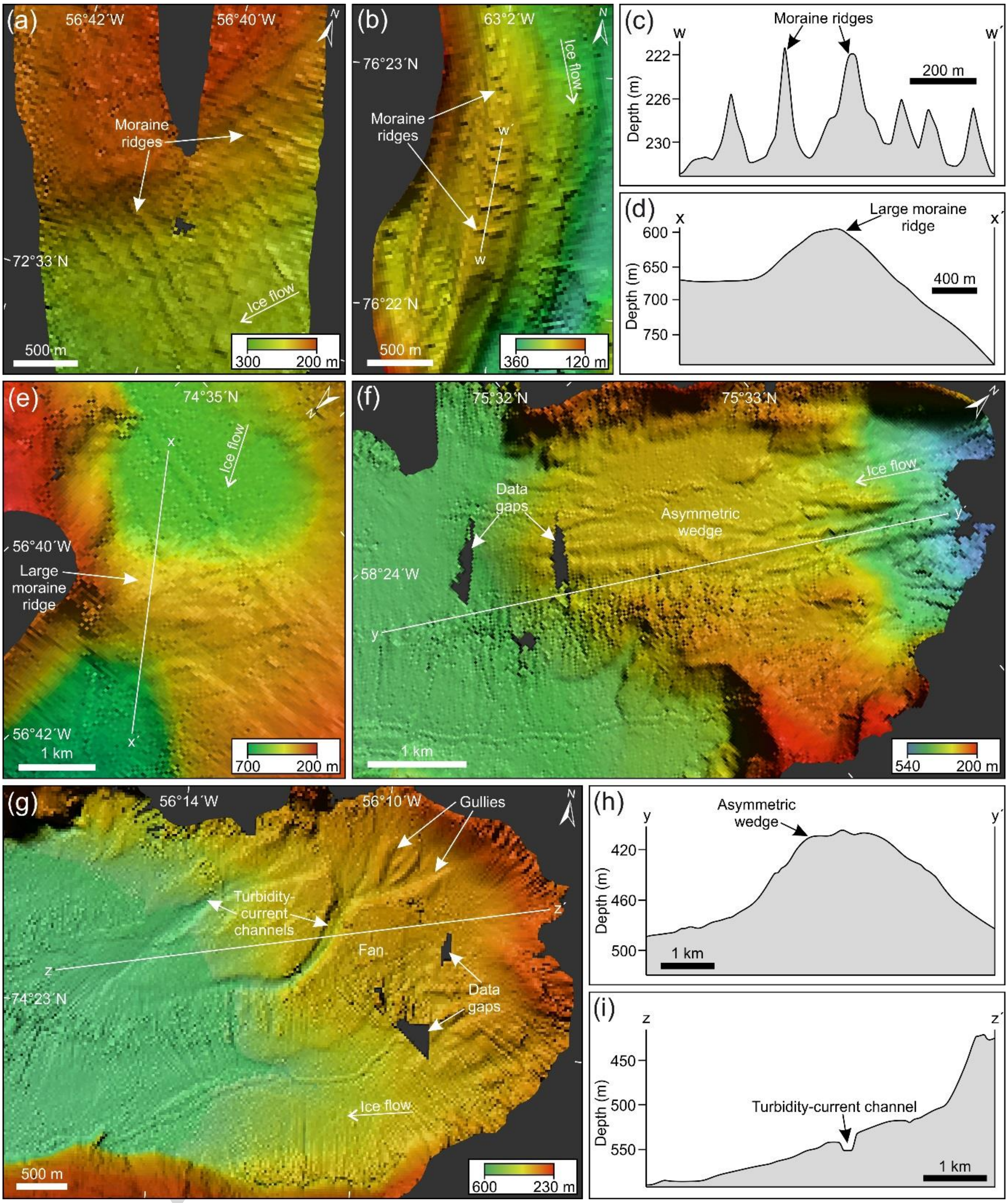
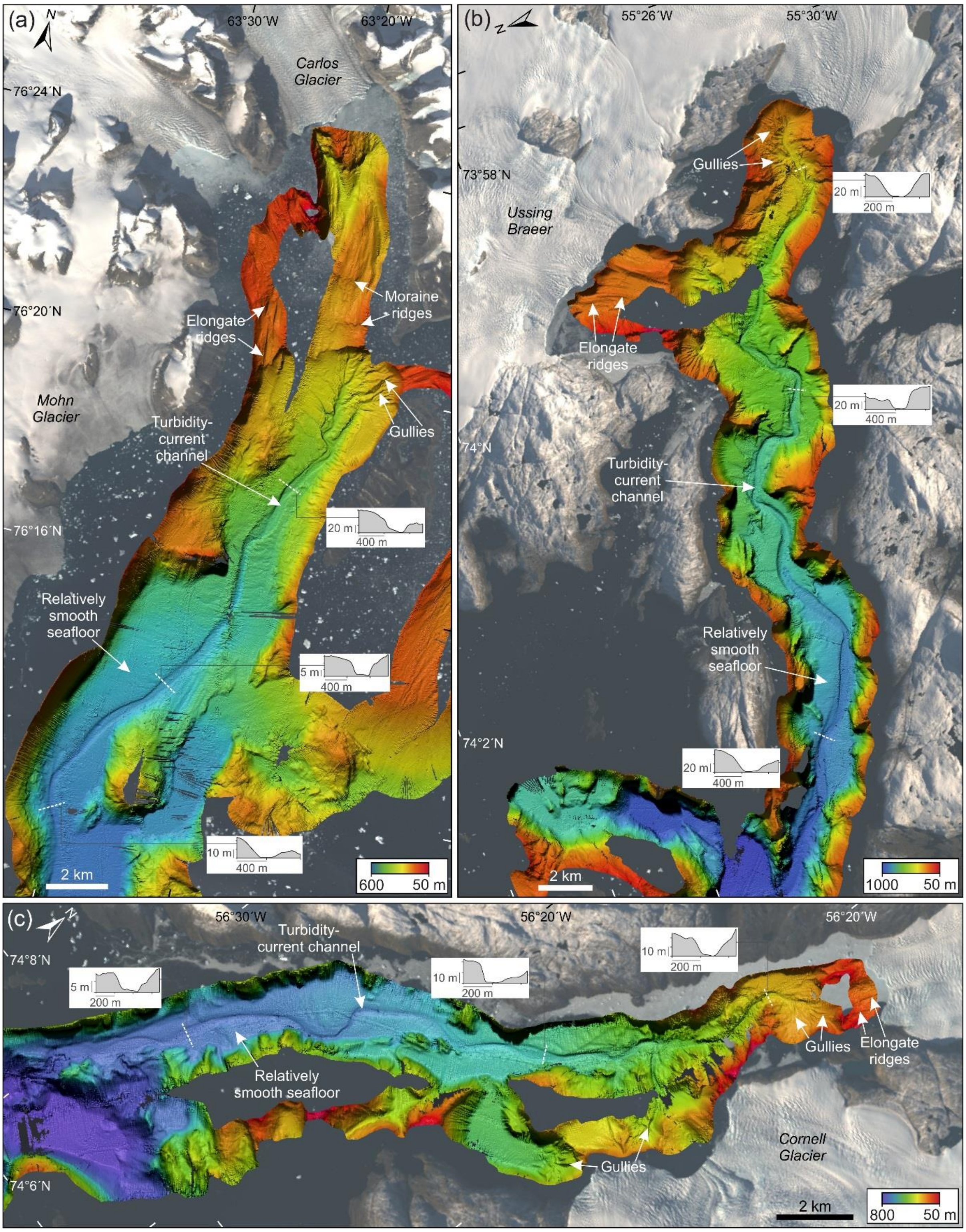
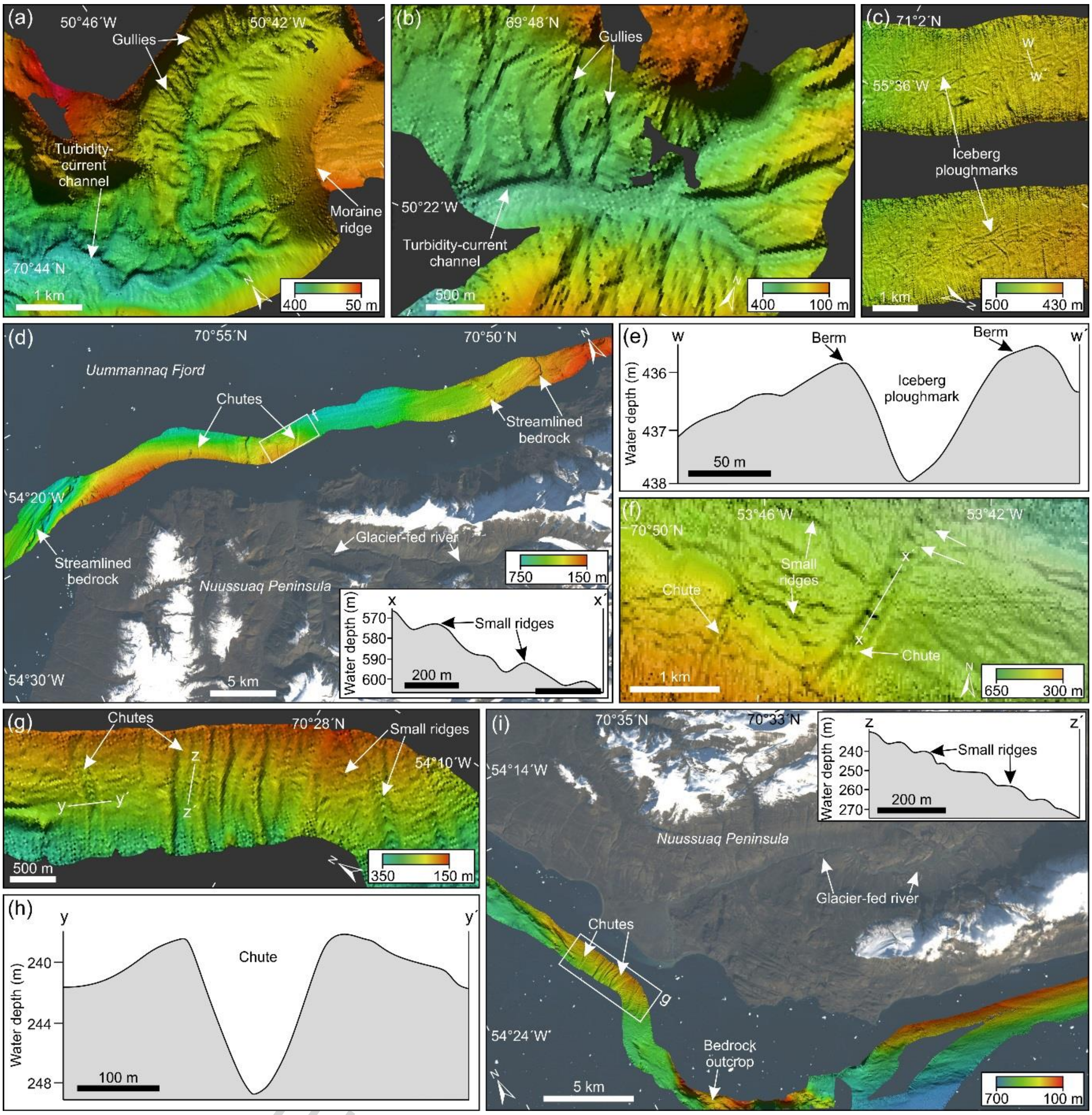

(a)
56°42´W
56°40´W
Moraine ridges
72°33´N
Ice flow
500 m
300
200 m
(b)
63°2´W
76°23´N
Ice flow
Moraine ridges
w´
w
76°22´N
500 m
360
120 m
(c)
Moraine ridges
w
w´
222
226
230
Depth (m)
200 m
(d)
x
x´
Large moraine ridge
600
650
700
750
Depth (m)
400 m
(e)
74°35´N
Ice flow
56°40´W
Large moraine ridge
56°42´W
1 km
700
200 m
(f)
75°32´N
75°33´N
Ice flow
Data gaps
Asymmetric wedge
58°24´W
y
y´
1 km
540
200 m
(g)
56°14´W
56°10´W
Gullies
Turbidity-current channels
Fan
Data gaps
74°23´N
Ice flow
500 m
600
230 m
(h)
Asymmetric wedge
y
y´
420
460
500
Depth (m)
1 km
(i)
z
z´
450
500
550
Depth (m)
Turbidity-current channel
1 km

Figure 6



(a)
N
63°30´W
63°20´W
Carlos Glacier
76°24´N
76°20´N
76°16´N
Moraine ridges
Elongate ridges
Mohn Glacier
Turbidity-current channel
Gullies
20 m
400 m
Relatively smooth seafloor
5 m
400 m
10 m
400 m
2 km
600
50 m
(b)
N
55°26´W
55°30´W
73°58´N
Ussing Braeer
Gullies
20 m
200 m
Elongate ridges
20 m
400 m
74°N
Turbidity-current channel
Relatively smooth seafloor
74°2´N
20 m
400 m
2 km
1000
50 m
(c)
N
56°30´W
56°20´W
56°20´W
74°8´N
Turbidity-current channel
5 m
200 m
10 m
200 m
10 m
200 m
Relatively smooth seafloor
Gullies
Elongate ridges
Cornell Glacier
74°6´N
2 km
800
50 m

Figure 7



(a)
50°46´W
50°42´W
Gullies
Turbidity-current channel
Moraine ridge
70°44´N
1 km
400
50 m
(b)
69°48´N
Gullies
50°22´W
Turbidity-current channel
500 m
400
100 m
(c)
71°2´N
55°36´W
w
w´
Iceberg ploughmarks
1 km
500
430 m
(d)
70°55´N
70°50´N
Uummannaq Fjord
Chutes
Streamlined bedrock
54°20´W
Glacier-fed river
Streamlined bedrock
Nuussuaq Peninsula
54°30´W
5 km
750
150 m
x
x´
Small ridges
Water depth (m)
570
580
590
600
200 m
(e)
w
w´
Berm
Berm
Iceberg ploughmark
Water depth (m)
436
437
438
50 m
(f)
53°46´W
53°42´W
70°50´N
Small ridges
Chute
Chute
1 km
650
300 m
(g)
Chutes
70°28´N
Small ridges
54°10´W
z
z´
y
y´
500 m
350
150 m
(h)
y
y´
Chute
Water depth (m)
240
244
248
100 m
(i)
70°35´N
70°33´N
54°14´W
Nuussuaq Peninsula
Glacier-fed river
Chutes
54°24´W
Bedrock outcrop
5 km
700
100 m
z
z´
Small ridges
Water depth (m)
240
250
260
270
200 m

Figure 8

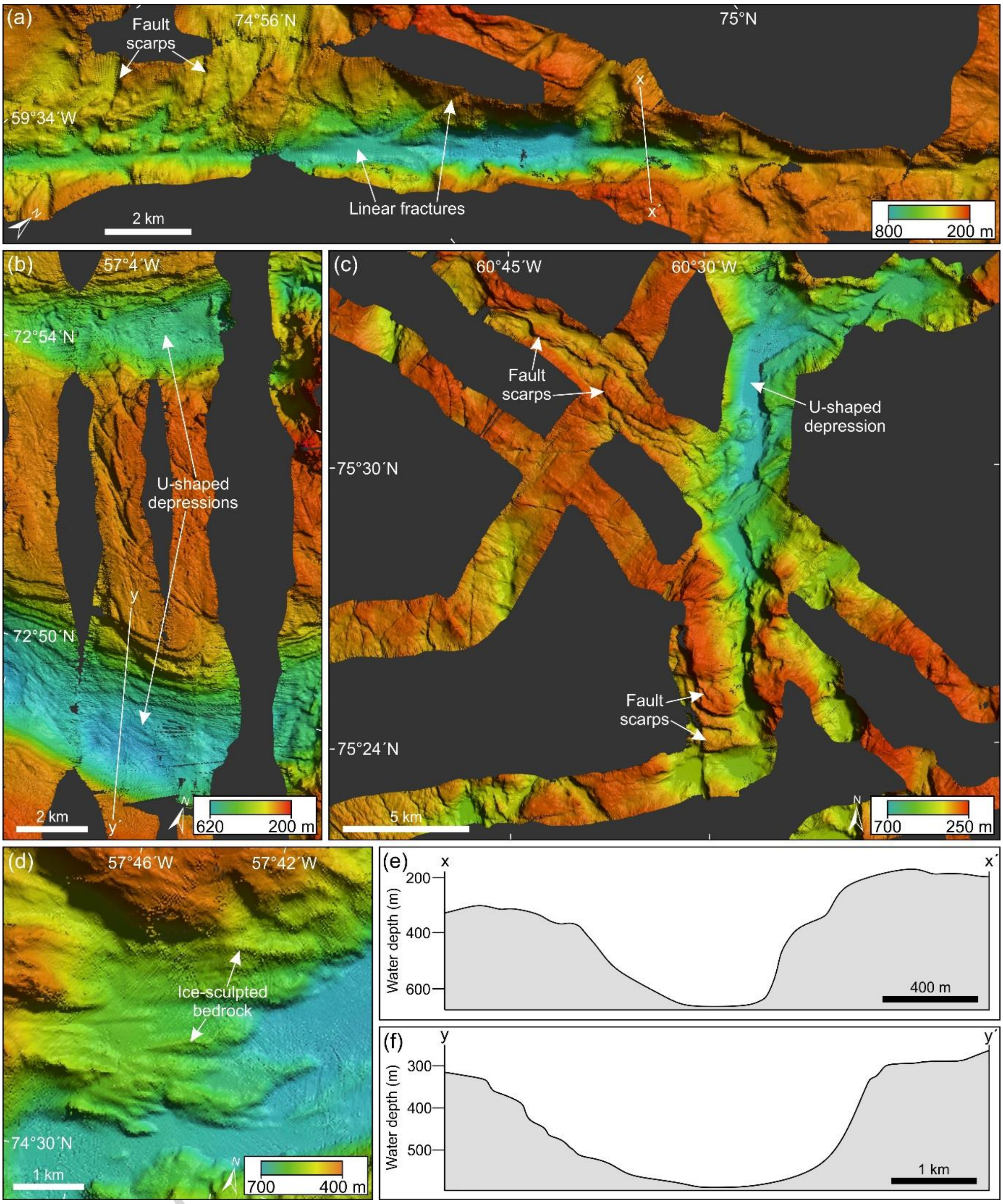

(a)
Fault scarps
74°56´N
75°N
59°34´W
Linear fractures
2 km
800
200 m
x
x´
(b)
57°4´W
72°54´N
U-shaped depressions
72°50´N
2 km
620
200 m
y
y´
(c)
60°45´W
60°30´W
Fault scarps
U-shaped depression
75°30´N
Fault scarps
75°24´N
5 km
700
250 m
(d)
57°46´W
57°42´W
Ice-sculpted bedrock
74°30´N
1 km
700
400 m
(e)
Water depth (m)
200
400
600
400 m
(f)
Water depth (m)
300
400
500
1 km

Figure 9

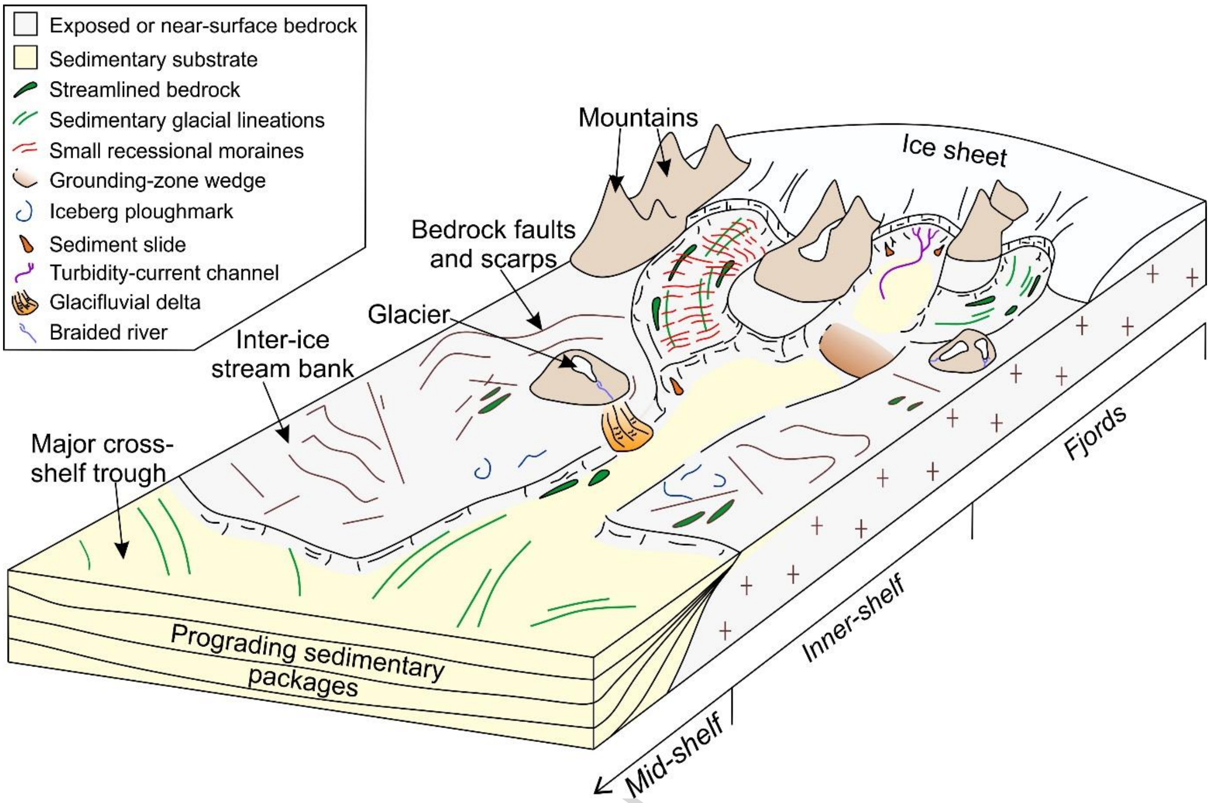

Exposed or near-surface bedrock
Sedimentary substrate
Streamlined bedrock
Sedimentary glacial lineations
Small recessional moraines
Grounding-zone wedge
Iceberg ploughmark
Sediment slide
Turbidity-current channel
Glacifluvial delta
Braided river
Mountains
Ice sheet
Bedrock faults and scarps
Glacier
Inter-ice stream bank
Major cross-shelf trough
Prograding sedimentary packages
Fjords
Inner-shelf
Mid-shelf

Figure 10

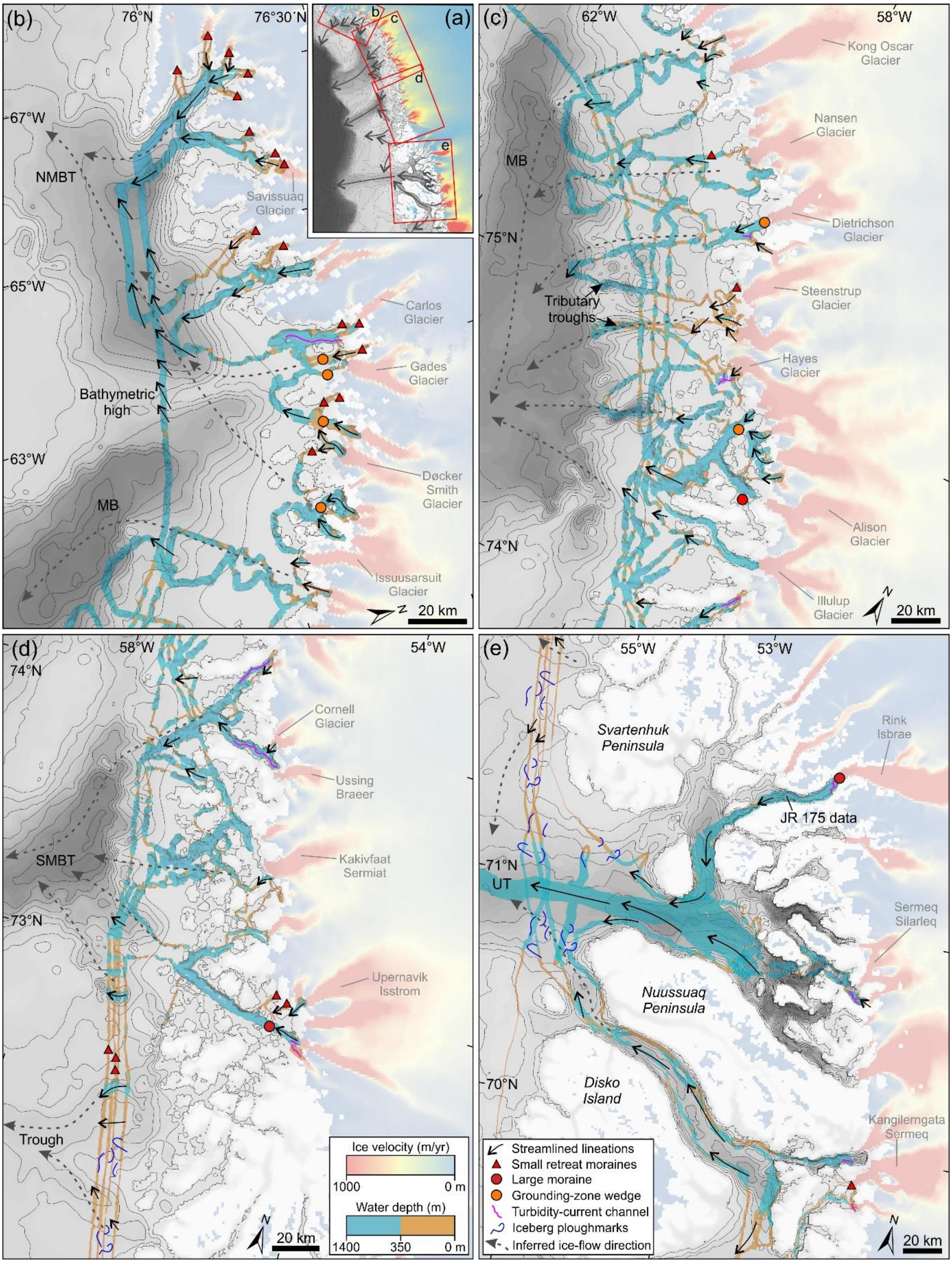

(a)
b
c
d
e
(b)
76°N
76°30´N
67°W
65°W
63°W
NMBT
Savissuaq Glacier
Carlos Glacier
Gades Glacier
Bathymetric high
Døcker Smith Glacier
MB
Issuusarsuit Glacier
20 km
(c)
62°W
58°W
Kong Oscar Glacier
Nansen Glacier
MB
75°N
Dietrichson Glacier
Steenstrup Glacier
Tributary troughs
Hayes Glacier
Alison Glacier
74°N
Illulup Glacier
20 km
(d)
58°W
54°W
74°N
Cornell Glacier
Ussing Braeer
SMBT
Kakivfaat Sermiat
73°N
Upernavik Isstrom
Trough
20 km
Ice velocity (m/yr)
1000
0 m
Water depth (m)
1400
350
0 m
(e)
55°W
53°W
Svartenhuk Peninsula
Rink Isbrae
JR 175 data
71°N
UT
Sermeq Silarleq
Nuussuaq Peninsula
70°N
Disko Island
Kangilerngata Sermeq
Streamlined lineations
Small retreat moraines
Large moraine
Grounding-zone wedge
Turbidity-current channel
Iceberg ploughmarks
Inferred ice-flow direction
20 km

Figure 11

Highlights

We present bathymetric data from the inner-shelf and fjords of North-West Greenland

We show the water depth and fjord geometry beyond the present-day ice margin

Streamlined subglacial landforms show the direction of Late Quaternary ice flow

Moraines and grounding-zone wedges show the locations of past ice-margin still-stands

The outlet glaciers experienced varying rates and styles of Holocene ice retreat