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## RESEARCH LETTER

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## Key Points:

- Extensive high-resolution geophysical data have been used to analyze glacial landforms on the northwest Greenland continental shelf
- Mega-scale glacial lineations indicate changes in ice flow dynamics on the outer shelf
- Large mid-shelf grounding-zone wedge suggests a period of intermittent ice margin stability at some stage during the last deglaciation

## Supporting Information:

- Supporting Information S1

## Correspondence to:

A. M. W. Newton,  
amwnewton@gmail.com

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## Ice stream reorganization and glacial retreat on the northwest Greenland shelf

A. M. W. Newton<sup>1,2</sup> , P. C. Knutz<sup>3</sup> , M. Huuse<sup>1,2</sup> , P. Gannon<sup>4</sup> , S. H. Brocklehurst<sup>1,2</sup> , O. R. Clausen<sup>5</sup> , and Y. Gong<sup>1</sup> 

<sup>1</sup>School of Earth and Environmental Sciences, University of Manchester, Manchester, UK, <sup>2</sup>Cryosphere Research at Manchester, Manchester, UK, <sup>3</sup>Department of Geophysics, Geological Survey of Denmark and Greenland, Copenhagen, Denmark, <sup>4</sup>Cairn Energy, Berkeley Square, London, <sup>5</sup>Department of Geoscience, Aarhus University, Aarhus, Denmark

**Abstract** Understanding conditions at the grounding-line of marine-based ice sheets is essential for understanding ice sheet evolution. Offshore northwest Greenland, knowledge of the Last Glacial Maximum (LGM) ice sheet extent in Melville Bugt was previously based on sparse geological evidence. This study uses multibeam bathymetry, combined with 2-D and 3-D seismic reflection data, to present a detailed landform record from Melville Bugt. Seabed landforms include mega-scale glacial lineations, grounding-zone wedges, iceberg scours, and a lateral shear margin moraine, formed during the last glacial cycle. The geomorphology indicates that the LGM ice sheet reached the shelf edge before undergoing flow reorganization. After retreat of ~80 km across the outer shelf, the margin stabilized in a mid-shelf position, possibly during the Younger Dryas (12.9–11.7 ka). The ice sheet then decoupled from the seafloor and retreated to a coast-proximal position. This landform record provides an important constraint on deglaciation history offshore northwest Greenland.

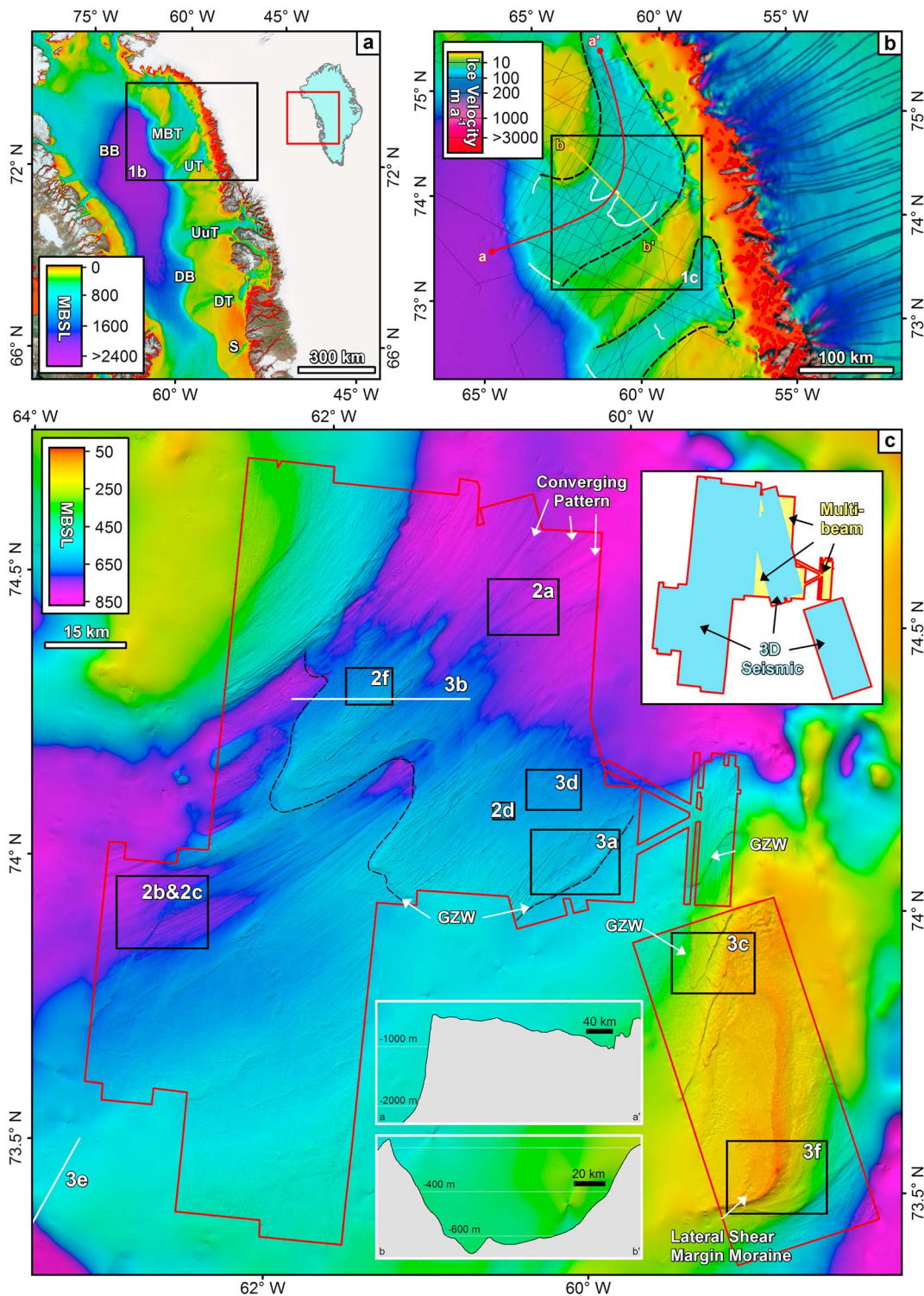
**Plain Language Summary** Reconstructing the extent and dynamics of the Greenland Ice Sheet during the last ice age are important for helping us to predict how it may change in the future. This study uses the topography of the seafloor to investigate for evidence of landforms left behind by the Greenland Ice Sheet during the last ice age. These landforms indicate that the ice sheet extended to the continental shelf edge when it was at its largest extent. The ice sheet then retreated 80 km to the middle shelf, likely during a period of climate cooling called the Younger Dryas. The ice sheet margin remained stable here until it retreated a further 100 km toward the coastline during the final deglaciation. During this second stage of deglaciation the ice sheet appears to have retreated faster than during the first stage. This possible dramatic collapse has possible implications for our understanding of the future evolution of the Greenland Ice Sheet.

## 1. Introduction

The Greenland Ice Sheet (GrIS) is currently experiencing mass loss and changes in ice sheet dynamics [Hanna *et al.*, 2013; Howat *et al.*, 2005; Joughin *et al.*, 2014]. These changes are of importance to the current and future contributions of the GrIS to sea level rise [van den Broeke *et al.*, 2016; Vaughan *et al.*, 2013]. By studying past GrIS behavior in response to other periods of climate warming, such as that which followed the Last Glacial Maximum (LGM), we can gain additional insight into how the ice sheet may evolve in the future.

Early models for the LGM expansion of the GrIS were based on onshore studies augmented with limited offshore observations of glacial deposits [Funder and Larsen, 1989]. Numerical Earth-system modeling supports a more expansive GrIS during the LGM than the present [Lecavalier *et al.*, 2014; Simpson *et al.*, 2009], but it relies on assumptions and simplifications of lithospheric flexure, ice sheet processes, and environmental changes. Consequently, until recently, much of the understanding on the LGM extent of the GrIS has been theoretical rather than observational. Thus, the geomorphological data presented herein provide a crucial constraint on past ice sheet extent in a setting that is otherwise poorly known and offers little to modelers for calibration.

With improvements in sampling and imaging techniques allowing for better core recovery and higher-resolution acoustic records, new data have been collected offshore Greenland, allowing different parts of the LGM margin to be reconstructed [Dowdeswell *et al.*, 2014; Evans *et al.*, 2009; Hogan *et al.*, 2016; Winkelmann *et al.*, 2010]. The continental shelf in Melville Bugt (Figure 1) contains Greenland's largest cross-shelf trough, and, based on the common association between troughs and ice streaming, it is assumed the trough was occupied by an ice stream at the LGM [Slabon *et al.*, 2016]. The axis of the trough is overdeepened, with water depths of ~500 m and ~1000 m in the outer and inner parts of the trough, respectively



**Figure 1.** Study site. (a) Bathymetry and satellite imagery for west and northwest Greenland showing several cross-shelf troughs that were once occupied by ice streams. Bathymetry from *Jakobsson et al.* [2012] and satellite data from ArcGIS online. Abbreviations are for locations mentioned in the text: Baffin Bay (BB), Disko Bugt (DB), Disko Trough (DT), Melville Bugt Trough (MBT), Sisimiut (S), Upernavik Trough (UT), and Ummannaq Trough (UuT). Location of Figure 1b is shown. (b) Melville Bugt study area offshore northwest Greenland. White lines show ice margin positions from this study and *Slabon et al.* [2016]. Black dashed lines show trough outlines. Gray lines show 2-D seismic data. Locations of elevation profiles in Figure 1c are shown. The ice velocity map shows fast-flowing outlet glaciers in the region. Velocity data from *Joughin et al.* [2010]. Location of Figure 1c is indicated. The bathymetry color bar is the same as Figure 1a. (c) Composite bathymetry covering the central part of the MBT and the northern part of the UT. Red outline is the area covered with high-resolution 3-D seismic and multibeam data. Locations of Figures 2 and 3 are indicated. Elevation profiles are for the MBT, and their locations are shown in Figure 1b. For a detailed geomorphological map, see Figure S1.

(Figure 1). In this paper, multibeam bathymetry is integrated with 2-D and 3-D seismic reflection data from the Melville Bugt Trough (MBT) and the northern part of the Upernavik Trough to document in detail the glacial geomorphology and retreat dynamics in Melville Bugt (Figure 1).

## 2. Glaciological Setting

During the LGM, the Greenland, Laurentide, and Innuitian Ice Sheets formed a continuous belt around Baffin Bay, with the GrIS presumed to have extended onto the shelf in most areas, including Melville Bugt [Dyke *et al.*, 2002; England *et al.*, 2006; Funder *et al.*, 2011; Vasskog *et al.*, 2015]. Although no geochronological data are currently available for the onset of deglaciation in Melville Bugt, numerical modeling suggests that deglaciation began at  $\sim 16.0$  ka and the ice front receded behind the coastline at  $\sim 9.0$  ka [Lecavalier *et al.*, 2014]. Dated lake sediments in Melville Bugt show the ice margin retreated to, or behind, the late Holocene position by  $\sim 9.6$  ka, which is 1.5–2 kyr earlier than elsewhere in western Greenland [Briner *et al.*, 2013]. It is currently unclear why this part of the ice sheet retreated earlier than others along the Greenland margin.

Multiple LGM studies suggest that ice streams extended onto the continental shelf offshore most of Greenland [Arndt *et al.*, 2017; Dowdeswell *et al.*, 2010; Evans *et al.*, 2002, 2009; Wilken and Mienert, 2006; Winkelmann *et al.*, 2010]. The majority of work has been carried out offshore western Greenland. In the Sisimiut area (Figure 1a) the LGM ice sheet extended across the inner shelf with the exception of the cross-shelf troughs where ice may have extended to the shelf edge [Funder *et al.*, 2011; Roberts *et al.*, 2009; Vasskog *et al.*, 2015]. In the Disko and Uummannaq Troughs (Figure 1a) the GrIS reached the outer shelf at the LGM before an asynchronous retreat [Dowdeswell *et al.*, 2014; Ó Cofaigh *et al.*, 2012]. In the Disko Trough, margin retreat from the shelf edge began at 16.2 cal ka B.P. until readvance during the Younger Dryas [Jennings *et al.*, 2014, 2017]. After 12.2 cal ka B.P. the margin retreated rapidly, predominantly through calving [Hogan *et al.*, 2016; Jennings *et al.*, 2014]. In the Uummannaq Trough, ice retreated from the shelf edge at 17.1 cal ka B.P. before stabilizing on the mid-shelf sometime after 13.9 cal ka B.P. and through the Younger Dryas, forming a large grounding-zone wedge, before retreating into the fjords [Dowdeswell *et al.*, 2014; Sheldon *et al.*, 2016]. Foraminiferal data from the Disko and Uummannaq Troughs suggest that the West Greenland Current was established by 14.0 cal ka B.P. and incursion onto the shelf proceeded after (and possibly promoted) retreat [Jennings *et al.*, 2017; Sheldon *et al.*, 2016].

There is an increasing but scattered body of evidence investigating the LGM extent, retreat dynamics, and Younger Dryas response of the GrIS [e.g., Jennings *et al.*, 2014; Larsen *et al.*, 2016]. The collected data are also heavily skewed toward Disko Bugt because of concerns about the stability of Jakobshavn Isbræ, an ice stream draining  $\sim 7\%$  of the contemporary GrIS [Joughin *et al.*, 2014]. This has meant that outside of Disko Bugt there is a poor understanding of deglacial dynamics and even the validity of supposed ice sheet extent offshore northwest Greenland. Presently, the catchment area of ice flowing toward the MBT is  $\sim 140,000$  km<sup>2</sup> compared to the  $\sim 110,000$  km<sup>2</sup> for Jakobshavn Isbræ. Although the MBT covers a similar area to the Disko Trough ( $\sim 28,000$  km<sup>2</sup>), water depths are deeper by up to 350–400 m in the MBT. Therefore, if the MBT was fully occupied by an ice stream at the LGM, it was likely draining more of the GrIS than Jakobshavn Isbræ, highlighting the need for a better understanding of its post-LGM evolution.

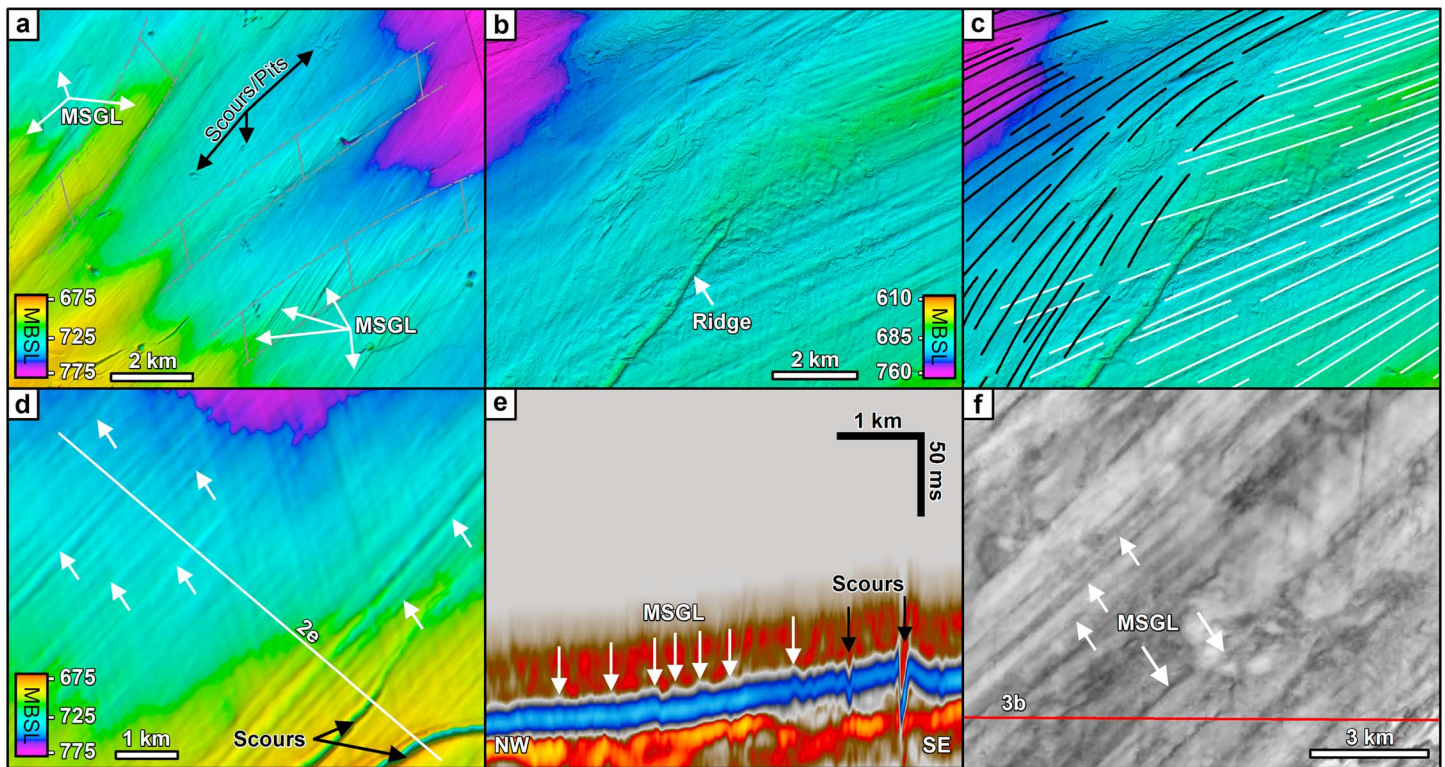
## 3. Data and Methods

Using conventional 2-D and 3-D post-stack time-migrated seismic reflection data (vertical resolution 10–15 m), the seafloor reflection was gridded at  $25 \times 25$  m and depth converted using a sound velocity of  $\sim 1480$  m s<sup>-1</sup>. This velocity was iteratively adjusted (by  $\leq 1\%$ ) to merge the seismic and multibeam data to create a  $25 \times 25$  m resolution composite bathymetry that was used to identify and digitize landforms (Figures 1b and 1c). The vertical seismic expressions of landforms identified in the 3-D data were used to explore the 2-D data for similar features. In the southwest part of the 3-D survey, acquisition artifacts make interpretation of seafloor features difficult to map confidently (see Figure S1 in the supporting information).

## 4. Description and Interpretation of Submarine Landforms

### 4.1. Mega-scale Glacial Lineations

Much of the seafloor is characterized by streamlined bedforms (Figure 1), typically 4–6 km long, 100–200 m wide, and 10–20 m high. These geometries and the setting within which they are observed lead us to

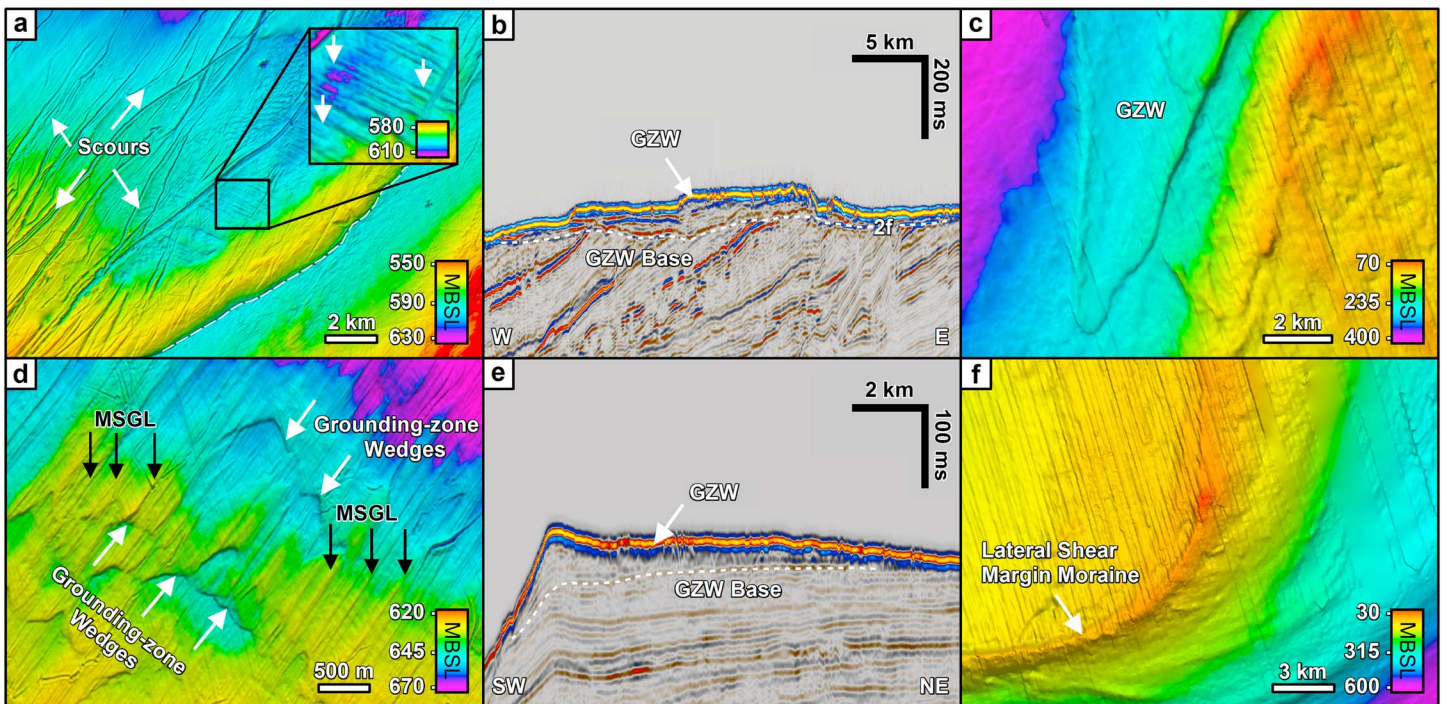


**Figure 2.** Glacial geomorphology. (a) MSGL superimposed on top of an older larger-scale lineated pattern (indicated by the gray dashed lines and interpreted as MSGL) in the eastern part of the study area. See also Figure 1c. (b) Crosscutting MSGL in the west. (c) Digitized record of MSGL from Figure 2b. MSGL indicated by the black lines crosscut those indicated by the white lines. (d) MSGL in the eastern part of the trough and ice berg scours. (e) Seismic cross section of MSGL within the 3-D seismic survey. Location is shown in Figure 2d. (f) Buried MSGL beneath the main grounding-zone wedge (profile shown in Figure 3b). See Figure 1c for locations of Figures 2a to 2f.

interpret these features as mega-scale glacial lineations (MSGL) formed by fast-flowing ice [cf. Clark, 1993; Spagnolo *et al.*, 2014]. Crosscutting MSGL provide a means of deducing relative timings of changes in ice flow patterns, and we discuss those observed here in order of probable chronology. In the east, a wider (1.2–1.4 km) lineated pattern converges through a window between north-northeast and east-northeast (Figures 1a and 2a). These features are larger than the MSGL described below (Figures 2b–2f) but are similar to MSGL described in Antarctica as bundle structures [Canals *et al.*, 2000]. These MSGL are interpreted to reflect the initial large-scale ice flow pattern, where ice funneled into the trough and sculpted the seafloor. The converging pattern is supported by streamlined features on the coastal Precambrian basement showing flow from the east-southeast into the MBT [Freire *et al.*, 2015].

The 3-D seismic data reveal that the converged MSGL continue beneath a large grounding-zone wedge on the mid-shelf (see section 4.2). These MSGL are orientated from northeast to the southwest (Figure 2f) and suggest that during initial ice advance across the shelf, ice flow was parallel to the trough axis here. This trough-parallel pattern continues on the lee side of the wedge where the buried MSGL protrude from beneath and continue for ~80 km to the outer shelf (Figures 2b and 2c). Crosscutting MSGL observed on the outer shelf suggest flow reorganization of the ice front. The older MSGL (white lines in Figure 2c) show an east-northeast to west-southwest pattern that is broadly parallel to the trough and matches the pattern observed beneath the wedge. As the ice stream reorganized, younger MSGL (black lines in Figure 2c) crosscut the trough-parallel MSGL, showing a change in ice flow to the south-southwest. This reorganization may reflect competition for trough drainage space of the ice masses that converged in the east, or the later dominance of ice flow from the northern bank area, causing a southward deflection, possibly during margin retreat.

Although acquisition artifacts and low resolution make interpretation of the ridge feature separating the crosscutting MSGL difficult (Figure 2b), we speculate that the ridge marks a shear zone between ice with different characteristics. After the outer shelf MSGL were formed, a mid-shelf wedge (see section 4.2) was



**Figure 3.** Glacial geomorphology. (a) Mid-shelf GZW with iceberg scours and corrugation ridges (inset) observed on top. White dashed line shows the base of the lee side of the wedge. (b) Cross section of the mid-shelf GZW. White dashed line shows the base of the wedge imaged in Figure 2f. (c) GZW on the southern flank of the MBT. (d) Series of stacked GZWs on the mid-shelf GZW. (e) GZW at the shelf edge of the MBT. White dashed line shows the GZW base. (f) Lateral shear margin moraine on the northern flank of the Upernavik Trough. See Figure 1c for example locations.

deposited onto this lamination set. On top of the wedge and superimposed upon the converging MSGL in the east, the final set of MSGL is observed (Figures 2a, 2d, and 2e). Crosscutting of the converging pattern by later MSGL (Figure 2a) shows that the ice stream flowed from the north-northeast and was broadly parallel to the northeastern part of the MBT during the latest stage of ice stream occupation.

#### 4.2. Grounding-Zone Wedge

In the central part of the MBT an asymmetric mound with relief of 40–70 m above the local base of the trough is interpreted as a grounding-zone wedge (GZW) (Figures 3a and 3b). GZWs are generally considered to be composed of meltout tills and ice-contact deposits accumulated at the grounding-line during a stillstand [Dowdeswell and Fugelli, 2012]. The wedge is approximately  $90 \text{ km}^3$  (using  $1800 \text{ m s}^{-1}$  sound velocity), and the MSGL beneath it mean that the GZW postdates ice reaching the shelf edge (Figure 2f). The good preservation of these MSGL might suggest that the ice stream decoupled from the bed and the MSGL were subsequently buried once GZW deposition began.

On top of the wedge a number of parallel ridges 2–3 m high and 150–200 m apart are thought to relate to ice shelf keels, mega-icebergs, or recessional moraines (Figure 3a). Although seismic resolution hinders interpretation, in cross section the corrugations appear as erosional furrows with adjacent depositional berms, similar to corrugation ridges formed by ice shelf keels or mega-icebergs [Graham *et al.*, 2013; Jakobsson *et al.*, 2011], rather than recessional moraines. Distinguishing between ice shelf keels and mega-icebergs is important because they imply different environments. Here, crosscutting of the corrugations by iceberg scours and the lack of corrugations within adjacent scours (see section 4.4) suggest that the corrugations and scours were formed at different times. The corrugations are therefore interpreted to have been formed by an ice shelf keel and were later partially reworked by deep-draft icebergs. This interpretation is preferred due to the limited spatial extent of the ridges and similar morphology to those observed elsewhere [Graham *et al.*, 2013] (Figure 3a). However, without higher-resolution data, the interpretation remains tentative.

MSGL are observed on top of the mid-shelf GZW, suggesting that ice streaming was active during this stillstand (Figure 3d). The smaller GZWs on the southern margin of the MBT (Figure 3c) and on the main GZW

(Figure 3d) are up to ~6 m high and suggest that during the initial retreat from the mid-shelf GZW, ice was in contact with the bed, briefly pausing to allow the accumulation of smaller grounding-zone deposits.

At the shelf edge, similar landforms are visible on 2-D seismic data (Figure 3e). These features are ~25–30 m high with an approximate volume of 25 km<sup>3</sup> (this is limited by data extent) and are interpreted as GZWs due to their asymmetric shape and similar internal character to the mid-shelf GZW. This interpretation is in agreement with *Dowdeswell and Fugelli* [2012] and *Batchelor and Dowdeswell* [2015] but counter to *Slabon et al.* [2016] who suggested that these features are moraine ridges superimposed on the GZW. The shape of the feature and seaward dipping reflectors indicating progradation support the GZW interpretation, but it is possible that the feature is a composite structure formed under variable conditions at the ice margin. More high-resolution bathymetric and geochronological data are required to elucidate further.

#### 4.3. Lateral Ice Stream Moraine

A ridge on the northern side of the Upernavik Trough is orientated in the same direction as the local MSGL (Figure 3f). It is 40–50 m high, 1.0–1.2 km wide, ~45 km long and recorded in water depths of ~50–150 m. Due to its orientation and location on the flank of the trough, the ridge is interpreted as either an ice stream lateral moraine or a lateral shear margin moraine. The hummocky terrain and observations of the smaller GZW (Figure 3c) on the bank area suggest that ice was grounded here. Thus, the ridge is most likely a lateral shear margin moraine at the transition between ice on the bank area and fast-flowing ice in the Upernavik Trough [*Batchelor and Dowdeswell*, 2016; *Stokes and Clark*, 2002].

#### 4.4. Iceberg Scours and Pits

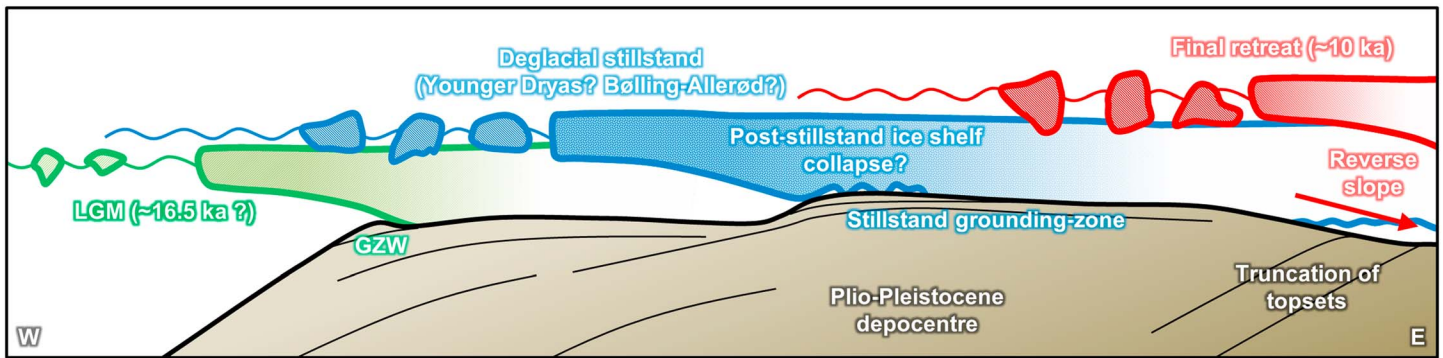
Linear and curvilinear incisions, typically ~2–4 km long, 100–300 m wide, and 5–10 m deep (Figures 2d and 3a), are interpreted as iceberg scours, formed when grounded icebergs were moved by ocean and tidal currents [*Newton et al.*, 2016; *Woodworth-Lynas et al.*, 1985]. Occasionally, scours are associated with pits formed by short-term grounding, probably in response to the tidal cycle or iceberg overturning. The scours are most common on the mid-shelf GZW, suggesting either softer sediment composition and/or that the topographic high of the GZW meant that it was more easily or more frequently scoured by deeper-draught icebergs than the deeper and more indurated seafloor unconformity to the east. The scours can be distinguished from MSGL because of their greater curvature and crosscutting relationships. The general east-west trend suggests that the calving margin was to the east and the icebergs scoured as they moved west away from the calving front.

### 5. Deglaciation of the Melville Bugt Ice Stream

The subglacial landform record presented here suggests that ice was grounded at the shelf edge at some time in the past. No dating constraints are currently available, and previous contrasting ice sheet reconstructions place the LGM margin at the shelf edge or on the mid-shelf [*Funder et al.*, 2011; *Slabon et al.*, 2016]. The landform assemblage on either side of the mid-shelf GZW appears continuous, suggesting that the wedge represents a stillstand during one glacial, rather than the separation of two distinct assemblages from different glacials. The landforms also show no evidence of significant reworking by iceberg scours or current winnowing, and it is therefore assumed that they are from the last glacial cycle. Although an older glaciation cannot be completely ruled out, this assumption is in line with numerical modeling studies of LGM ice sheet extent [*Lecavalier et al.*, 2014] and dated landform records to the south [*Jennings et al.*, 2017; *Sheldon et al.*, 2016].

MSGL and ice streamlining of sediment indicate that fast-flowing ice converged from the north-northeast and east-northeast in the eastern part of the study area before advancing to the shelf edge as a composite ice stream with a marine terminus (Figure 4). This evidence corroborates modeling work suggesting extensive ice cover at ~16.5 ka along northwest Greenland [*Lecavalier et al.*, 2014]. At the shelf edge, the presence of a GZW on the outer shelf may provide evidence that an ice shelf extended into Baffin Bay, as has been previously hypothesized [*Simon et al.*, 2014]. However, this remains a tentative interpretation until more data become available. A lateral shear margin moraine on the bank area between the two troughs, along with evidence for MSGL in the Upernavik Trough, provides evidence for ice streaming to the shelf edge, in agreement with *Slabon et al.* [2016].

Modeling studies of Melville Bugt suggest that ice margin retreat from the shelf edge began after 16.0 ka [*Lecavalier et al.*, 2014]. Our observations show that retreat was not continuous but halted temporarily at the mid-shelf GZW. Crosscutting MSGL between the shelf edge and mid-shelf GZWs indicate reorganization of



**Figure 4.** Schematic showing the possible chronology of events in the MBT as ice reached its maximum extent at  $\sim 16.5$  ka (i.e., the local rather than global LGM). During the retreat through the trough the GZW indicates a period of stability before the ice retreated rapidly on the reverse slope.

ice stream flow, possibly during the initial retreat phase (Figure 2b). The absence of observable meltwater channels or ice-marginal deposits between the two GZWs suggests that retreat could have been steady, such that any pauses of the grounding-line were insufficiently long to accumulate deposits. Alternatively, the retreat could have been more rapid if the ice front decoupled from the substrate and the grounding-line migrated between the wedges, as is possibly indicated by good preservation of MSGL in front of and beneath the mid-shelf GZW.

The precise timing of the mid-shelf GZW formation is uncertain. Logically, one might expect a period of slow retreat or even readvance during the Younger Dryas (12.9–11.7 ka) (Figure 4), as has been observed in the Disko and Uummanaq Troughs [Dowdeswell *et al.*, 2014; Hogan *et al.*, 2016; Jennings *et al.*, 2014, 2017]. In particular, the landform assemblage in the Uummanaq Trough, with evidence for a shelf edge maximum and a mid-shelf stillstand during retreat, is similar to that observed here.

Alternatively, retreat may be decoupled from climate forcing and could reflect a period of stillstand due to ice sheet dynamics during retreat. Observations in Antarctica show that grounding-line stability can be maintained on reverse slopes due to enhanced lateral drag [Jamieson *et al.*, 2012]. In the MBT the mid-shelf GZW is observed immediately downstream of the converging MSGL (Figure 2a) and it is possible that funneling of ice as the trough narrows by  $\sim 10$  km may have led to increased lateral drag and grounding-line stability. If a preexisting topographic high were present on the mid-shelf, this could have provided a pinning point. However, the topography beneath the mid-shelf GZW provides no compelling evidence for such a scenario. Another mechanism for a nonclimatic stillstand is related to isostatic rebound, whereby water depths on the inner parts of a glaciated margin can remain sufficiently stable after the LGM so that the grounding-line does not migrate. This effect is observed in southeast Greenland, where rebound outpaced sea level rise at  $\sim 13.8$  ka [Bennike *et al.*, 2002]. Thus, an ice stream in the MBT could have been stable during a climate warming phase, such as the Bølling-Allerød interstadial (14.7–12.9 ka), if isostatic rebound outpaced sea level rise or if lateral ice stream drag increased.

Once the margin moved behind the mid-shelf GZW, a new phase of retreat and margin instability was established which eventually led to the final stage of shelf deglaciation. Marine-based ice sheet instability has long been acknowledged [Hughes, 1981], and a perturbation of the grounding-line on a reverse slope, such as that observed here (Figure 1a), can lead to a positive feedback loop of retreat and greater ice discharge [Joughin and Alley, 2011]. A number of smaller wedges superimposed on the stoss side of the mid-shelf GZW (Figure 3d) indicate that ice margin retreat was punctuated by shorter periods of stability (assuming that grounding-line sediment flux was similar throughout). These intermittent stability phases are likely associated with the grounding-line increasingly decoupling from the bed as the margin retreated into deeper water. Once the grounding-line encountered water depths of  $\sim 700$ – $750$  m (the landward limit of the mid-shelf GZW), a threshold was reached on the steeply dipping reverse slope of the MBT (Figure 1a). Such a threshold is supported by the lack of ice margin landforms throughout the inner part of the trough where the seafloor truncates older strata. After the threshold was reached, ice retreat could have accelerated, until the ablation of onshore ice began at  $\sim 10.0$ – $9.5$  ka [Briner *et al.*, 2013; Funder *et al.*, 2011; Lecavalier *et al.*, 2014; Vasskog *et al.*, 2015].



The crosscutting of the corrugation ridges by later iceberg scours suggests that the features were formed at different times. This can be explained if an ice shelf was present at the mid-shelf GZW and an ice shelf keel sculpted the corrugation ridges. Subsequent calving from the shelf as it retreated could have provided the deep-draught icebergs that later scoured the mid-shelf wedge. Ice shelf collapse could have increased instability on the reverse slope due to alleviation of buttressing backstresses.

If the mid-shelf GZW was deposited during the Younger Dryas and ice margin retreat from the shelf edge began in unison with ice streams to the south at 17–16 ka [Jennings *et al.*, 2017], then retreat between the shelf edge and mid-shelf GZWs (~80 km) would have occurred at ~20–25 kyr<sup>-1</sup>. Likewise, if grounding-line retreat from the mid-shelf GZW began after the Younger Dryas, it would have retreated ~100 km to the coastline by ~10 ka, a retreat rate of ~60 km kyr<sup>-1</sup>. It is also possible that deposition of the mid-shelf GZW began before and/or continued after the Younger Dryas as is perhaps suggested by the large size of the mid-shelf GZW compared to the shelf edge GZW. Although an increased rate of ice margin retreat on the reverse slope could account for onshore observations indicating that northwest Greenland deglaciated earlier than most areas around Greenland [Briner *et al.*, 2013], without geochronological data, the precise style of retreat remains sparsely constrained and hypothetical.

Previous studies in the region suggest that warm subsurface waters of North Atlantic origin penetrated through the Davis Strait and played a key role in triggering climate changes during deglaciation, notably during the Bølling-Allerød interstadial and early Younger Dryas [Knutz *et al.*, 2011; Sheldon *et al.*, 2016]. Several ocean warming phases in the Uummannaq Trough are thought to have promoted initial retreat from the shelf edge before multiple pulses of ocean cooling. This was associated with cold freshwater release in northern Baffin Bay that occurred intermittently after 14.3 cal ka B.P. and helped promote formation of the large mid-shelf GZW in the Uummannaq Trough [Jennings *et al.*, 2017]. Reduced northward advection of heat across Uummannaq implies cooler conditions in the MBT and similar landform assemblages between the two troughs might suggest that oceanographic changes resulted in a comparable evolution of the ice sheet margin. As is also observed in the Uummannaq Trough [Jennings *et al.*, 2017], once the ice margin retreated onto the reverse slope of the MBT, rapid mass loss could be exacerbated by increased incursion of warmer subsurface water masses onto the shelf after the Younger Dryas. The presence of an ice shelf in the MBT, as suggested above, would have meant that the ice margin was vulnerable to melting from above and below.

The data presented in this study provide evidence for a post-LGM glacial stillstand positioned on the mid-shelf of the MBT. Although the cause and timing of this stillstand remain enigmatic, for the mid-shelf GZW to accumulate in a trough that is overdeepened by as much as ~500 m (Figure 1a) requires sufficiently stable grounding-line conditions. Without dating constraints, it is currently unclear whether the ice margin stabilized on the mid-shelf due to mass increase or reduced loss due to oceanographic changes, enhanced lateral drag, or through decreased relative sea level owing to isostatic rebound. The MBT paleo-ice stream is an important analogue for understanding contemporary and future ice stream changes (e.g., Jakobshavn Isbræ and the Pine Island and Thwaites Glaciers in West Antarctica), and dating the landform assemblage should be a priority that will help elucidate the processes controlling grounding-line migration.

## 6. Conclusions

This new record of glacial landforms from the Melville Bugt Trough provides new insights into the extent of the Greenland Ice Sheet and shows that an ice stream advanced to the shelf edge at the Last Glacial Maximum. Mega-scale glacial lineations show that ice dynamics changed whilst ice was grounded on the outer shelf. A grounding-zone wedge at the shelf edge suggests that the ice margin was stable here before the onset of deglaciation. After initial retreat, the ice margin restabilized in a mid-shelf position, possibly prior to or during the Younger Dryas, before the grounding-line retreated onto the reverse slope. Ice shelf collapse and increased grounding-line instability on the reverse slope could account for onshore observations indicating that this part of the Greenland Ice Sheet retreated earlier than in other parts of Greenland.

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