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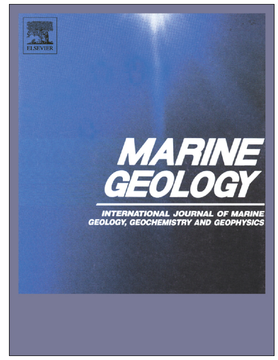

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The role of meltwater in high-latitude trough-mouth fan development: the Disko Trough-Mouth Fan, West Greenland

Colm Ó Cofaigh[1], Kelly A. Hogan[2], Anne E. Jennings[3], S. Louise Callard[1], Julian A. Dowdeswell[4], Riko Noormets[5], and Jeff Evans[6]

[1] *Department of Geography, Durham University, Durham, DH1 3LE, UK*

[2] *British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB30ET, UK*

[3] *INSTAAR and Department of Geological Sciences, University of Colorado, Boulder, CO 80309-0450, USA*

[4] *Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK*

[5] *The University Centre in Svalbard (UNIS), P.O. Box 156, N-9171 Longyearbyen, Norway*

[6] *Department of Geography, University of Loughborough, Loughborough, UK*

Abstract

The Disko Trough-Mouth Fan (TMF) is a major submarine sediment fan located along the central west Greenland continental margin offshore of Disko Trough. The location of the TMF at the mouth of a prominent cross-shelf trough indicates that it is a product of repeated glacigenic sediment delivery from former fast-flowing outlets of the Greenland Ice Sheet, including an ancestral Jakobshavn Isbrae, which expanded to the shelf edge during successive glacial cycles. This study focuses on the uppermost part of the fan stratigraphy and analyses multibeam swath bathymetry and sub-bottom profiler records, supplemented by a series of vibrocores up to 6 m in length. The swath bathymetry data show that the surface of the fan is prominently gullied and channelled with channels extending downslope from a series of shelf-edge incising gullies. Sub-bottom profiles from across- and down-fan show that the fan sediments are often acoustically stratified. Glacigenic-debris flows (GDFs) were recovered in sediment cores from the uppermost slope but they are absent in cores from elsewhere on the fan. Instead, glacimarine lithofacies in the Disko TMF are dominated by turbidites, hemipelagic sediments and IRD. The gullied and channelled surface of the fan implies erosion at the base of dense, sediment-laden, turbidity currents related to the delivery of meltwater and sediment from an ice sheet grounded at the shelf edge. Such meltwater-related fans have been documented previously on mid-latitude, glacier-influenced margins, but they have rarely been described from high-latitude settings. Although GDFs are often regarded as the building blocks of TMFs, the morphology and sedimentary architecture of the uppermost, Late Quaternary part of the Disko TMF indicates that it represents a clear example of a fan in which sediment delivery is strongly influenced by meltwater. This implies that there is a spectrum of TMFs on glaciated continental margins that reflects the relative dominance of meltwater processes vs. GDFs. It highlights the variability in fan morphology and mechanisms of sediment delivery on high-latitude TMFs and shows that the classic Polar

North Atlantic model of GDF dominated fans is but one of a number of styles for such large-scale, high-latitude glacimarine sedimentary depocentres.

Keywords: Trough-mouth fans; ice streams; meltwater; glacigenic debris-flows; West Greenland.

1. Introduction

Trough-mouth fans (TMFs) are large submarine sedimentary depocentres which form during successive full-glacials when ice streams, flowing in bathymetric troughs, advance to the continental shelf edge and deliver glacigenic debris directly onto the upper slope (Aksu and Piper, 1987; Aksu and Hiscott, 1992;; King et al., 1996; Dowdeswell et al., 1998; Nygård et al., 2005; O'Brien et al., 2007; Li et al., 2011; Rydningen et al., 2016; Pope et al., 2016; Laberg et al., in press). Over successive shelf-edge glaciations repeated sediment delivery to fans results in their progradation into deeper water as expressed in the development of outward-bulging bathymetric contours in front of trough mouths (Batchelor and Dowdeswell, 2014). The large size of these submarine glacigenic depocentres is linked to sediment delivery from ice streams on the continental shelf and the presence of these fans along glaciated continental margins is regarded as diagnostic of streaming ice flow (Vorren and Laberg, 1997; Ó Cofaigh et al., 2003). The highest sedimentation rates and maximum periods of fan growth occur during glacial maxima when ice streams are grounded at the shelf edge. In contrast, during interglacials, the fans become ice-distal glacimarine environments with low sedimentation rates, and glacigenic sediment delivery to the fans is limited to iceberg rafting (Dowdeswell and Elverhøi, 2002).

The classical work on high-latitude TMFs was carried out in the Polar North Atlantic in the late 1980's and 1990's and much of this work emphasises the importance of glacigenic debris-flows (GDFs) to fan formation (e.g., Vorren et al., 1989, 1990; Laberg and Vorren 1995, 1996; Dowdeswell et al., 1996, 1997; King et al., 1996, 1998; Elverhøi et al., 1997). GDFs are sourced from diamicton that is advected to the shelf edge as soft deforming-bed, sub-ice stream till that then undergoes remobilisation downslope. GDFs are characterised by long run-out distances (exceptionally up to 200 km) on low gradient slopes (often $\leq$ 1°) (Laberg et al., 2000). Stacked packages of GDFs separated by stratified sediments record individual episodes of shelf-edge terminating glaciation and fan progradation. Although much of this previous work on high-latitude TMFs highlights the role of GDFs, a few studies have also highlighted the role of other glacimarine processes such as meltwater delivery and iceberg-rafting to fan formation and investigated their acoustic (e.g. Dowdeswell et al., 1997; Pedrosa et al., 2011) and, more rarely, sedimentological characteristics (Taylor et al., 2002; Ó Cofaigh et al., 2013a; Lucchi et al., 2013). This work has shown how glacimarine sediment delivery varies temporally and spatially across individual TMFs with debris-flow delivery along the fan apex in front of the trough-mouth being replaced laterally by suspension settling from turbid meltwater plumes and turbidity current deposition. Investigations of mid-latitude TMFs have shown a clear, and often dominant, contribution of meltwater delivery, often in large volumes, to fan morphology and stratigraphy (e.g., Hesse et al., 1997, 1999; Piper et al., 2007, 2016).

Along the West Greenland continental margin bordering Baffin Bay a series of large TMFs are apparent from bathymetric data (Jakobsson et al., 2000; Ó Cofaigh et al., 2013a; Slabon et al., 2016) (Fig. 1). These fans are situated at the mouths of prominent bathymetric troughs that extend across the wide continental shelf to terminate in water depths of 400-500 m at the shelf edge (Batchelor and Dowdeswell, 2014). Until recently the morphological and sedimentological characteristics of these fans were unknown. However, a recent study investigated the sedimentology and mineralogy of the Uummannaq Fan offshore of Uummannaq Trough (Ó Cofaigh et al., 2013a). It showed that GDFs deposited on the upper slope prior to 14.1 cal. ka BP transition into a range of different lithofacies across the fan, which record turbidity current activity, hemipelagic settling, and iceberg-rafting. Mineralogical studies of the <2-mm sediment fraction in cores from the fan indicated that most of the sediment is derived from Uummannaq Trough but that there were intervals when

IRD and hemipelagic sediment from northern Baffin Bay sources dominated (Ó Cofaigh et al., 2013a; Jennings et al., 2017).

Further south along the West Greenland margin another large TMF extends into southern Baffin Bay from offshore of the mouth of Disko Trough, a 350-400 m deep trough that opens onto the upper slope on the south side of the fan (Fig. 1). Termed here the 'Disko Trough Mouth Fan' (here-after the 'Disko TMF'), this submarine depocentre is ca. 23,300 km² in size and it can be traced down to 2000 m water depth in the abyssal plain. Hofmann et al. (2016) recently investigated the longer-term Quaternary evolution and seismic stratigraphic architecture of the Disko TMF using 2D- and 3D-seismic reflection data and seabed bathymetry. They inferred three stages in the development of the fan from Pliocene-Early Pleistocene to Late Pleistocene. The fan originated during the Pliocene-early Pleistocene as a depocentre located beneath the present day continental shelf and formed by sediment progradation from at least two ice-flow pathways controlled by the pre-glacial topography. During the middle stage, the loci of deposition shifted from the shelf to two areas fringing the outer margin. The final stage of fan development is inferred to have occurred during the late Pleistocene to Holocene with a shift in deposition from the marginal depocentres back to the mid-outer shelf.

Our focus in this paper is on the late Pleistocene part of the Disko TMF and specifically its slope morphology, acoustic stratigraphy and sedimentology. We present the first significant multibeam swath coverage of a Greenland TMF and use the multibeam bathymetry, acoustic stratigraphy and core data to investigate the nature of glacigenic sediment delivery to the fan as well as how this is expressed sedimentologically and geomorphologically in terms of fan lithofacies, sediment architecture and slope morphology. We then discuss the implications of our findings for glacimarine sedimentary processes and depositional models of high-latitude TMFs.

2 Glacial History

Until recently, there was, with one exception (Zarudski, 1980) no data on the offshore record of glaciation, particularly the LGM extent and timing of subsequent ice sheet retreat along the entire West Greenland margin. As a result, there was considerable uncertainty regarding the extent of the Greenland Ice Sheet there at the LGM (Funder et al., 2011). Since 2013, however, a growing body of work focused on the cross-shelf bathymetric troughs and the adjoining continental slope and has sought to reconstruct the LGM during the last glacial-deglacial cycle using marine geology and geophysics (Ó Cofaigh et al., 2013a, 2013b; Jennings et al., 2014; Dowdeswell et al., 2014; Hogan et al., 2016; Sheldon et al., 2016; Slabon et al., 2016). This work has shown that Uummannaq and Disko troughs (Fig. 1A) were occupied by fast-flowing, grounded ice streams which extended to the shelf edge at the LGM. In Uummannaq Trough evidence for this is seen in the form of streamlined, subglacial bedforms recorded on multibeam seafloor imagery, subglacial tills in sediment cores, an outer shelf moraine and glacigenic mass flows on the adjoining fan. A large grounding-zone wedge mapped by Dowdeswell et al. (2014) on the mid-shelf of Uummannaq Trough has been proposed to date a grounding-line stabilisation event during the Younger Dryas (Sheldon et al., 2016).

Similarly, in Disko Trough, streamlined bedrock and lineations formed in sediment combined with subglacial till in sediment cores record the flow of grounded ice along the trough and onto the outer shelf (Ó Cofaigh et al., 2013b; Hogan et al., 2016). However, radiocarbon dates on reworked shells in till from a sediment core in the outer-shelf trough indicate that much of this evidence dates to the Younger Dryas which represents the most recent advance to the outer shelf in Disko Trough (Ó Cofaigh et al., 2013b). Hence, much of the evidence of grounded ice flow across the outer shelf in Disko Trough likely post-dates the

LGM. Nonetheless dates of 27-18 cal ka BP in glacigenic mass flows in cores from the fan provide maximum ages for the delivery of glacigenic sediment onto the slope and imply a grounded ice margin at the shelf edge at the LGM (Ó Cofaigh et al., 2013b).

Ice sheet retreat from the shelf edge of Uummannaq Trough was initially dated to 15 cal. ka BP from glacimarine sediments on the outer shelf (Ó Cofaigh et al., 2013b; Sheldon et al., 2016). The timing of initial retreat in Disko Trough was based on radiocarbon dates on mass flow deposits in sediments cores from the Disko TMF (including several discussed below in this paper) and inferred to have occurred by about 13.8 cal. ka BP (Ó Cofaigh et al., 2013b). More recently, however, Jennings et al. (2017) investigated three sediment cores from the Disko and Uummannaq TMFs. They used core lithostratigraphy, micropalaeontology, provenance and radiocarbon dating to determine the timing of initial (post-LGM) ice sheet retreat and to investigate the drivers of that retreat. Jennings et al. (2017) show that both ice streams retreated from the shelf edge of the central west Greenland margin under the influence of warm, subsurface Atlantic Water with retreat in the deeper Uummannaq Trough underway first at ~17.1 cal. ka BP and retreat in Disko Trough somewhat later at ~16.2 cal. ka BP. This episode of initial retreat did not, however, involve large-scale calving and the grounding lines of both ice streams remained buttressed by fringing ice shelves until until ca. 15.1-15.3 cal. ka BP, when large-scale calving retreat commenced during another interval of ocean warming.

3. Data and Methods

Geophysical and geological data were acquired during cruise JR175 of the NERC research vessel the RRS *James Clark Ross* to the West Greenland continental margin and Baffin Bay in 2009. Multibeam swath bathymetry data were collected using a hull-mounted Kongsberg-Simrad EM120 system which allowed detailed mapping of sea floor morphology. The EM120 system has a 1˚ by 1˚ beam configuration and emits 191 beams, each with a frequency of 12 kHz. Post-processing of the swath data involved removal of anomalous data points and the application of corrected sound-velocity profiles. Typical vertical and horizontal uncertainties of the swath data are about 1 m and 5 m, respectively.

Information on sediment thickness and acoustic stratigraphy was obtained using a hull-mounted Kongsberg TOPAS parametric sub-bottom profiler with a secondary frequency of 0.5 to 5 kHz. The maximum sediment thickness imaged by the system was ~ 50 m. Vertical resolution is better than about 2 m. The TOPAS and multibeam data were acquired simultaneously during the cruise. Navigation data were acquired using differential GPS.

Sediment cores (Figures 1B, 2A and Table 1) were collected using a British Geological Survey vibrocorer. Cores targeted different acoustic facies identified from the sub-bottom profiler data arranged into two depth related transects downslope. Following collection, the cores were stored horizontally at +4º C. The split cores were described from core sections and x-radiographs with regard to grain size, sedimentary and deformation structures, nature of bedding contacts, bed thickness and sorting. Shear-strength measurements were performed every 10 cm (or closer depending on lithological boundaries) using a Torvane. Core chronology is provided by radiocarbon dates published in previous studies from the Disko TMF, including on several of the cores discussed in this paper (Ó Cofaigh et al., 2013b; Jennings et al., 2017). They indicate that the sediments are LGM-deglacial in age.

4. Results and Interpretations

4.1 Slope morphology: description

With an areal footprint of more than 20,000 km^2 the Disko TMF represents a major submarine sediment depocentre on the Greenland margin bordering Baffin Bay (Fig. 1A). It has a straight-line width at the shelf edge of 180 km and a maximum downslope width of 225 km (see Vorren and Laberg, 1997 for definitions of widths). The shelf break between outer Disko Trough and the fan occurs at 350-400 m present-day water depth (Fig. 1B) and, based on the outward bulging contours in the regional bathymetric grid (IBCAO; Jakobsson et al., 2002), it appears to extend close to abyssal plain depths (2000 m), although this needs to be confirmed with core data and (or) seismic profiles. The fan is bordered to the south by the Davis Strait High that rises to water depths as shallow as 500 m (Fig. 1A), and basal fan strata onlap directly on to the high (Hofmann et al., 2016). On the adjacent continental shelf, the Disko Trough forms a well-defined trough (up to 25 km wide and 540 m deep) on the inner to mid-shelf with a steeper northern flank surrounded by banks 50-200 m deep (Fig. 1B; Hogan et al., 2016). On the outer shelf the narrow trough remains well-defined but dog-legs towards the southwest and the surrounding shelf deepens to 200-350 m depth resulting in a broad, deeper outer shelf (Fig. 1A). A second shallower trough (<400 m deep), named Northern Trough by Hoffmann et al. (2016), branches from Disko Trough on the mid-shelf and broadens to the northwest on the outer shelf (Fig. 1B).

Continental slope gradients on the fan vary from gentler (average ~2°) on the northern part and its flanks, to steeper on the southern part of the fan (2.5-3.5°) with more convex slope morphologies (Fig. 1C). Our multibeam bathymetric data coverage is mostly from the southern part of the fan adjacent to the mouth of Disko Trough (Fig. 2A). There, the upper slope (550-1100 m water depth) is dissected by a series of predominantly v-shaped gullies that extend for up to 5 km downslope. The gullies have average widths and depths of 795 m and 36 m respectively (for definition of parameters see Figure 2 of Noormets et al., 2009) (Fig. 3A). Gully heads are gentle and more or less isometric in planform but do not reach the shelf break. In a few places the shelf break is incised by small, complex-shaped depressions up to 15 m deep that widen downslope (Fig. 3A). Smaller gullies are present on the slope just north of the Disko Trough mouth at the shelf break, and again about 40 km north of this at the same water depths. Further north still, where we only have two thin strips of multibeam data (Fig. 1B), the upper slope is characterised by a series of elongate, scallop-shaped depressions oriented along-slope, with small berms on either side. The depressions are typically 20 m deep, flat-bottomed, and between 250-550 m wide; the berms are up to 6 m high.

On the middle slope beyond Disko Trough (water depths 1100-1400 m) is a set of larger, well-developed gullies most often with v-shaped profiles (Figs. 2 and 3). Average widths and depths of these gullies are 1995 m and 26 m, respectively. The smaller gullies on the upper slope do appear to feed into those on the mid-slope with gullies often coalescing to form a single channel downslope (c. 1250 m water depth). In several places, the inter-gully fan areas are incised by a few sharp, v-shaped depressions oriented along-slope, and up to 35 m deep and 700 m wide (arrowed on Fig. 2B). On the lower slope (>1400 m) the gullies develop into a channel-levee system with the channels being either straight or sinuous, eventually merging downslope into a few large, flat-bottomed channels (Figs. 2 and 3). Average channel dimensions are 2100 m and 15 m for width and depth, respectively. On the slope north of Disko Trough the fan has a similar morphology to that beyond the trough, but the large gullies and channel-levee system on the mid-lower slope are more subdued in character with the gully edges and inter-gully crests being less well-defined (Fig. 2A).

4.1.1 Slope morphology: interpretation

The surface morphology of the Disko TMF is dominated by erosional features. Gullies on the upper slope occur predominantly in front of Disko Trough (Fig. 2C) indicating their formation is probably related to high fluxes of sediment and meltwater delivered to the fan by streaming ice in the trough. The absence of upper slope gullies on the fan beyond the trough margins, and the relatively small size and extent of the gullies, suggests that they may be recent features that formed during the last glacial when streaming ice reached the shelf edge (Ó Cofaigh et al., 2013b). Although the multibeam coverage is more sparse on the northern fan the occurrence of gullies around 59° 46.5'W, 68° 17.3'N (Fig 2A) may be related to meltwater/sediment production from ice flow in the Northern Trough (Hoffman et al., 2016).

The process most often cited for gully development on high-latitude margins is the downslope flow of sediment-laden meltwaters (e.g. Lowe and Anderson, 2002; Dowdeswell et al., 2006, 2008; Noormets et al., 2009). Morphologically, however, the Disko TMF upper slope gullies are most similar to the Type II gullies of Gales et al. (2013) with their non-branching form, high width to depth ratios, and limited downslope extent (<10 km). Gales et al. (2013) interpreted this type of gully as being formed by small-scale upper slope failures consistent with high bedloads. The fact that the gullies on the Disko TMF do not reach the shelf edge appears to support their formation via slope failures rather than the down-slope flow of dense meltwaters, which typically form gullies that incise the shelf edge (Noormets et al., 2009; Pedrosa et al., 2011; Lucchi et al., 2013; Gales et al., 2013). Other evidence of upper slope failures come from the small complex depressions (Fig. 3A) that are recognised as slide scars (cf. Baeten et al., 2013); similar slide scars occur on the upper slope beyond Uummannaq Trough some 260 km further north on the West Greenland margin (Dowdeswell et al., 2014). The limited number of upper slope gullies in front of Disko Trough and the lack of multibeam coverage further south means that it is not possible to determine whether the gullies increase in cross-sectional area towards the trough margins reflecting routing of subglacial meltwaters towards ice-stream margins, as has been documented in gully sets in front of other glacial troughs (e.g. Noormets et al., 2009).

Larger, well-defined gullies on the middle slope that transition to a large channel-levee system on the lower continental slope of the Disko TMF (Fig. 2A, B) are reminiscent of similar systems on the Labrador margin (Piper et al., 2012; Dowdeswell et al., 2016) and

Antarctic slopes (offshore Halley Trough; Gales et al., 2014). Both of these systems were interpreted to have formed by erosion by turbidity currents initiated on the upper-mid slope, although a contribution from contour current activity is also possible. We suggest that the turbidity currents are probably linked to the downslope flow of sediment-laden meltwater from the shelf edge. The relatively straight gullies that converge into a smaller number of sinuous channels on the Disko TMF indicate repeated erosion of gullies by turbidity currents presumably exacerbated by additional slope failure processes (retrogressive slide/slumps) and downslope focussing of flows into a few larger channels. However, we note that the channels turn northwards at the base of the fan, which may be related to strong along-slope (contour) currents, or simply turned northwards by the Coriolis force. Erosion of the fan has predominantly occurred on the mid-lower slope where there is a change from the upper slope gullies to the lower slope gully-channel system. There is a subtle change in average slope gradient at c. 950 m water depth (below the upper slope gullies) from 3.4° above 950 m to 1.1° below, which coincides with the transition from small gullies to the better-developed gully-channel system, suggesting that sediment transport may be strongly linked to slope gradient in this setting.

The last features of interest are the scallop-shaped depressions on the northern fan and the sharp, v-shaped depressions on the southern fan both oriented along-slope (Fig. 1B). The shallow, elongate depressions with berms on either side are easily interpreted as iceberg ploughmarks even at the water depths that they occur here (up to 1050 m water depth). The elongate scallop-shaped depressions on the northern fan coincide with features described from side-scan sonar and sub-bottom profiles by Kuijpers et al. (2007) who interpreted them to have been ploughed by icebergs with keels of at least 950 m drifting in a southerly direction by a southward counter-current to the West Greenland Current. Our data confirm that these along-slope ploughmarks extend for at least 65 km along the Disko TMF and we observe a few individual ploughmarks formed by icebergs that also impinged on the southern fan in deep water (1250 m present day water depth and 1130 m full glacial water depth).

4.2 Acoustic facies: description

The shallow stratigraphy of the Disko TMF is described by defining the following five acoustic facies from sub-bottom profiles (Figs. 4-6).

Acoustic Facies I: This facies has an acoustically impenetrable, variable strength upper reflection that ranges from prolonged to, on slopes, diffuse. No sub-bottom reflections are present. Acoustic Facies I ocurs on the shelf and upper slope (<1200 m water depth); on the shelf it defines a rugged seafloor surface with small- to meso-scale topography with several tens of metres of relief. Cores from this acoustic facies recovered diamicton (see lithofacies section below).

Acoustic Facies II: Facies II is a thin, (<5 m thick), acoustically structureless drape overlying a laterally continuous moderate strength reflection. It is typically found on the mid-slope between 1200-1300 m water depth but also occurs in discrete areas on the lower slope. Although generally conformable with the underlying reflection, the drape unit can thin over highs and down-slope.

Acoustic Facies III: This is an acoustically homogeneous facies of variable thickness with typical thicknesses being 5-15 m. Its upper reflection is strong, continuous and prolonged with subdued relief of a few metres. This facies unconformably overlies a low strength, discontinuous reflection on the shelf that is relatively flat-lying. On the upper slope this facies forms, lobate-shaped units in cross-section that are typically less than 10 m thick in their centres.

Acoustic Facies IV: Acoustic Facies IV is characterised by up to two acoustically homogeneous units with occasional weak, discontinuous sub-parallel internal reflections. The units and internal strata are approximately conformable. The seafloor reflection has a moderate to high strength and is prolonged, although in some areas it appears as a thin (a few metres), conformable drape unit over a strong reflection. Where two homogeneous units are present they are separated by a discontinuous, low to moderate strength reflection that can be prolonged. This facies is confined to the southern part of our dataset on the mid-lower slope and is up to 50 m thick. It grades laterally and down-slope into Acoustic Facies V.

Acoustic Facies V: This facies is acoustically stratified with homogeneous to transparent strata that can thicken in depressions; individual strata have thicknesses up to 3 m and can appear either acoustically homogeneous or transparent. In places, two distinct acoustically-stratifed sub-units can be identified separated by a moderate strength, continuous reflection. Sub-units are up to 60 m thick in depressions but are usually <40 m thick although thicknesses of this unit generally increase downslope on the fan. Cores from this acoustic facies recovered a range stratified-graded sands and silts (lithofacies associations 2 and 4).

4.2.1 Acoustic facies: interpretation

Acoustic Facies I: The acoustically impenetrable character of Acoustic Facies I and the rugged seafloor surface is similar to the sub-bottom profiles of many high-latitude shelf/upper slope environments (e.g. Damuth, 1978; Vorren et al., 1989), including those on the West Greenland shelf (e.g. Dowdeswell et al., 2014). We presume that its acoustically impenetrable nature is due to the presence of stiff tills, winnowed hardgrounds, and (or) iceberg-scoured areas on the shelf that act as strong reflectors of acoustic energy. Indeed, multibeam bathymetry confirms small iceberg scours occur on the outer shelf adjacent to the fan (Fig. 2a). On the upper slope, the impenetrable character probably relates to the slope gradient scattering the acoustic energy away from the ship's receivers, but it also likely reflects the association of Acoustic Facies I with stiff, coarse-grained diamictons (see Lithofacies Association 1 below) which would act to spread the acoustic signal.

Acoustic Facies II: This conformable facies is interpreted as a hemipelagic drape related to the stable accumulation of sediment on the slope. The extent of this facies which is limited to a particular depth range suggests that the drape facies transitions in to acoustically stratified units very quickly downslope, presumably where slope gradients favour gravity-flow deposition. The area of Acoustic Facies II on the lower part of the fan is probably the upper part of a stratified unit where penetration of the TOPAS signal was not as great as in other areas and, therefore, sub-bottom stratification was not imaged.

Acoustic Facies III: On the shelf this acoustically homogenous unit with variable thickness is interpreted as a diamictic unit, most likely comprising a glacial till. The mixed grain sizes of diamictons act to scatter acoustic energy so these units appear homogenous on sub-bottom profiles. On the upper slope the lobate geometries of this facies suggest that it probably consists of debris-flow deposits comprising diamictic material delivered to the shelf edge by grounded ice. This is supported by the sediment-core lithofacies (see section 4.3) that indicate the presence of diamicitic debris-flow deposits on the upper fan. We suggest therefore that there are probably more debris-flow deposits on the upper fan than are seen on sub-bottom profiles but that the acoustic penetration of diamictic material on slopes was not good enough to show these on the TOPAS data.

Acoustic Facies IV: The two conformable but acoustically homogenous units of Acoustic Facies IV are interpreted as stratified units of Facies V but in areas where the 3.5 kHz source did not reveal the internal reflections. This is based on the conformable nature of both facies and identical thicknesses and distribution of the facies on mid-lower slope with Acoustic Facies IV being confined to the southern part of our dataset. The lack of acoustic penetration of this unit in this area may be due to increasing slope gradients on the southern fan (Fig. 1c) leading to increased scattering of the acoustic signal.

Acoustic Facies V: The acoustically-stratified units of Acoustic Facies V are interpreted as having been largely deposited from sediment-gravity flow processes most likely turbidity currents, although we do not rule out an along-slope contribution from contour currents in a mixed-type system. A turbidity current origin is also supported by several other lines of evidence. First, this acoustic facies is associated with stratified-graded sands and silts of lithofacies associations 2 and 4 below that are interpreted as turbidity current deposits. Second, the morphology of the fan shows clear evidence of down-slope sediment movement through gullies and channels, the latter incising the uppermost units on the upper-mid slope (see Fig. 4b); we also note that there is no along-slope large-scale morphological expression of contourite formation (e.g. sediment mounds). Thirdly, some sub-bottom profiles show units that thicken in their central parts and taper out which is clear evidence for down-slope sedimentation (e.g. transparent unit in Acoutsic Facies V, Figure 6). Turbidity currents probably developed from slope failures on the upper-mid slope, or from sediment-laden meltwater that bypassed the upper slope but then entrained sediments and deposited them on the lower fan. As slope gradients reduce on the lower fan the energy of the flows would decrease and most of the sediment load would be deposited resulting in the observed increased thickness of this facies on the lower part of the fan. In general, individual strata of Acoustic Facies V do not terminate across the large gullies on the mid-lower fan (Fig. 5A, B) but rather are continuous through them indicating that the most recent period of deposition was characterised by deposition from non-channelized turbidity currents across the lower fan, possibly augmented by some deposition from along-slope contour currents. Assuming that recent deposition was related to sediment delivery to the fan during the last glacial period, erosion of the large mid-lower slope gullies may have occurred before this. In contrast, reflections in this facies do terminate or are cut by the sinuous, v-shaped channels on the lowermost fan (Fig. 4B). This suggests that turbidity currents were still being channelized by the time they reached the lower fan, even during the latest phase of deposition on the fan.

Interestingly, there seem to be at least two major sub-units of both acoustic facies IV and V on the mid-lower fan (Fig. 4B), with each unit being around the same thickness e.g. 20-30 m thick on the mid-slope. Our sediment cores are too shallow to penetrate the boundary between these units so we can only speculate what the boundary represents but presumably these units have built up due to cycles or phases of deposition on the fan relating to (climatically-controlled?) sediment delivery to the slope. The aggradational style of Acoustic Facies IV and V during the latest phase of deposition on the fan is consistent with a recent study of the architecture of the entire fan from seismic reflection profiles which showed that the last stage of fan development occurred by aggradation over outer shelf and slope (Hofmann et al., 2016).

4.3 Core lithofacies

Five lithofacies associations were identified on the basis of core sedimentology and geotechnical (shear strength) properties. These are described and interpreted in turn below. Core logs and shear strength plots are shown in Figures 7 and 8 and x-radiographs of core facies are shown in Figure 9. The locations of the sediment cores are shown on Figure 1B. Lithofacies codes where used below are based on Evans and Benn (2004).

Lithofacies Association 1(LFA1): Matrix-supported diamicton (Dmm; minor Dms)

Description

LFA1 was observed in three cores (VC30, VC32 and VC36) (Figs 7, 8 and 9A and B) and it corresponds to Acoustic Facies I. It comprises a dark grey to very dark grey (5Y 4/1 and 5Y

3/1) diamicton with a silty sand matrix supporting subrounded to subangular gravel- and pebble-sized clasts and occasional shell fragments. The diamicton is massive with clasts dispersed throughout the matrix but it is notable that internally it contains relatively sharp contacts that separate beds of diamicton that are ca. 5-40 cm in thickness. These bedding contacts range from horizontal to inclined and are demarcated by subtle changes in grain size and/or tonal contrasts on the x-radiographs. In core VC30 the uppermost 5 cm of the diamicton exhibits faint stratification. The diamicton in core VC36 is particularly clast-rich (Fig 9A). Core VC30 bottomed out in the diamicton, but LFA1 does not form the basal facies in either VC32 (Figs. 7A and 9B) or VC36. Instead it is underlain by stratified sand and mud or sand and gravel in VC32 and VC36 respectively. In both these cores the lower boundary is sharp, but dipping in VC32. In core VC32, LFA1 is a very soft Dmm of only 4-11 kPa from 55-81 cm becoming firmer below this interval (averaging 31 kPa and ranging between 11-58 kPa). Torvane measurements could not be taken on core VC36 due to the high concentrations of gravel and pebble sized clasts. In VC30 shear strength increases from 19 kPa at the top of the unit to a maximum of 181 kPa at the base (179 cm).

Interpretation

The depositional location at the top of the continental slope, the association with Acoustic Facies I, the massive, matrix-supported nature of the diamicton, the presence of bedding and the variable contacts which range from horizontal to inclined, but which are always sharp, are all consistent with an origin for LFA1 as a series of GDFs (Laberg and Vorren, 1995; King et al., 1998; Laberg et al., 2000). The GDFs were most likely sourced from glacigenic sediments that were delivered onto the upper slope by a shelf-edge terminating ice stream in Disko Trough and then remobilised downslope under the influence of gravity as cohesive debris flows. The high shear strength values of some of the beds are difficult to reconcile with an origin as GDFs. It is possible that compaction of the sediment occurred during, or after, deposition, for example by reworking from grounded icebergs calved from the ice stream margin, or that the original source material was highly consolidated subglacial till advected onto the slope from beneath the ice stream but only underwent downslope transport for a short distance thereby maintaining its integrity and high shear strength.

Lithofacies Association 2 (LFA2): Stratified and laminated silty sand and sandy silt (Fl and Fs)

Description

LFA2 occurs in 5 cores (VC27-29 and VC33 and VC35) and comprises grey (5Y 5/1) and dark grey (5Y 4/1), cross- and horizontally stratified and laminated silty fine sand and sandy silt (Figs. 7, 8 and 9) occuring in beds 9-238 cm thick. The characteristics of the stratification and lamination are variable and include (i) weakly stratified and bioturbated silty sand and sandy silt with diffuse and blurred contacts between individual beds, (ii) continuous horizontal/planar laminations (ranging from 0.5-1.5 cm) or stratification with sharp contacts between individual laminae (Fig 9C and 9D), and (iii) contorted and discontinuous stratified/laminated silty sand and sandy silt with load, flame and water escape structures that often have sharp but irregular boundary contacts, although these can also be diffuse (Fig 9E). This contorted sub-facies is particularly pervasive in core VC35 (Figs. 8 and 9E). The lower bed contact is typically sharp, but occasionally gradational. The upper contact is more variable ranging from sharp, with the occasional undulating or dipping surface contact, to gradational. There does not appear to be a systematic pattern to the nature of the upper contact.

Interpretation

The characteristics of LFA2 are consistent with deposition from turbidity currents associated with sediment and meltwater delivered from an ice sheet situated at the shelf break. This interpretation is supported by the stratified to laminated nature of the facies, presence of cross-bedding, variable contacts between laminae and beds ranging from sharp to gradational and presence of a range of soft-sediment deformation structures indicative of rapid emplacement such as water-escape, load and flame structures and the stratified nature of Acoustic Facies V (see above). Deformation with variable degrees of preservation of the original strata probably relates to downslope slumping related to rapid deposition of sediment onto the slope (cf. Eyles and Eyles, 2000).

Lithofacies Association 3 (LFA3): massive clay and silt with bioturbation (Fm, Fmb)

Description

LFA3 forms the uppermost lithofacies in 7 of the cores. It is predominantly dark grey to very dark grey in colour (5Y 4/1 to 5Y 3/1) and largely composed of silty clay or slightly sandy silt, but is occasionally clay. The individual beds range from 5 cm to over 2 m thick and are typically characterised by gradational upper and lower contacts, although occasionally they can also be sharp to diffuse. Internally the muds of LFA3 can vary between (i) massive with no structural features (Fm) (Fig 9F), and (ii) bioturbated and characterised by a mottled and streaked appearance (Fmb). The shear strength of this lithofacies is low averaging 4.5 kPa.

Interpretation

Massive, bioturbated muds are a common facies from many glacier-influenced high-latitude environments from fjord to shelf to slope (Ó Cofaigh et al., 2001, 2013b; Evans et al., 2002; Forwick and Vorren, 2011; Streuff et al., 2017). The muddy matrix, massive structure, bioturbation and, typically, its capping stratigraphic position in the cores from the Disko

TMF are all consistent with an interpretation for LFA3 as glacimarine mud deposited by suspension settling from meltwater plumes in a distal glacimarine environment with minimal contribution of iceberg-rafted or sea-ice rafted debris.

Lithofacies Association 4 (LFA4): Massive, normally graded and stratified sand (Sm, Suf, Ss)

Description

LFA4 is composed of well-sorted fine to coarse massive sand that is occasionally silty. The individual beds range in thickness from a few cm to a maximum of 86 cm and bed contacts are characteristically sharp. Normal grading of this lithofacies can occur and fines upwards from a coarse or medium sand to a medium to fine sand (e.g. Fig 9H). The colour often gets darker down core changing from a greyish brown, grey or olive grey (2.5Y 5/2, 2.5Y 5/1 and 5Y 4/2 respectively) to a dark grey (5Y 4/1). However, in core VC33 (Fig. 8) the colour gets lighter downcore from a very dark grey (5Y 3/1) to grey (2.5Y 5/1). Four cores (VC27, VC30, VC32, VC33) contain stratified sand (Ss) that is characteristically discontinuous to crudely stratified and dark grey to very dark grey in colour (5Y 4/1 to 5Y 3/1). The upper bed contact ranges from sharp to gradual with the lower contact commonly gradual although occasionally sharp and dipping (e.g. Fig 9H). In core VC33, from 127-182 cm depth, LFA4 is laminated. The laminae are0.2-2cm thick and consist of alternating fine to medium sand.

Interpretation

Massive, graded and stratified sand facies with sharp contacts are consistent with deposition from sediment gravity flows. Massive and normally graded facies are characteristic of turbidites. They represent the lowermost Ta division of the Bouma sequence and were produced by rapid deposition from turbulent currents with overlying stratified facies probably indicative of deposition of the Tb and Tc divisions (cf. Walker, 1992; Kneller and Buckee, 2000; Carto and Eyles, 2012). A sediment gravity flow origin is also consistent with the characteristics of Acoustic Facies V (see above).

Lithofacies Association 5 (LFA5): Massive to crudely stratified pebbly mud and sand (Fmd; Smd)

Description

This lithofacies association is characteristically massive to crudely stratified pebbly mud (Figs. 8 and 9I, J and K) that contains angular to subrounded gravel and pebble-sized clasts that lack a systematic orientation on x-radiographs (e.g., Fig. 9I). Facies Fmd is a sandy silt clay that contains occasional sandy intraclasts and occasional to frequent gravel to pebble-sized clasts. It often occurs as a series of beds within a core, with individual beds separated by units of Fm and Fl. Individual beds tend to be massive and bed thickness ranges from 5-100 cm; particularly clast-rich beds occur within the upper 1.5m of cores VC27, VC33, VC34 and VC35 (Fig. 8). For core VC35 the clast-rich beds appear to be crudely stratified and clasts show an upwards fining pattern (coarse-tail normal grading) between 130 and 160 cm (Fig 9I). Core VC29 (Fig 9J) contains a clast-rich, crudely stratified silty mud bed deeper down the core at 422-433 cm, but no grading is evident. The upper and lower boundaries of facies Fmd are often gradational to diffuse, but can be sharp such as in cores VC27 and VC28.

Facies Smd is similar to Fmd except coarser, containing a dominant sand component that ranges from coarse to fine sand. This facies comprises occasional to frequent, subrounded and angular, granule to pebble sized clasts in either a massive or crudely stratified, dark grey (5Y 4/1), sand matrix. It forms the upper facies in three cores (VC30, VC32 and VC36) where it directly overlies LF1 (e.g., Fig 9K). In core VC36 this subfacies also forms the basal lithofacies bracketing the Dmm in this core. Individual beds reach a maximum of 30 cm in thickness and have gradational lower boundaries. An exception is a single 30 cm bed in core VC34 (at 226 cm down the core) that has sharp dipping/loaded upper and lower boundaries.

Interpretation

Massive to crudely stratified pebbly muds (facies Fmd) and their sandier counterparts (facies Smd) are interpreted as having been deposited by a combination of rain-out and downslope resedimentation in a two-stage process. Initial sediment delivery onto the slope was by the rain-out of coarse ice-rafted debris from icebergs and sea-ice combined with suspension settling of the finer grained matrix from meltwater plumes. Downslope remobilisation of this sediment then occurred prior to final deposition and likely reflects the delivery of high volumes of sediment onto the slope during deglaciation with associated depositional over-steepening. A sediment gravity flow interpretation is consistent with the muddy matrix (facies Fmd), crude bedding, a massive to crude coarse-tail normally graded internal structure to the beds and variable bedding contacts, which range from sharp to gradational. The crude grading suggests the onset of weak turbulence (Walker, 1992).

5. Discussion

TMFs are a morphologically distinctive type of glacimarine depocentre that form on glaciated continental margins during full-glacial periods when ice streams ground to the shelf edge and deliver glacigenic sediment onto the slope (e.g., Paaschier et al., 2003; O'Brien et al., 2007; Li et al., 2011; Rydningen et al., 2015; Montelli et al., 2017). Models of high-latitude TMF formation have often emphasised the role of GDFs (e.g., Laberg and Vorren 1995, 2000; King et al., 1998; Laberg and Dowdeswell 2016), and these are a key component of fan development. However, it is increasingly clear that the processes of sediment delivery to these large submarine fans are heterogeneous and that meltwater may be important (Taylor et al., 2002; Ó Cofaigh et al., 2003, 2013a; Lucchi et al., 2013; Dowdeswell et al., 2016); this is particularly the case on mid-latitude fans (e.g., Hesse et al., 1999; Piper et al., 2007, 2012, 2016). The high-latitude Disko TMF shows a clear acoustic and sedimentary imprint of meltwater-related processes in its stratigraphically uppermost, LGM-Younger Dryas aged section.

Morphologically, swath data from the Disko TMF show well-defined gully systems on the mid-slope which evolve into large channel-levee systems on the lower slope. In its morphological form the gully-channel system is consistent with meltwater-dominated systems described from offshore of other glaciated troughs (see section 4.1.1 above). Although gully systems have been described in the Holocene record from southeast Greenland fjords (Evans and Dowdeswell, 2016), and major turbidity-current channel systems have been observed on the East Greenland margin (Ó Cofaigh et al., 2004; Wilken and Mienert, 2006; Garcia et al., 2013, 2016), to our knowledge this is the first time such features have been described from the late Quaternary record of Greenland TMFs. These gully-channel systems were produced by erosion from turbidity currents moving down the surface of the fan into deeper water. The turbidity currents would have been sourced from meltwater and sediment released at the grounding-line of a shelf-edge terminating ice stream in Disko Trough (cf. Ó Cofaigh et al., 2013b; Hogan et al., 2016; Jennings et al., 2017), probably augmented by sediment failure and slumping on the slope itself. This interpretation is supported by Acoustic Facies V (mass flows and turbidites), the occurrence of slide scars on the upper slope (e.g. Fig. 2A), and the presence of a variety of sandy and muddy turbidite facies recorded in sediment cores from the mid-slope, including laminated and stratified sandy silts, as well as massive and normally graded sands.

Radiocarbon dates indicate that the mass-flow facies on the mid-slope of the Disko TMF date to between $\geq$22 and12.2 cal. ka BP (see Ó Cofaigh et al., 2013b; Jennings et al., 2017). This indicates that meltwater delivery to the fan last occurred during the LGM-Younger Dryas. Hence, the timing of meltwater delivery onto the slope is consistent with an ice sheet source during, and after, a shelf edge maximum position. Hofmann et al. (2016) proposed that the last phase of fan deposition, inferred by them to be of Late Pleistocene-Holocene age, was associated with only a lightly grounded ice sheet on the outer shelf. However, the strong meltwater signal implied from the sedimentological, acoustic and morphological data is probably more consistent with a fully grounded, shelf-edge, terminating ice stream that was characterised by high subglacial melt and sedimentation rates during maximum extent and initial retreat from the shelf edge. Turbidity current channels on the East Greenland margin offshore of Kaiser Franz Josef Trough also appear to be active in glacial rather than interglacial periods, when ice was present at the shelf edge (Ó Cofaigh et al., 2004).

It is notable that the gullies on the upper slope of the Disko TMF do not incise the shelf edge, suggesting that they are more likely to be a product of intermittent downslope mass failure rather than direct meltwater delivery to the slope from a grounding-line at the shelf edge (cf. Gales et al., 2013). This implies that meltwater delivery to the Disko TMF essentially bypassed the uppermost slope with erosion/deposition then occurring on the mid- to lower slope. As noted above there is a decrease in slope gradient below the upper slope gullies from 3.4° above 950 m water depth to 1.1° below suggesting that sediment transport and deposition reflect, at least in part, the control of slope gradient. Similarly, the turbidity current channels offshore of Kaiser Franz Josef Trough in East Greenland appear to form only from about 1500 m downwards (Ó Cofaigh et al., 2004; Garcia et al., 2016).

Sediments interpreted to be derived from GDFs were recovered in cores from the fan (see section 4.3 above). However, they appear to be restricted to the upper slope, being replaced by sorted muddy-sandy facies further downslope; the latter record formation by suspension settling, turbidity currents and iceberg-rafting. Thus the long-run out distances (>100 km) which are a characteristic of GDFs on Polar North Atlantic TMFs (cf. Vorren et al., 1998; Laberg and Vorren, 2000; Nygård et al., 2005) are not replicated on the Disko TMF. This also differs from the adjacent Uummannaq TMF further to the north. There, although GDFs occur on the slope in front of the trough-mouth and extend down to at least 1800 m water depth on the mid-slope, they were not recovered in cores lateral to the trough mouth (Ó Cofaigh et al., 2013a); rather, these areas are dominated by hemipelagic deposits and turbidites. This substantiates earlier proposals that there is a spectrum of TMFs on high-latitude glaciated margins (Ó Cofaigh et al., 2003; Batchelor and Dowdeswell, 2014; Dowdeswell et al., 2016) that reflect the relative contribution of GDFs vs. meltwater processes in fan formation (cf. Hesse et al., 1999; Piper et al., 2016). The Disko TMF can be regarded as a clear example of a high-latitude TMF that was strongly influenced by meltwater-delivery on the basis of its morphology, acoustic stratigraphy and sedimentology (Fig. 10), with similarities to mid-latitude depocentres on the eastern Canadian margin (Hesse et al., 1999; Piper et al., 2012, 2016). It can be contrasted with, for example, the Bear Island Fan (SW Barents Sea margin) where, although meltwater deposits have been recorded (Taylor et al., 2002), the most characteristic sediment facies on the low gradient fan are the long-run out GDFs formed from the remobilisation of sub-ice stream tills advected to the shelf edge. TMFs such as the Storfjorden (SW Barents Sea margin) and Uummannaq fans (West Greenland margin) are, in some respects, 'hybrid' types, which sit between the GDF- and meltwater-end members.

Earlier work on TMFs suggested that the gradient of the continental slope was an important control on depositional processes on TMFs, and thus on the form of the fan itself, such that on steeper slopes GDFs would evolve more quickly downslope into turbidity currents (Ó Cofaigh et al., 2003; Tripsansas and Piper, 2008). For example, there is evidence from the relatively steep Antarctic margin, such as that offshore of Marguerite Bay, that sediment by-passes the upper slope, to the extent that a major TMF is absent (Ó Cofaigh et al., 2003; Dowdeswell et al., 2004). The gradient of the Disko TMF, particularly on the northern fan, is not significantly steeper than some of the Polar North Atlantic TMFs such as the Scoresby Sund Fan (East Greenland margin), although it is steeper than large fans like the Bear Island and North Sea fans (Fig. 1; see section 4.1 above and also Vorren et al., 1998). Hence, although it is possible that slope gradient controlled the relative dominance of turbidity currents vs. GDFs, particularly on the southern Disko TMF where upper slope gradients can be >3.1°, it is difficult to explain the meltwater-influenced form of the fan solely on the basis of slope gradient. Indeed, we suggest that it is likely that there is no single control that can explain all the variation (cf. Batchelor and Dowdeswell, 2014).

We suggest that the contribution of meltwater vs. GDF delivery to high-latitude TMF formation is also influenced, at least in part, by the nature of the subglacial drainage system operating beneath the ice stream feeding the fans and, related to that, the coarseness of the substrate. Sandy sediments delivered on to the slope are more likely to transform downslope into turbidity currents more quickly than soft diamictic subglacial tills which may maintain longer run-out distances down-fan as GDFs (cf. Talling et al., 2002). Furthermore a relatively more efficient channelised subglacial drainage system may result in the delivery of higher volumes of meltwater to the grounding line than cases where drainage is achieved via Darcian flow through the till itself. There is geomorphological evidence for channelised meltwater flow in Disko Trough recorded by Hogan et al. (2016), which suggests the former presence of an organised subglacial drainage system beneath the ice stream on the inner shelf during the last glaciation. We note this, however, with the caveat that this channelised system was present some 200 km inshore of the trough-mouth and was cut, in part at least, into outcropping bedrock. Little evidence for channelised meltwater flow has been observed to date across the soft-bed of the outer Disko Trough although observations of such channels on deforming bed substrates are rare.

6. Conclusions

- Along the continental margin of West Greenland bordering Baffin Bay, a series of large submarine sediment fans is located at the mouths of prominent cross-shelf bathymetric troughs. These TMFs record the former delivery of sediment from ice streams grounded at the shelf edge during full glacial periods. One of these fans, termed here the Disko TMF, formed from sediment delivery by an ancestral Jakobshavn Isbrae ice stream over many glacial cycles.
- Morphological, acoustic stratigraphic and sedimentological data show that the LGM-Younger-Dryas aged section of the Disko TMF is strongly-influenced by meltwater-related processes, particularly the action of turbidity currents sourced from an ice sheet terminating at the shelf edge, augmented by smaller scale sediment failures on the slope itself.
- The surface of the fan is gullied and channelised implying erosion at the base of dense, sediment-laden turbidity currents. Sub-bottom profiles show that acoustically stratified sediments are common down the fan, but particularly on the mid-slope. Cores from the fan recovered a range of facies including laminated and stratified muds and massive and graded sands that are consistent with a turbidity current and suspension settling origin. GDFs do occur in the LGM-Younger Dryas part of the Disko TMF but they appear to be restricted to the uppermost slope and were not recovered in cores from elsewhere on the fan.
- Collectively, the geophysical and sedimentological data presented here indicate that the Disko TMF is a clear example of a high-latitude TMF that was strongly influenced

by meltwater-delivery, similar to the mid-latitude Laurentian Fan, in which GDF delivery is subsidiary to meltwater processes, and particularly turbidity currents moving down the fan surface (Fig. 10). It implies that a spectrum of TMFs form on high-latitude glaciated continental margins during full glacial periods. This spectrum reflects the relative dominance of meltwater processes vs. GDFs and it highlights the variability in fan morphology and mechanisms of sediment delivery on high-latitude TMFs.

- Controls on fan morphology and the processes of glacimarine sediment delivery to TMFs are complex and likely reflect a combination of factors including slope gradient. We suggest that subglacial processes on the shelf, in particular the nature of subglacial drainage system, and substrate coarseness, are also important and may influence the style of fan produced on the continental margin.

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List of figures and tables

Fig. 1. Location map of the study area. (a) Baffin Bay region showing bathymetry, surrounding landmasses and TMFs on the West Greenland margin; DT is Disko Trough, UT is Uummannaq Trough, DSH is Davis Strait High. (b) Bathymetry of the Disko TMF showing extent of swath coverage, ship tracks and core sites; NT is Northern Trough. (c) Continental slope profiles from shelf edge to base of slope (five in total; one either side of fan (1, 5) and three down the fan itself (2-4)). Profiles are located in Figure 1B.

Fig. 2. Colour shaded relief multibeam swath bathymetric images of the Disko TMF. (a) Swath image of the entire fan. Small shelf edge incisions interpreted as slide scars are arrowed. (b) Detail of mid-lower slope channels; white arrows point to channels, black arrows indicate deep iceberg ploughmarks discussed in the text, and c marks channel confluences. (c) Detail of gullies along upper slope; examples of gullies are arrowed.

Fig. 3. Distance-depth transects across the Disko TMF showing gully and channel morphology and dimensions. (a) Upper slope ; (b) mid-slope , (c) lower slope.

Fig. 4. Downslope TOPAS sub-bottom profiles showing sediment architecture and acoustic stratigraphy on the Disko TMF. Location of profiles is shown in Figure 2. (a) Shelf edge and upper slope. Note prolonged upper reflection implying coarse-grained slope material (Acoustic Facies I). Sediment cores from the uppermost slope recovered diamictic debris flows (Lithofacies 1). (b) Channels and acoustically stratified sediments (Acoustic Facies V) on mid-lower slope. Note stacked sub-units of acoustically stratified sediment incised by channels.

Figure 5. Across-slope TOPAS sub-bottom profiles showing sediment architecture and acoustic stratigraphy on the Disko TMF. Location of profiles is shown in Figure 2. (a) Acoustically stratified conformable strata from the mid-slope. Note the draped geometry and thinning against slopes (Acoustic Facies V). (b) Acoustically stratified conformable sediments across the lower slope of the fan (Acoustic Facies V) with sub-units. Note that all the sub-units imaged are conformable through the lower slope channels suggesting that the channels have occupied the same locations for some time.

Figure 6. Acoustic Facies distribution and characteristics of facies I-V on the Disko TMF; core locations are also shown.

Figure 7. Lithofacies logs and shear strength plots of cores taken along a down-fan transect on the northern Disko TMF. Radiocarbon dates from core VC29 are shown alongside and are from Jennings et al. (2017). For location of cores see Figure 1B and 2A.

Figure 8. Lithofacies logs and shear strength plots of cores taken along a down-fan transect on the southern Disko TMF in front of the trough mouth. Radiocarbon dates from cores VC34 and VC35 are shown alongside and are from Ó Cofaigh et al. (2013b). For location of cores see Figure 1B and 2A.

Figure 9. X-radiographs of representative lithofacies from the Disko TMF sediment cores and their Lithofacies Associations (LFA). (A) Massive, matrix supported diamicton, clast rich (LFA1). (B) Massive, matrix supported diamicton (LFA1) overlying sharply, with a dipping lower contact, a massive mud (LFA3) that is likely a load structure. (C) Laminated mud (LFA2 (sub-facies 2ii)). Note the normal fault towards the base of this section. (D) Laminated

and stratified mud (LFA2 (sub-facies 2i and ii)) sharply over and underlying massive medium sand (Lithofacies Association 4). (E) Highly contorted laminated mud (LFA2 (sub-facies 2iii)). (F) Massive mud (LFA3). (G) Normally graded sand unit with isolated clast at toward the top of this unit (LFA4). (H) Stratified and laminated sand (LFA4). (I) Pebble-rich sandy silt with clast abundance and size decreasing up-core (LFA5). (J) Clast-rich mud (LFA5) overlain by a massive mud (Lithofacies Association 3). Note sharp upper boundary of LFA5 . (K) Gravel to pebble rich sand with clast abundance and size decreasing up-core (LFA5).

Fig. 10. Depositional model for the formation of the high-latitude, meltwater-influenced Disko Trough-Mouth Fan, West Greenland.

Table 1. Site information on sediment cores discussed in text

Table 1. Site information on sediment cores discussed in text				
Core	**Date of collection**	**Grid Reference**	**Water depth (m)**	**Recovery (m)**
VC27	23/08/09	68º 06.55'N, 060º 15.69'W	1547 m	6 m
VC28	24/08/09	68º 06.76'N, 059º 59.83'W	1414 m	6 m
VC29	24/08/09	68º 07.35'N, 059º 44.36'W	1064 m	5.80 m
VC30	24/08/09	68º 08.30'N, 059º 40.74'W	825 m	1.85 m
VC31	24/08/09	68º 08.50'N, 059º 38.62'W	745 m	0.23 m
VC32	24/08/09	68º 09.96'N, 059º 37.43'W	690 m	2.34 m
VC33	24/08/09	67º 34.29'N, 059º 49.46'W	1455 m	3.88 m
VC34	25/08/09	67º 33.36'N, 059º 53.03'W	1476 m	3.45 m
VC35	25/08/09	67º 42.03'N, 059º 20.54'W	1267 m	5.36 m
VC36	25/08/09	67º 46.08'N, 059º 06.59'W	767 m	0.57 m

Fig. 1

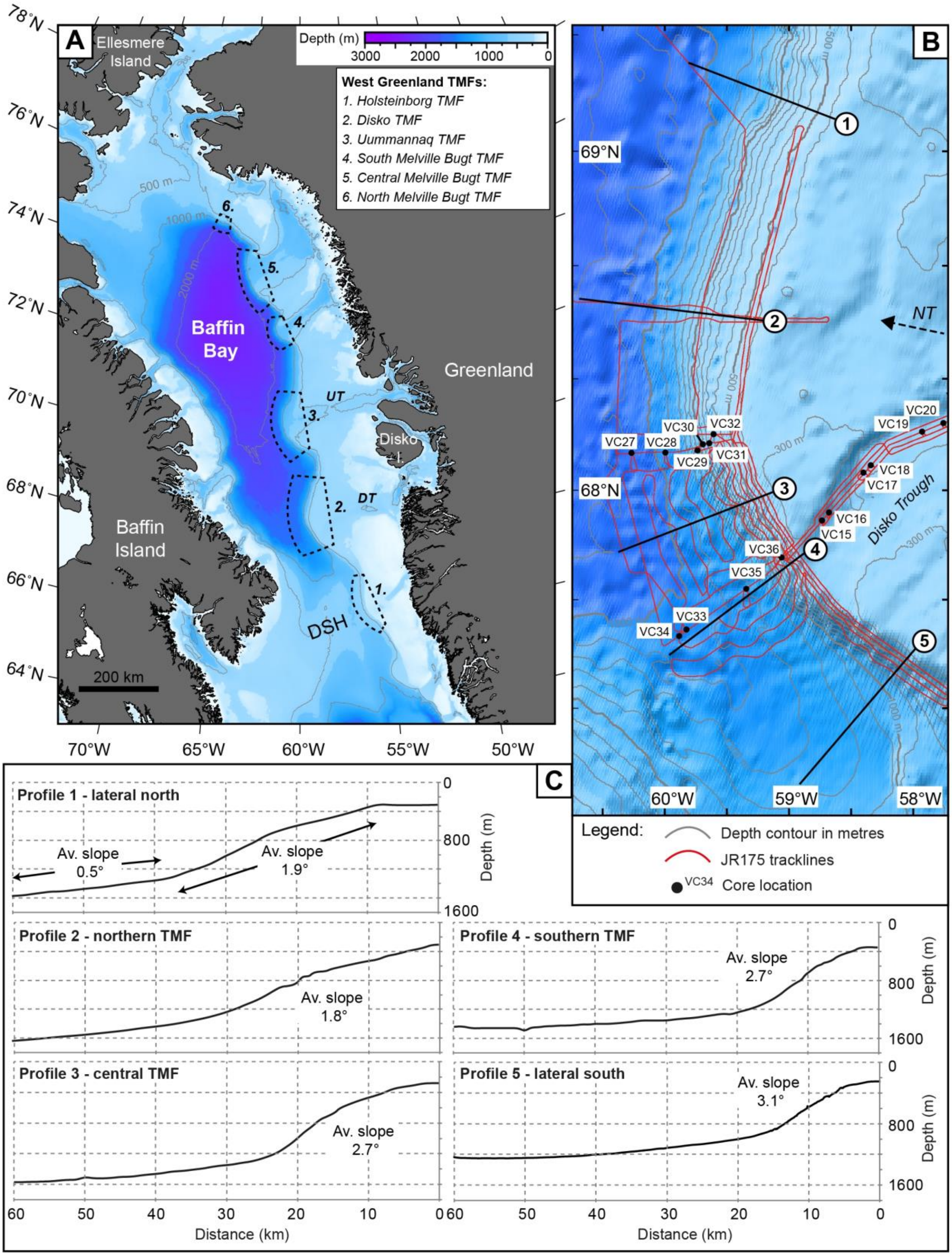

A
B
C
Ellesmere Island
Depth (m)
3000 2000 1000 0
West Greenland TMFs:
1. Holsteinborg TMF
2. Disko TMF
3. Uummannaq TMF
4. South Melville Bugt TMF
5. Central Melville Bugt TMF
6. North Melville Bugt TMF
Baffin Bay
Greenland
Baffin Island
Disko
UT
DT
DSH
200 km
78°N
76°N
74°N
72°N
70°N
68°N
66°N
64°N
70°W 65°W 60°W 55°W 50°W
69°N
68°N
NT
Disko Trough
VC15 VC16 VC17 VC18 VC19 VC20 VC27 VC28 VC29 VC30 VC31 VC32 VC33 VC34 VC35 VC36
60°W 59°W 58°W
Legend:
Depth contour in metres
JR175 tracklines
Core location
Profile 1 - lateral north
Av. slope 0.5°
Av. slope 1.9°
Profile 2 - northern TMF
Av. slope 1.8°
Profile 3 - central TMF
Av. slope 2.7°
Profile 4 - southern TMF
Av. slope 2.7°
Profile 5 - lateral south
Av. slope 3.1°
Depth (m)
Distance (km)

Fig. 2

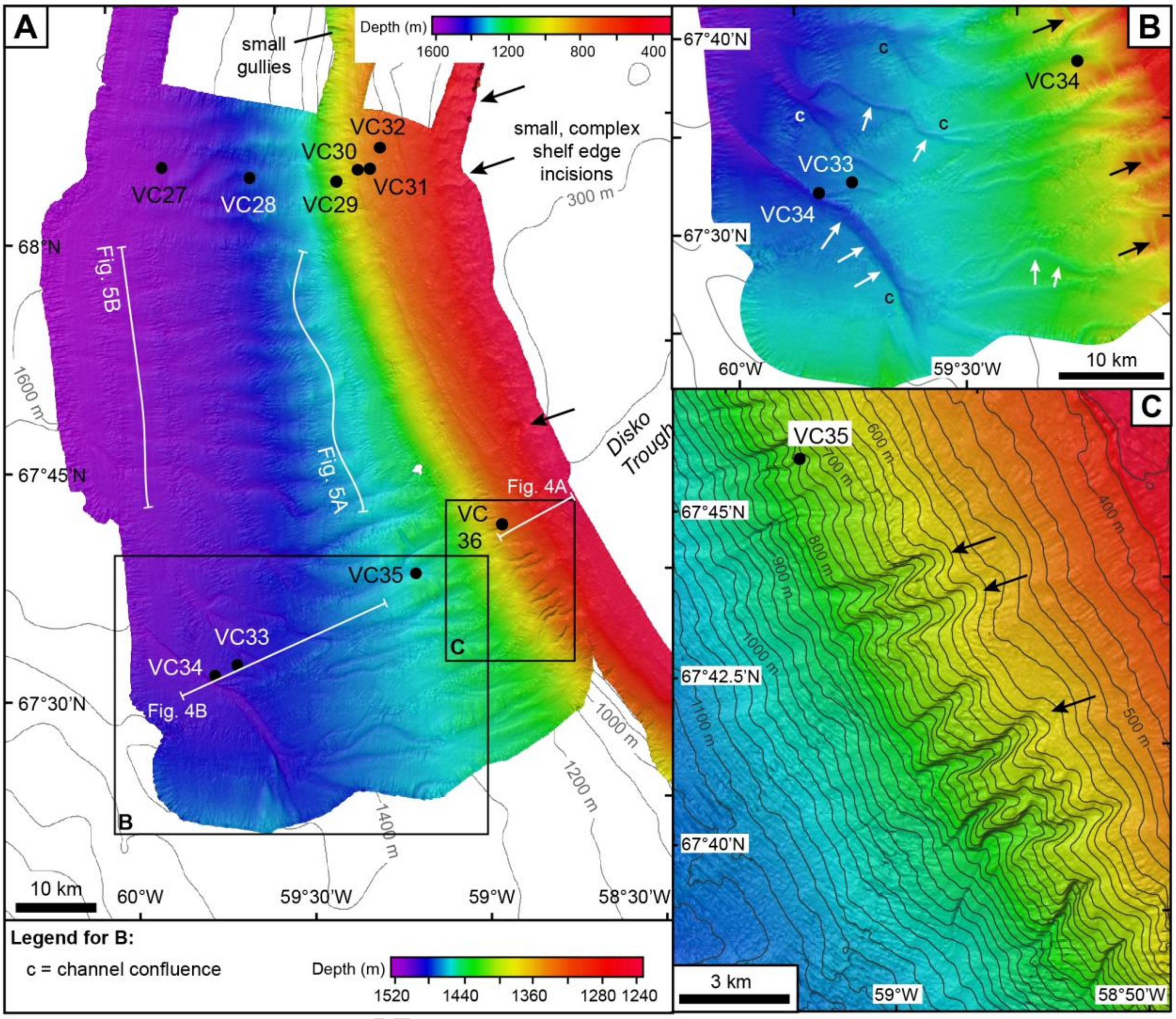

A
small gullies
Depth (m)
1600
1200
800
400
small, complex shelf edge incisions
300 m
VC27
VC28
VC29
VC30
VC31
VC32
68°N
Fig. 5B
Fig. 5A
1600 m
67°45'N
Disko Trough
Fig. 4A
VC 36
VC35
VC33
VC34
Fig. 4B
67°30'N
1000 m
1200 m
1400 m
B
C
10 km
60°W
59°30'W
59°W
58°30'W
Legend for B:
c = channel confluence
Depth (m)
1520
1440
1360
1280
1240
67°40'N
67°30'N
c
10 km
VC35
600 m
700 m
800 m
900 m
1000 m
1100 m
400 m
500 m
67°45'N
67°42.5'N
67°40'N
3 km
59°W
58°50'W

Fig. 3

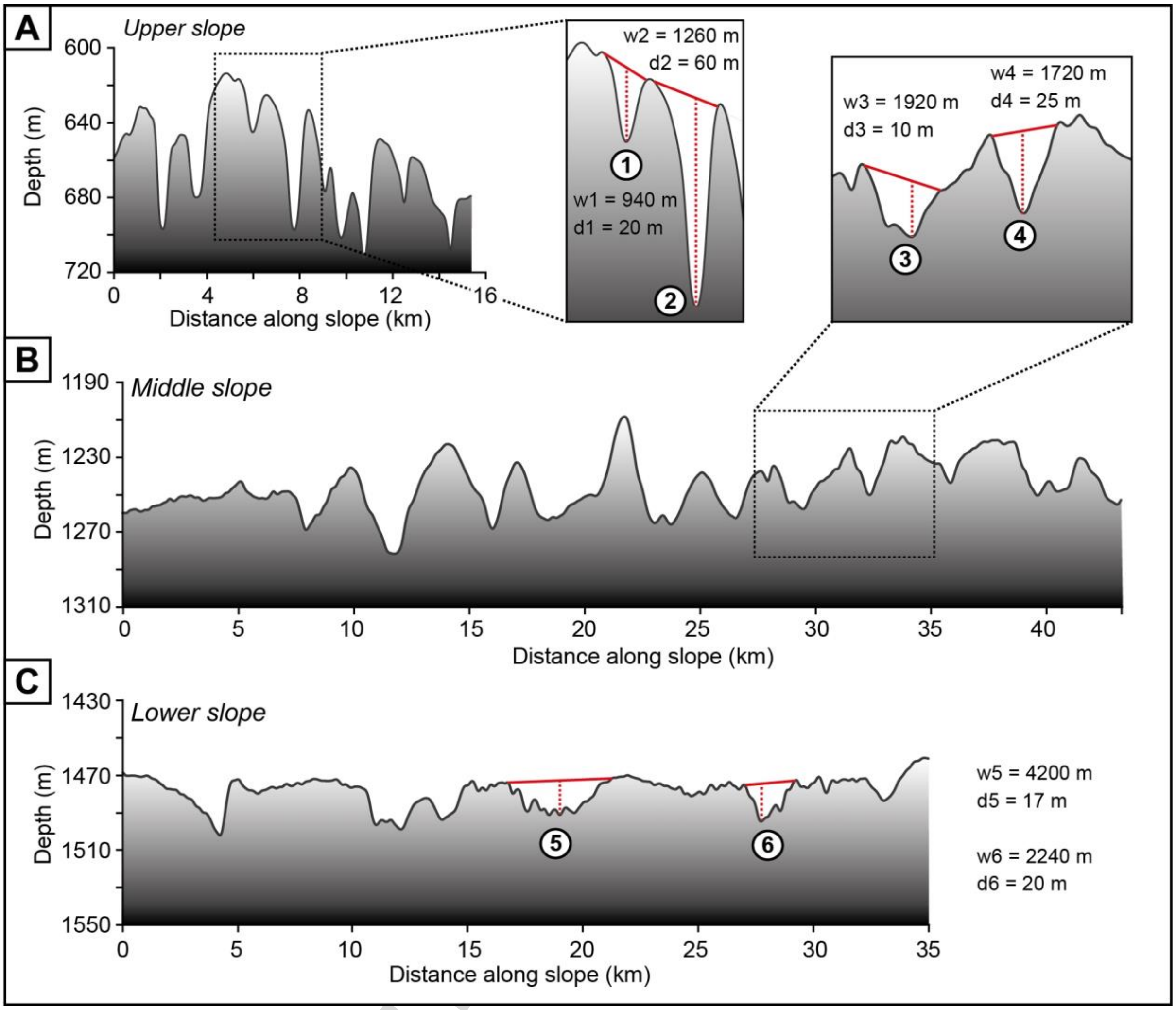

A
Upper slope
Depth (m)
600
640
680
720
0
4
8
12
16
Distance along slope (km)
w2 = 1260 m
d2 = 60 m
w1 = 940 m
d1 = 20 m
1
2
w4 = 1720 m
d4 = 25 m
w3 = 1920 m
d3 = 10 m
3
4
B
Middle slope
1190
1230
1270
1310
0
5
10
15
20
25
30
35
40
Distance along slope (km)
C
Lower slope
1430
1470
1510
1550
5
6
w5 = 4200 m
d5 = 17 m
w6 = 2240 m
d6 = 20 m

Fig. 4

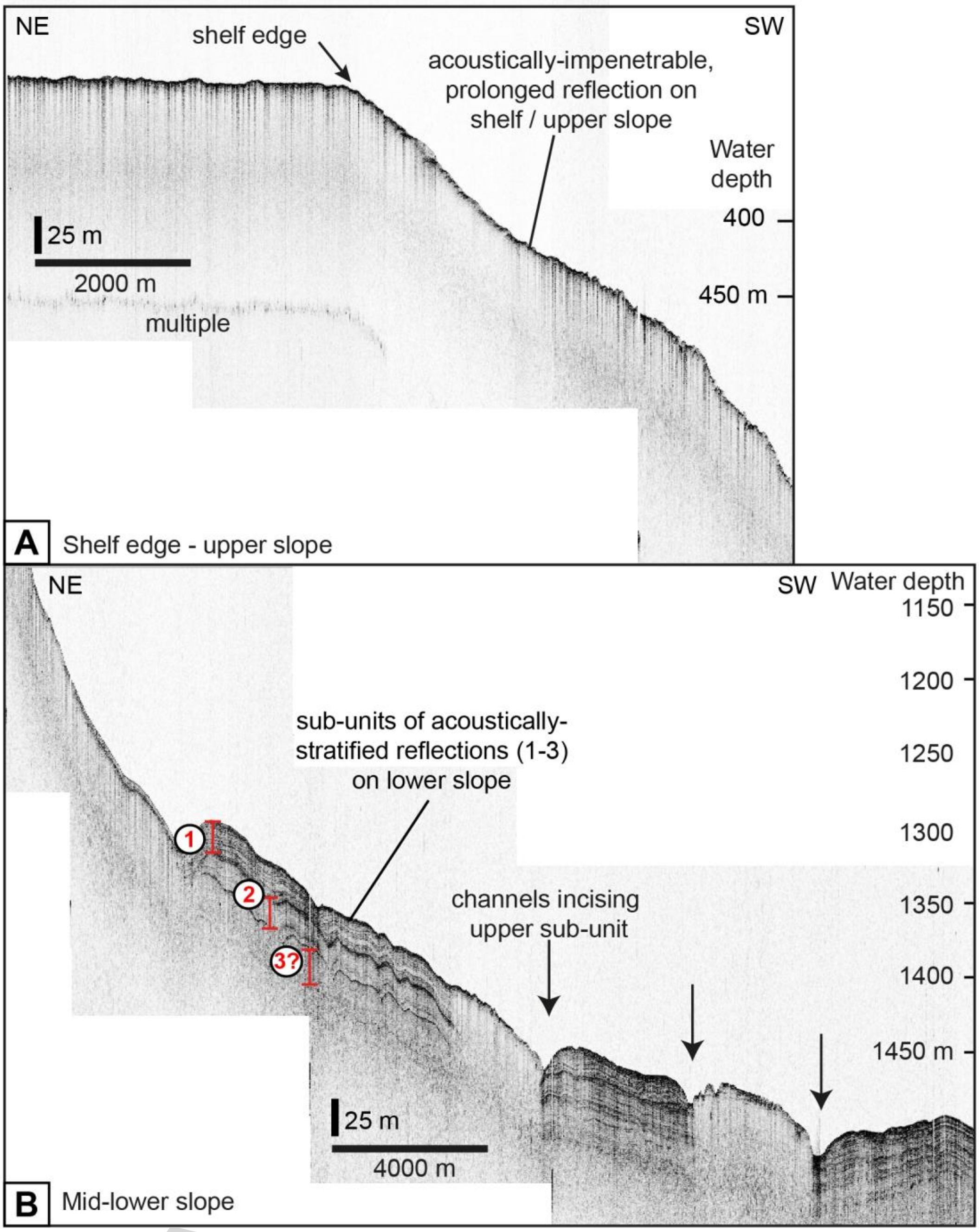

NE
shelf edge
SW
acoustically-impenetrable, prolonged reflection on shelf / upper slope
Water depth
400
450 m
25 m
2000 m
multiple
A
Shelf edge - upper slope
NE
SW
Water depth
1150
1200
1250
1300
1350
1400
1450 m
sub-units of acoustically-stratified reflections (1-3) on lower slope
1
2
3?
channels incising upper sub-unit
25 m
4000 m
B
Mid-lower slope

Fig. 5

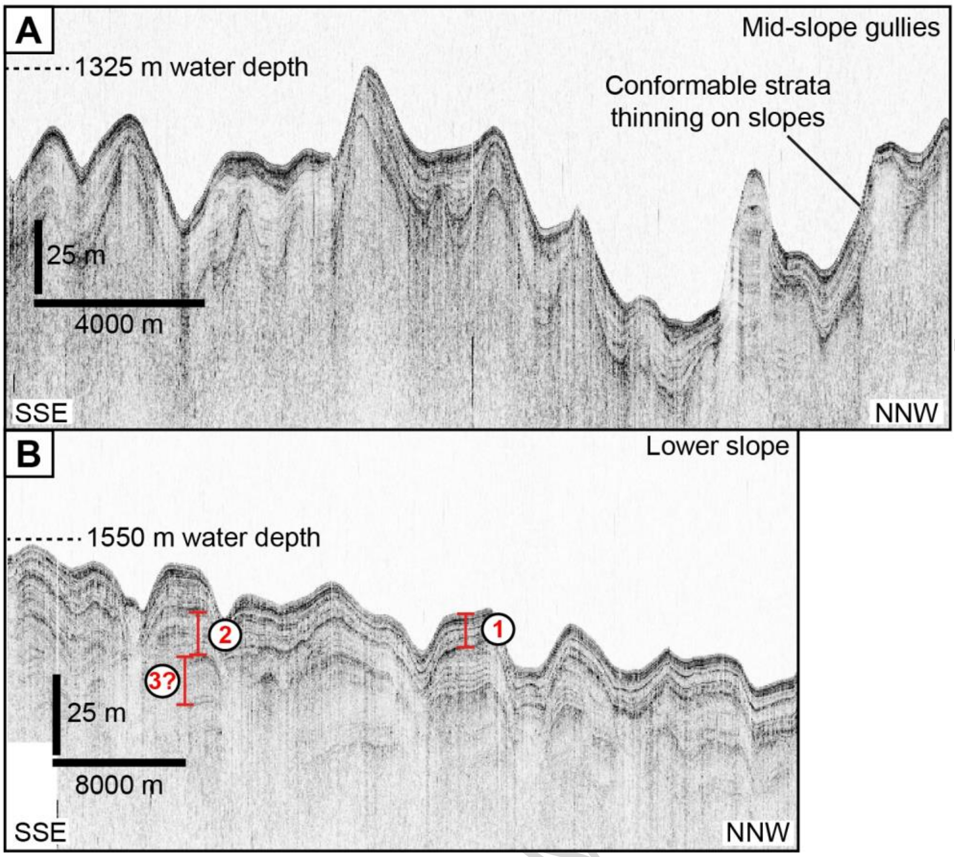

A
Mid-slope gullies
1325 m water depth
Conformable strata
thinning on slopes
25 m
4000 m
SSE
NNW
B
Lower slope
1550 m water depth
2
1
3?
25 m
8000 m
SSE
NNW

Fig. 6

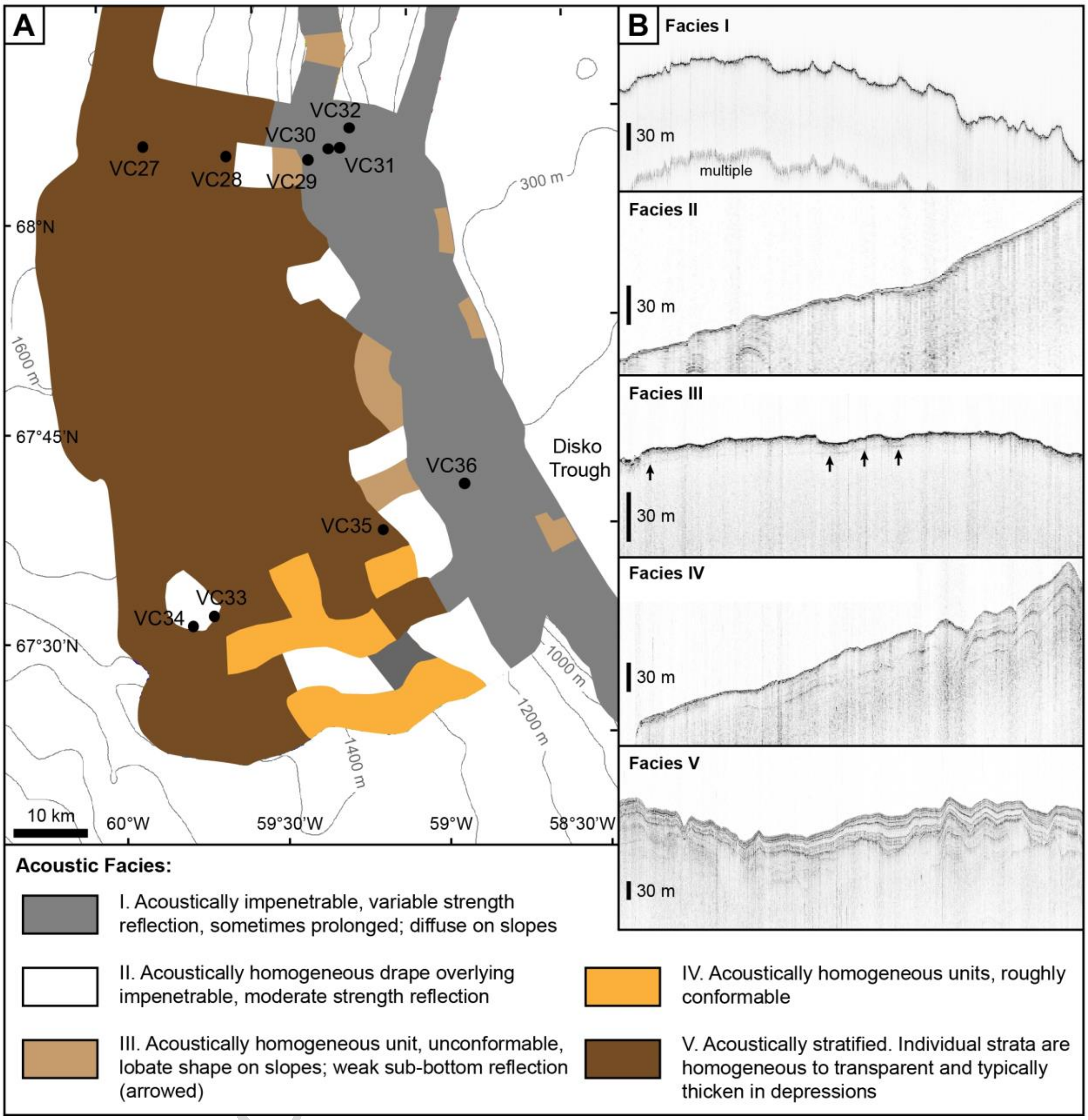

A
VC32
VC30
VC27
VC28
VC29
VC31
300 m
68°N
1600 m
67°45'N
Disko
Trough
VC36
VC35
VC33
VC34
67°30'N
1000 m
1200 m
1400 m
10 km
60°W
59°30'W
59°W
58°30'W
B
Facies I
30 m
multiple
Facies II
30 m
Facies III
30 m
Facies IV
30 m
Facies V
30 m
Acoustic Facies:
I. Acoustically impenetrable, variable strength reflection, sometimes prolonged; diffuse on slopes
II. Acoustically homogeneous drape overlying impenetrable, moderate strength reflection
III. Acoustically homogeneous unit, unconformable, lobate shape on slopes; weak sub-bottom reflection (arrowed)
IV. Acoustically homogeneous units, roughly conformable
V. Acoustically stratified. Individual strata are homogeneous to transparent and typically thicken in depressions

Fig. 7

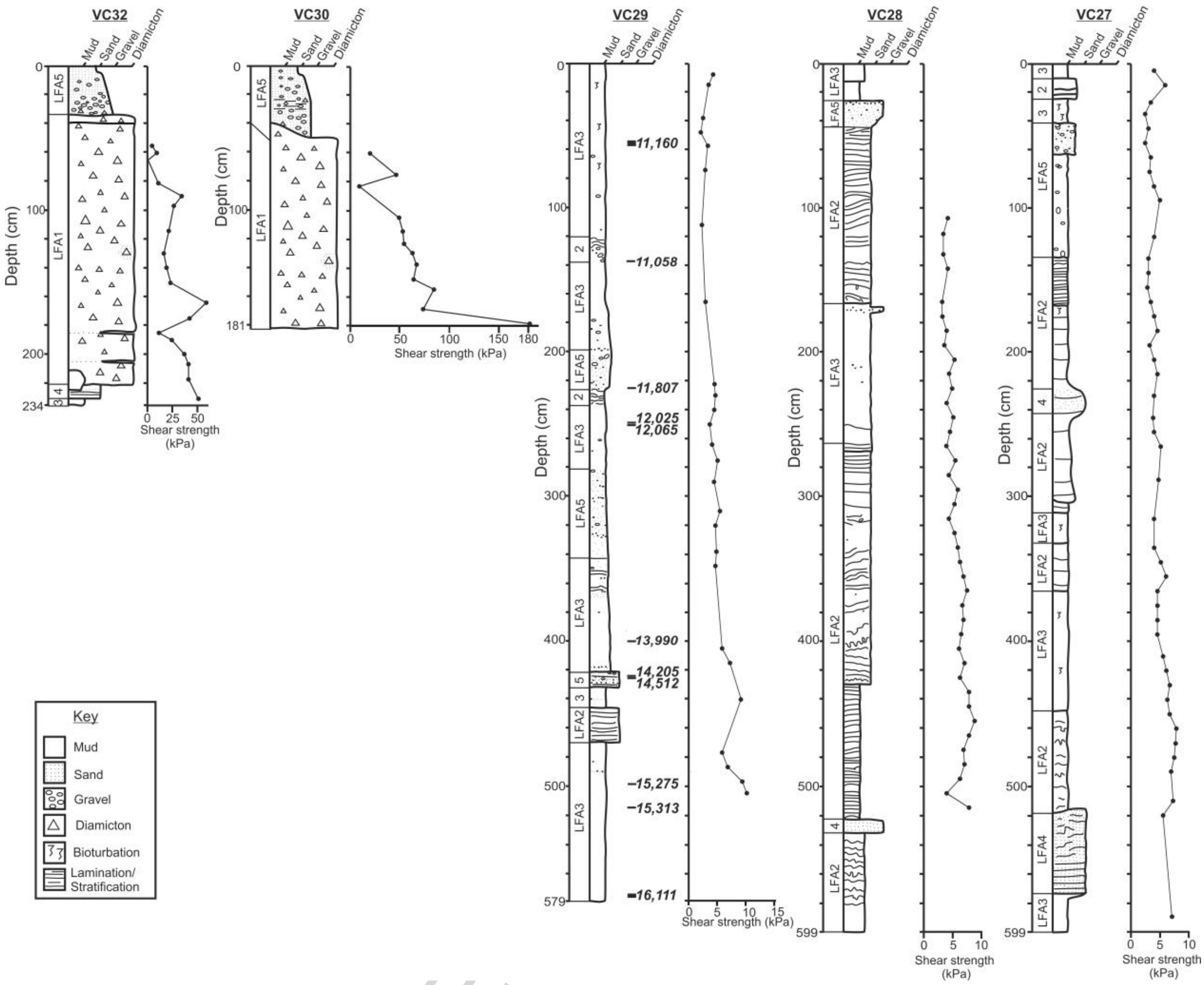
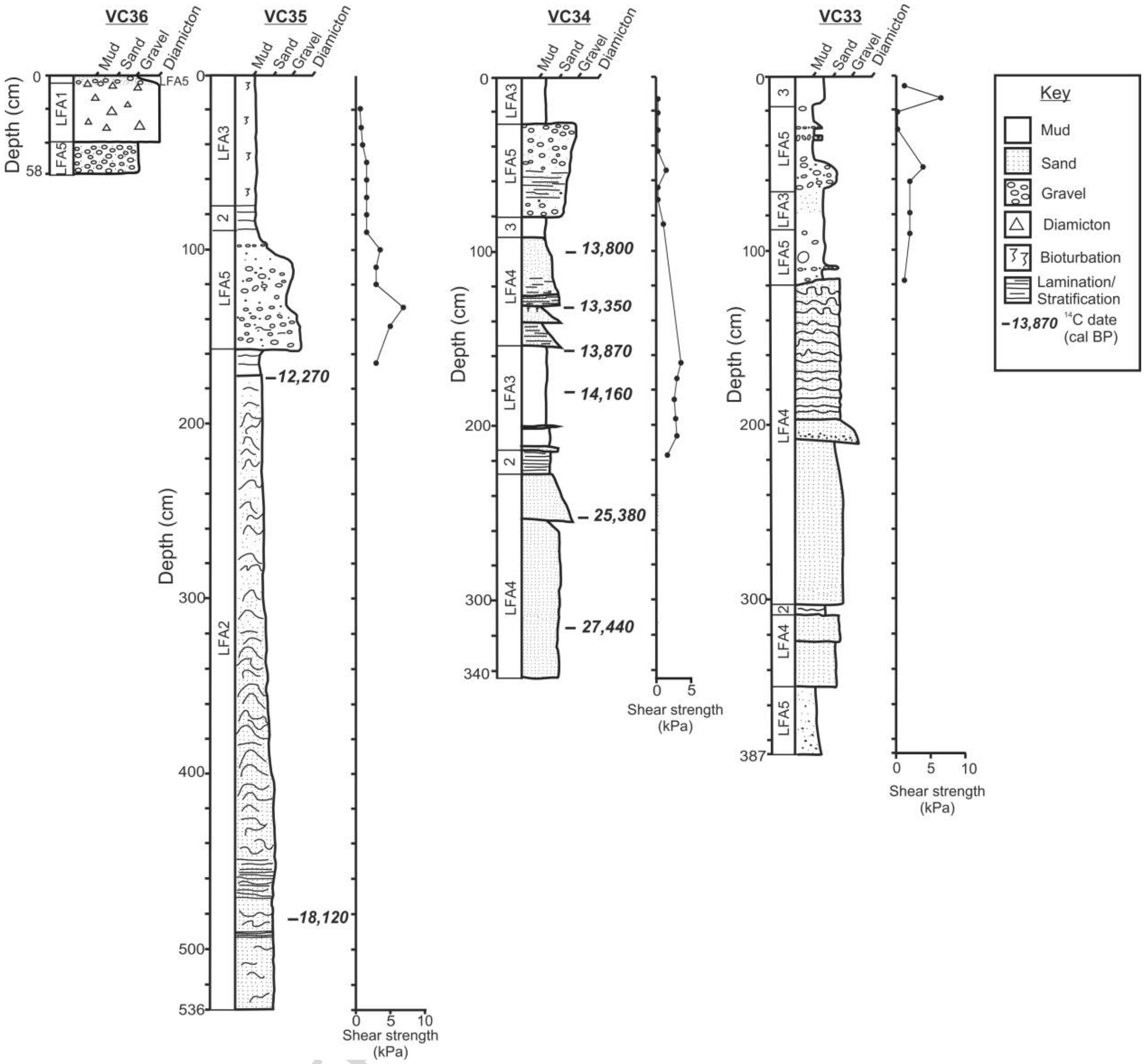

VC32
VC30
VC29
VC28
VC27
Mud
Sand
Gravel
Diamicton
Depth (cm)
Shear strength (kPa)
LFA1
LFA2
LFA3
LFA4
LFA5
11,160
11,058
11,807
12,025
12,065
13,990
14,205
14,512
15,275
15,313
16,111
Key
Mud
Sand
Gravel
Diamicton
Bioturbation
Lamination/
Stratification

Fig. 8



VC36
VC35
VC34
VC33
Mud
Sand
Gravel
Diamicton
Depth (cm)
LFA1
LFA5
LFA3
LFA2
LFA4
12,270
18,120
13,800
13,350
13,870
14,160
25,380
27,440
Shear strength (kPa)
Key
Mud
Sand
Gravel
Diamicton
Bioturbation
Lamination/ Stratification
13,870 14C date (cal BP)

Fig. 9

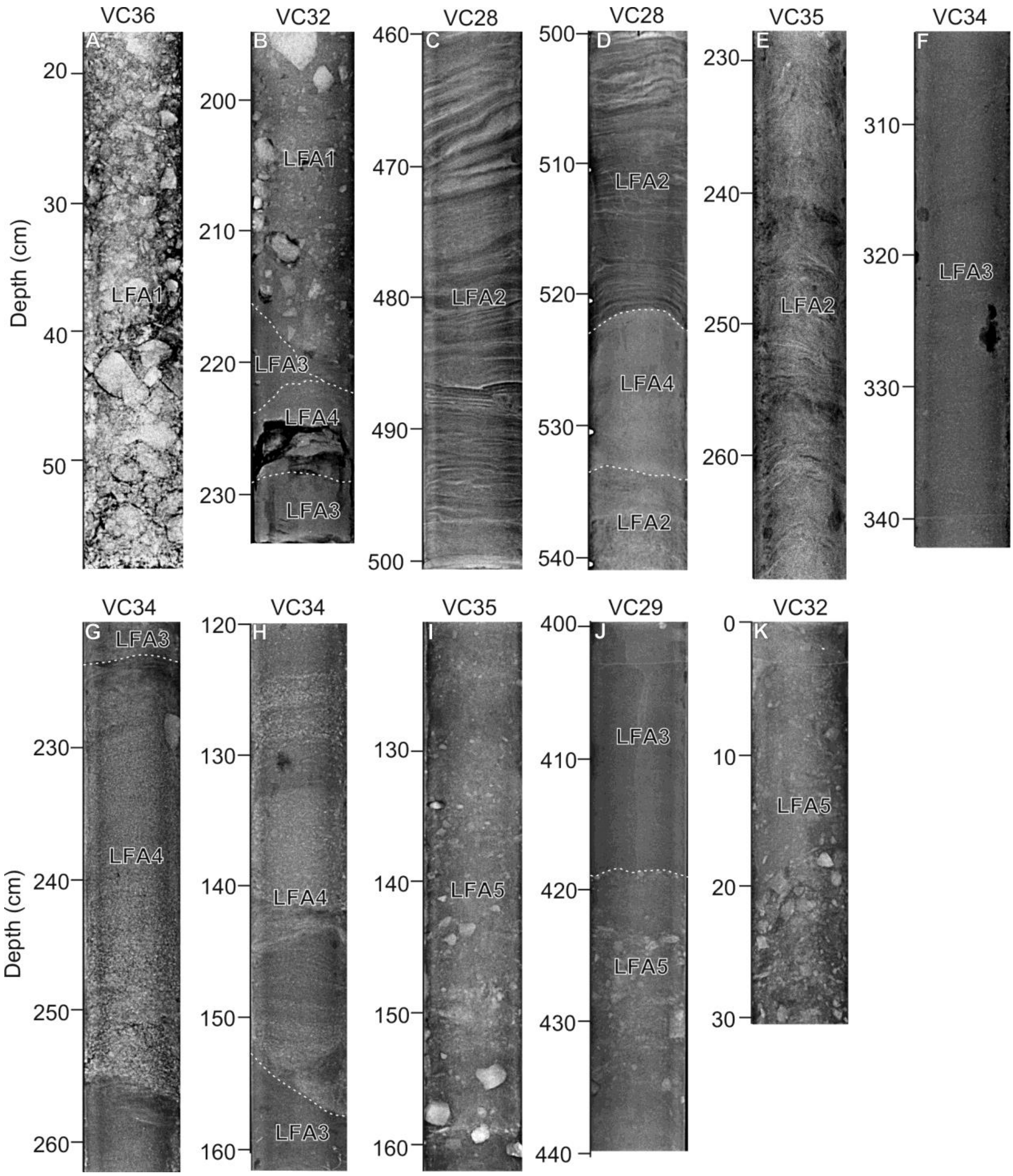
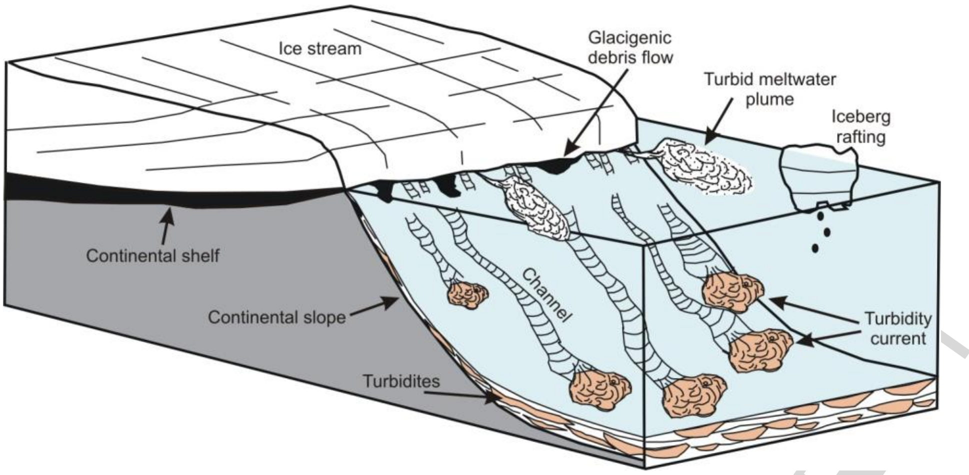

VC36
A
LFA1
Depth (cm)
VC32
B
LFA1
LFA3
LFA4
LFA3
VC28
C
LFA2
VC28
D
LFA2
LFA4
LFA2
VC35
E
LFA2
VC34
F
LFA3
VC34
G
LFA3
LFA4
VC34
H
LFA4
LFA3
VC35
I
LFA5
VC29
J
LFA3
LFA5
VC32
K
LFA5

Fig. 10


Ice stream
Glacigenic debris flow
Turbid meltwater plume
Iceberg rafting
Continental shelf
Continental slope
Channel
Turbidity current
Turbidites

MARGO_2017_179

The role of meltwater in high-latitude trough-mouth fan development: the Disko Trough-Mouth Fan, West Greenland

Colm Ó Cofaigh, Kelly A. Hogan, Anne E. Jennings, S. Louise Callard, Julian A. Dowdeswell, Riko Noormets, and Jeff Evans

Highlights

Geophysical and sedimentary study of the LGM-Younger Dryas part of the Disko Trough-Mouth Fan (TMF), a major submarine sediment fan offshore of central west Greenland.

The Disko TMF is a product of repeated glacigenic sediment delivery from former fast-flowing outlets of the Greenland Ice Sheet, including an ancestral Jakobshavn Isbrae, which expanded to the shelf edge during glacial maxima.

Morphological, acoustic- and lithofacies data show that formation of the Disko TMF was strongly influenced by meltwater delivery and sedimentation. It thus bears similarities to TMFs formed on mid-latitude, glacier-influenced margins but rarely described from high-latitude settings.

Implies there is a spectrum of TMFs on glaciated continental margins that reflects the relative dominance of meltwater processes vs. glacigenic debris flows and highlights the variability in fan morphology and mechanisms of sediment delivery on high-latitude TMFs.