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

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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.

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); (Dowdeswell et al., 1998; King et al., 1996; Laberg et al., 2018; Li et al., 2011; Nygård et al., 2005; O'Brien et al., 2007; Pope et al., 2016; Rydningen et al., 2016)). 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 (Ó Cofaigh et al., 2003; Vorren and Laberg, 1997). The highest sedimentation rates and maximum periods of fan growth occur during

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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., (Laberg and Vorren, 1995; Laberg and Vorren, 1996; Vorren et al., 1989; Vorren et al., 1990); Dowdeswell et al., 1996; (Dowdeswell et al., 1997; Elverhøi et al., 1997; King et al., 1996; King et al., 1998)). 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 ≤1°) (Laberg and Vorren, 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 (Lucchi et al., 2013; Ó Cofaigh et al., 2013a; Taylor et al., 2002). 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; Hesse et al., 1999; Piper et al., 2007; Piper et al., 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 (Jennings et al., 2017; Ó Cofaigh et al., 2013a).

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 km^2 in size and it can be traced down to 2000 m water depth in the abyssal plain. Hofmann et al. (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 (Zarudzki, 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 has focused on the cross-shelf bathymetric troughs and the adjoining continental slope and has sought to reconstruct the Greenland Ice Sheet during the last glacial-deglacial cycle using marine geology and geophysics (Dowdeswell et al., 2014; Hogan et al., 2016; Jennings et al., 2014; Ó Cofaigh et al., 2013a; Ó Cofaigh et al., 2013b; 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. (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 (Hogan et al., 2016; Ó Cofaigh et al., 2013b). 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. (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. (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