2018-01-01

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http://hdl.handle.net/10026.1/10383

10.1144/sp475.7
Geological Society Special Publication

Processes influencing differences in Arctic and Antarctic Trough Mouth Fan sedimentology

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Abstract

Trough Mouth Fans (TMFs) are sediment depocentres that form along high-latitude continental margins at the mouths of some cross-shelf troughs. They reflect the dynamics of past ice sheets over multiple glacial cycles and processes operating on (formerly) glaciated continental shelves and slopes, such as erosion, reworking, transport and deposition. The similarities and differences in TMF morphology and formation processes of the Arctic and Antarctic regions remain poorly constrained. Here, we analyse the dimensions and geometries of 15 TMFs from Arctic and Antarctic margins and the grain-size distribution of 82 sediment cores centred on them. We compare the grain-size composition of sub- and proglacial diamictons deposited on the shelves and glacigenic-debris flows (GDFs) deposited on the adjacent TMFs and find a significant difference between Arctic and Antarctic margins. Antarctic margins show a coarser grain-size composition for both GDFs and shelf diamictons. This significant difference provides insight into high-latitude sediment input, transportation and glacial/interglacial regimes. We suggest that surface run-off and river discharge are responsible for enhanced fine-grained sediment input in the Arctic compared to in the Antarctic.

Introduction

Ice streams are the main drivers of erosion, transport and deposition along high-latitude continental margins. Their past extent and dynamics control not only the volume, but also the location and type of the deposited sediments. They ultimately shape how the continental shelves and slopes have evolved during past glaciations, along with the tectonic history and slope processes operating independently from climatic stages. Ice streams are thought to have reached the shelf edge along much of the Arctic and Antarctic margins during the Quaternary (e.g. Denton & Hughes, 1981; Laberg & Vorren, 1995; Anderson, 1999; Vorren & Plassen, 2002; Cooper et al., 2008; Ruther et al., 2013; Rydningen et al., 2013; Jakobsson et al., 2014; The RAISED Consortium et al., 2014). This caused, or at least contributed to, the erosion of large cross-shelf bathymetric troughs, the formation of subglacial and glacially-influenced bedforms across the continental shelf and, at the mouths of some palaeo-ice stream troughs, the deposition of large volumes of sediment at the shelf edge to form prograding Trough Mouth Fans (TMFs) (Vorren et al., 1989).

The occurrences of TMFs are far fewer in the Antarctic compared to the Arctic (Figs. 1 and 2). In bathymetric profiles across polar continental margins, TMFs are identifiable by distinctive convex-outward morphologies at the mouths of some cross-shelf troughs (Vorren et al., 1998; Kuvaas & Kristofersen, 1991; Dowdeswell et al., 2008; Livingstone et al., 2012; Batchelor et al., 2014). They reflect the dynamics of past ice sheets over multiple glacial cycles and thus are important palaeoclimate archives (Vorren and Laberg, 1997). TMFs are mainly composed of poorly sorted and glacially-influenced sediments, predominantly glacigenic debris flows (GDFs) formed of diamictons. These diamictons consist of subglacially-eroded, unsorted debris that had been transported to the shelf edge as tills at the base of a grounded ice stream or ice sheet. Additional sediments commonly found on TMFs comprise glacimarine hemipelagic sediments and turbidites (Vorren et al., 1989; Laberg & Vorren, 1995; Dowdeswell et al., 1996, 1997; King et al., 1996; Lucchi et al., 2013). The composition of these sediments can be expected to provide insight into past ice advance and retreat and may shed light on processes operating on high-latitude continental margins, for example meltwater plume deposition. The main seismostratigraphic components of TMFs are prograding outer shelf – upper slope strata which are constructed predominantly of foresets comprising debris flow units and topsets commonly formed of subglacially-deposited tills (Damuth, 1978). Gravitational downslope deposits, including submarine landslides and debris lobes, as well as erosional bedforms, such as channel / levee systems and gullies, are also common features of TMFs.

TMFs are of global significance in terms of sediment transport to the deep ocean, carbon storage and evaluation of slope stability and resulting hazard risks (e.g. Elverhøi et al., 1997; Mienert et al., 2002; Covault, 2011; Talling et al., 2015; Cartapanis et al., 2016). It remains poorly constrained how Arctic and Antarctic TMFs differ in terms of sediment composition, morphology and processes operating in these regions and the factors controlling these differences. Despite a vast number of previous studies that investigated the local morphology and sedimentology of TMFs, only a few studies focussed on differences between Arctic and Antarctic margins (e.g. Ó Cofaigh et al., 2003; Nielsen et al., 2005; Gales et al., 2013). These previous studies largely focussed on gross architecture, geometry and geomorphology of the TMFs in comparison to portions of other polar margins, whereas here, we focus on the differences in the grain-size composition of the TMF sediments.

In our study we address the following key questions:

1) How does the sedimentology of Arctic and Antarctic TMFs vary and differ?

2) What are the causes for the observed differences?

3) What can this tell us about processes operating on high-latitude continental margins?

Previous work: TMF formation and sedimentology

TMFs on both Arctic and Antarctic margins have been studied in detail with 20 TMFs identified on Arctic margins and three on Antarctic margins (Batchelor et al., 2014; Livingstone et al., 2012; Table 1). TMF formation has been attributed to two major processes. The first comprises erosion and remobilization of sediments deposited landward of and on the shelf by ice streams and their subsequent redeposition as debris flows on the outer continental shelf and upper slope (e.g. Vorren et al., 1989; Laberg & Vorren, 1995; Dowdeswell et al., 1996, 1997; King et al., 1996). Seismic-reflection and sub-bottom profiler data show the signature of these debris flow deposits as prograding sigmoidal / oblique reflections and (stacked) semi-transparent lenses or opaque wedges (Damuth, 1978; Vorren et al., 1989; King et al., 1996; Laberg and Vorren, 1995). On Arctic margins, the debris flows are suggested to result from the intermittent failure of clay-rich, subglacial soft tills which were deposited rapidly under full-glacial conditions at the shelf edge (Laberg & Vorren, 1995; Dowdeswell et al., 1996; Elverhøi et al., 1997; Ó Cofaigh et al., 2003). The second mechanism of TMF formation comprises deposition of mass flows and the suspension load of turbid meltwater plumes (e.g. Ó Cofaigh et al., 2003; Lucchi et al., 2013; Rebesco et al., 2013). Turbid meltwater plumes released at the grounding line of ice-sheets result in dense flows of sediment-laden water across the outer shelf and down the continental slope. Suspension settling from these flows enhances fan formation (Lucchi et al., 2013). This process may occur alongside debris flow activity during glacial periods, or during deglaciation/interglacials (Ó Cofaigh et al., 2003). These processes are modulated by environmental factors such as the slope gradient, the underlying geological substrate and the abundance of meltwater (Ó Cofaigh et al., 2003).

Sediment cores recovered from the outer shelf sections of palaeo-ice stream troughs and the adjacent TMFs provide important insights into processes operating in these areas. Diamictons on the shelf may have been formed by (1) subglacial deposition beneath grounded ice (= till), (2) melt-out of glacigenic debris from the base of floating ice (= glacimarine diamicton), either under an ice shelf proximal to the grounding line or from debris-rich icebergs (= iceberg-rafted diamicton), (3) reworking of subglacial and/or glacial-marine sediments by iceberg ploughing (= iceberg turbate), or (4) deposition of glacigenic debris flows (= GDFs) (e.g. King et al., 1998; Anderson, 1999; Domack et al., 1999; Lowe and Anderson, 2002; Hillenbrand et al., 2005;). Distinguishing the formation processes usually takes into account factors including shear strength, density, porosity, water content as well as the presence, preservation and composition of biogenic material, sedimentary structures, grain-size distribution, and age constraints (e.g. Kurtz & Anderson, 1979; Laberg & Vorren, 2000; Evans and Pudsey, 2002; Hillenbrand et al., 2005; Ó Cofaigh et al., 2005). In contrast, diamictons on TMFs are likely to have been deposited as GDFs or glacimarine / iceberg-rafted diamictons. The latter process is unlikely to play a significant role for deposition on TMFs as embayments that are capable of trapping icebergs at an ice front can be expected to form on a continental shelf but are less common above the continental slope. In Antarctica, strong ocean currents flowing parallel to the shelf break (e.g. Antarctic Circumpolar Current, Antarctic Coastal Current, Weddell Gyre) and the predominant offshore wind direction due to katabatic winds (Turner et al., 2009) would have driven icebergs quickly further seaward during times when the grounding line was located at, or near to, the shelf edge.

Study Areas

The Antarctic study areas include the Belgica Trough Mouth Fan in the Bellingshausen Sea, the Crary Trough Mouth Fan in the southern Weddell Sea, and the Prydz Channel Trough Mouth Fan in the Cooperation Sea (Fig. 1; Table 1). TMFs analysed from margins in the Arctic include the Vilkitsky-Khatanga Trough Mouth Fan, Voronin Trough Mouth Fan, St Anna Trough Mouth Fan and Franz Victoria Trough Mouth Fan on the northern Barents-Kara Sea margin, the Kongsfjorden Trough Mouth Fan, Isfjorden Trough Mouth Fan, Bellsund Trough Mouth Fan, Storfjorden Trough Mouth Fan, Kveithola Trough Mouth Fan and Bear Island Trough Mouth Fan on the western Barents Sea margin, the North Sea Trough Mouth Fan, and the Scoresby Sund Trough Mouth Fan on the eastern Greenland margin (Fig. 2; Table 1).

Extensive ice sheets advanced episodically across the continental shelves in East Antarctica since 34 Ma and in West Antarctica since at least the Late Miocene (e.g. Florindo & Siegert 2008; Barrett, 2008). Northern Hemisphere glaciation started during the middle to late Miocene in Greenland, intensified around ~4 Ma and 2.6 Ma along the Norwegian margin (Larsen et al., 1994; Thiede et al., 1998), and ice-sheets there are thought to have reached their greatest extent around 1 Ma (Knies et al., 2009). Along many Antarctic and Arctic margins grounded ice reached the shelf edge during glacial periods of the Late Quaternary (e.g. Cooper et al., 2008; Mangerud et al., 2011; Jakobsson et al., 2014).

The underlying geology and tectonic history of our study areas have been well documented (e.g. Kenyon, 1987; Larter & Barker, 1991; Kuvaas and Kristofferson, 1991; Nitsche et al., 1997; Cunningham et al., 2002; Eagles et al., 2004, 2009; Stoker et al., 2005; Faleide et al., 2008). The Belgica Fan is situated above a relict subduction zone which has been inactive since 55 Ma (Cunningham et al., 2002). The Crary Fan margin has been a passive margin since the Jurassic period (Jokat et al., 1996; Bart et al., 1999). Offshore Prydz Bay, sediments include pre-Cenozoic non-marine sedimentary rocks and Cenozoic diamictons (Hambrey et al., 1991). The location is a passive margin on the boundary between between where India rifted away from Antarctica in the Early Cretaceous and where Australia rifted away in the Late Cretaceous. The geological setting of the NW European margin reflects a passive margin, which during the Cenozoic underwent various tectonic movements resulting in variations from a classic post-rift development (STRATEGEM Partners, 2003). Early Pliocene uplift and basin subsidence resulted in a significant shift in the depositional style, from sedimentation controlled by ocean current-induced erosion and transport to sedimentation dominated by shelf progradation (STRATEGEM Partners, 2003).

Materials and methods

Examination of Arctic and Antarctic TMFs included morphometric analysis (e.g. TMF geometry and dimensions) from regional bathymetric data and grain-size analysis. Grain-size data of individual sediment samples taken from 76 gravity cores and six drill sites from the outer shelf and upper slope of Arctic and Antarctic TMFs and the surrounding areas were investigated (Table 2). Cores were selected based on their vicinity to the shelf edge and only cores recovered from GDFs deposited on the slope or diamictons deposited on the shelf are considered here. The core locations are shown in Figures 1 and 2.. Average grain sizes for gravel (> 2mm), sand (63 μm - 2 mm), silt (2 μm - 63 μm) and clay (< 2 μm) from the

GDF/diamicton section of each core were either measured for this study (most cores from Belgica TMF; Fig. 3a), or the data were taken from the published literature. Where no published grain-size data could be obtained from the authors, grain-size composition (gravel-sand-silt-clay) was estimated for the diamicton section of a core by measuring the percentage of a grain-size fraction as displayed in high resolution figures of the source publications (Fig. 3b; Table 2). The approach used for each core is detailed in Table 2. This approach may give rise to an error of ≤3% percent. Grain-size data are expressed either as sand-silt-clay or as gravel-sand-mud (with mud= silt+clay).

Although the exact methods of grain-size analyses may differ between the various studies, the techniques predominantly followed the same standard procedures: subsamples were treated with 3% hydrogen peroxide solution and 10% acetic acid to remove total organic carbon (TOC) and $CaCO_3$ and gravel, sand and mud (silt and clay) fractions were separated by wet sieving (e.g. Hillenbrand et al., 2005). In some cores from the Belgica TMF, Crary TMF and Prydz TMF (e.g. Passchier et al., 2003) biogenic material had not been removed by chemical treatment before the grain-size analysis, but this should not have affected the results of our comparison because diamictons from the Antarctic shelf and slope have been shown to consist almost entirely of terrigenous detritus (e.g. Kurtz & Anderson, 1979; Anderson et al., 1980; Hillenbrand et al., 2005; Licht et al., 1999). The silt and clay fractions were either separated using settling tubes, or their contents were measured with a particle size analyser, such as Sedigraph, laser particle analyser or Coulter Counter. Although the use of different techniques and instruments for measuring the grain-size distribution in the fine fraction <63 μm may result in different silt and clay contents (e.g. Konert & Vandenberghe 1997; Beuselinck et al., 1998; Bianchi et al., 1999; Molinaroli et al., 2000; McCave et al., 2006), this will not affect our comparison of gravel, sand and mud contents.

International Bathymetric Chart of the Arctic Ocean (IBCAO) and International Bathymetric Chart of the Southern Ocean (IBCSO) data were used to quantify TMF morphometrics including slope gradient, geometry, trough length and TMF area. Trough length is measured from modern ice shelf limits to the continental shelf edge. Data on drainage basin sizes for palaeo-ice streams were either taken from the literature (Table 1) or, if unavailable, estimated from published palaeo-ice divide data (Table 1). The statistical significance of the results were tested using regression analysis. Standard deviation calculations were used to identify whether the variances between Arctic and Antarctic TMFs were greater than within the datasets.

Results

Geometry and dimensions of TMFs

The locations and parameters of many Arctic and Antarctic TMFs have been described previously (Table 1). Figure 4A shows clear relationships between some TMF parameters, including trough length, trough relief at the shelf edge, slope gradient, fan area and palaeo-drainage basin size. Bear Island Fan and the North Sea Fan are clear outliers due to the very large fan areas (215,000 km^2 and 142,000 km^2 respectively). These data were therefore excluded in regression calculations for correlations.

The matrix plot of the 15 measured TMF parameters (Fig. 4A, Table 1) shows a strong positive correlation between trough length and fan area (r^2= 78%). Fan area also increases with paleo-drainage basin size for both Arctic and Antarctic TMFs. For Arctic TMFs, this correlation is very strong (r^2= 89%). The correlation decreases with the addition of Antarctic TMFs, although this may be affected by errors introduced by estimating palaeo-drainage basin sizes. There is a strong positive correlation between trough relief and fan area, with fan area increasing with cross-shelf trough relief (r^2= 61%). There are weak negative correlations between slope gradient and trough length (r^2<47%) and between slope gradient and palaeo-ice stream drainage basin size (r^2= 43%) for both Arctic and Antarctic TMFs. There is also a weak negative relationship between cross-shelf trough relief and slope gradient (r^2= 37%).

The geometry and gradients of the TMFs show generally low gradient (<4°) (Fig. 4B). Antarctic TMFs on average typically show the lowest slope gradients (<1.5°). Slope geometries generally show concave profiles with gradients that decrease with distance down-slope.

Grain-size distribution of GDFs from TMFs and shelf diamictons in adjacent palaeo-ice stream troughs

The grain-size distributions in GDFs and shelf diamictons were analysed from 82 cores from Arctic and Antarctic TMFs and adjacent palaeo-ice stream troughs (Fig. 5). The results show that Arctic GDFs and shelf diamictons are characterised by generally finer grain-size composition compared to their Antarctic counterparts (Fig. 5C, D). Within the shelf diamictons and GDFs of the 39 sediment cores from the Antarctic margin (Fig. 5C; 15 cores from the slope; 24 cores from the outer shelf), the grain-size distribution is relatively constant and shows an average sand content of 43%, average silt content of 36% and average clay content of 21%. Antarctic diamictons were significantly coarser than those from the Arctic margins (Fig. 5D; 32 from the slope; 11 from the outer shelf). Within the 43 Arctic GDFs and shelf diamictons, the average sand content is 17%, average silt content is 43% and average clay content is 40% (Fig. 5). Average grain sizes for the analysed diamictons were generally coarser on the shelf compared to the slope for both the Arctic and the Antarctic. For the Antarctic diamictons, the average sand content varies from 47% on the shelf to 39% on the slope. For the Arctic diamictons, the average sand content is 18% on the shelf and 17% on the slope. Where gravel (>2 mm grain-size) data were available (Fig. 5B), GDFs/diamictons also show a coarser grain-size composition on the shelf in the Antarctic. The standard deviations for both Arctic and Antarctic GDFs/diamictons were less than the difference between the mean Arctic and Antarctic values. This indicates that the difference in grain-size composition between Arctic and Antarctic GDFs/diamictons are significant as these are greater than the variances within the datasets.

Discussion

Analysis of the grain-size distributions of GDFs and shelf diamictons recovered in 82 sediment cores from 15 TMFs and the adjacent palaeo-ice stream troughs show distinct differences between the Arctic and the Antarctic. Antarctic diamictons from both the shelf and the slope are significantly coarser grained (average sand content of 43%) than their counterparts from the Arctic margin (average sand content of 17%). The coarse fraction content in diamictons from the slope is lower than in diamictons from the shelf for both the Arctic and the Antarctic margin, although for the Arctic the difference is small (~1%).

These differences have important implications for the processes operating on the continental shelves and at the mouths of cross-shelf troughs and the factors controlling TMF sedimentation and evolution. In the following section we discuss three possibilities causing the differences between Arctic and Antarctic TMFs: (1) mechanisms for the enrichment of coarse-grained detritus in diamictons from the Antarctic shelf and slope; (2) mechanisms for the depletion of fine-grained material in diamictons from the Antarctic shelf and slope; and (3) mechanisms for the enrichment of fine-grained detritus in diamictons from the Arctic shelf and slope. Mechanisms that may have depleted coarse-grained detritus in Arctic diamictons cannot be identified.

Mechanisms causing the enrichment of coarse-grained detritus in Antarctic diamictons

The composition of bedrock on the shelf may influence the rate and volume of sediment eroded by over-riding ice and thus may influence the character of sediment transported to the slope (Solheim et al., 1998; O Cofaigh et al., 2004). This may also influence the observed difference in grain-size composition between Arctic and Antarctic margins. Till composition is largely influenced by the subglacial relief and the subglacial substrate, i.e. hinterland geology, initial sediment concentration and lithology, and physical properties of the subglacial debris, as well as the mode of glacial erosion, comminution and transport (Clark, 1987). The difference in source rock type between Arctic and Antarctic margins does not appear to influence grain-size distribution on the outer shelf and slope. For example, the diamicton composition in Belgica Trough is influenced by reworking and recycling of older sediments, as well as debris from different sedimentary and crystalline source areas in the West Antarctic hinterland (Hillenbrand et al., 2009). Diamictons from the western Barents Sea margin are also suggested to consist largely of eroded sedimentary substrate (e.g. Elverhøi et al., 1998), however display significantly finer grain-size distributions. Diamictons in Prydz Bay are sourced from crystaline and sedimentary rocks which vary depending on the source area (Forsberg et al., 2008) similar to diamictons recovered from Filchner Trough, adjacent to Crary Fan (Michels et al., 2002), resulting in a coarser grained composition compared to tills from mainly sedimentary source areas such as the Belgica Trough (Fig. 4a). The north east Greenland shelf has an igneous substrate (Escher & Pulvertaft, 1995), however the observed grain-size distributions of GDF/diamicts are fine-grained.

Subglacial sediment transport distances may also influence grain-size distribution on the outer shelf and slope due to erosion, subglacial deformation and comminution (Anderson et al., 1980; Domack et al., 1980; Menzies, 1996; Evans et al., 2006). On Antarctic margins, dispersal distances of a hundred to 100s of km are assumed based on trough length, topography and presence of subglacial bedforms (e.g. Ó Cofaigh et al. 2005; Hillenbrand et al., 2009). Trough length (or shelf width) can be used to infer transport distance, with studies suggesting that ice reached the shelf edge around many parts of the Arctic and Antarctic during the Quaternary (e.g. Denton & Hughes, 1981; Anderson, 1999; Cooper et al., 2008; The RAISED Consortium et al., 2014). For both Arctic and Antarctic margins, no significant variation in grain-size distribution with trough length was observed. Most troughs on Arctic margins show a fine-grained grain-size distribution, independent of trough length. Troughs of various lengths (e.g. Bear Island Trough, 700 km; Scoresby Sound Trough, 480 km, and Isfjorden Trough, 180 km) have similar average sand contents. In contrast, troughs of similar lengths on Arctic and Antarctic margins (e.g. Belgica Trough, 490 km; Scoresby Sund

Trough, 480 km) display significant differences in grain-size distribution suggesting that transport distance has little overall influence on grain-size distribution in shelf diamictons and GDFs.

Ice stream characteristics, such as the basal properties (warm-based or cold-based ice), palaeo-drainage basin size, roughness, till coverage and basal hydrological system may influence the volume, erosion and average grain size of detritus transported from the hinterland towards the outer shelf and shelf edge. We identify no significant relationship observed between palaeo-drainage basin size and grain-size distribution, with areas of significantly different drainage basin sizes (e.g. Bear Island Fan, 500000 km^2; Isfjorden, 14000 km^2) showing similar grain-size compositions along the Arctic margin. Antarctic palaeo-drainage basin sizes are generally larger (up to 1600000 km^2) than in the Arctic (<150 000 km^2), with the Bear Island Fan and the St Anna Fan being exceptions. Antarctica experienced a more extensive and prolonged glaciation, i.e. here ice streams eroded and reworked older sedimentary strata and bedrock substrate over tens of millions of years. It follows that greater erosion, reworking and comminition under prolonged glacial conditions, as can be expected for Antarctic margins, would result in a finer grain-size composition of the diamictons. However, coarser grained GDFs and tills are observed on Antarctic margins (Fig. 5), suggesting that palaeo-ice sheet drainage basin size (and trough length) has little influence on overall grain-size distribution.

The depth of the cross-shelf troughs at the shelf edge, with respect to the surrounding shelf, may give an indication of the amount of erosion the shelf has undergone over progressive glacial cycles where ice streams have formed in the same locations over several glacial cycles. Some of the relief, however, is likely to be due to aggradation of the adjacent banks during the Quaternary. With increased palaeo-drainage basin size, trough relief at the shelf edge increases, indicating the shelf has undergone prolonged erosion over time. However, under more unstable ice sheet configurations over repeated glacial cycles, flow switching may occur leading to erosion of a particular trough that is not that pronounced. There is a strong correlation between fan gradient and drainage basin size, and trough length and fan area increase with both of these parameters (Fig. 4). This indicates that a greater volume of sediment was transported toward the shelf edge under ice sheets with larger drainage basin sizes/longer troughs (or wider shelves), leading to a reduction of slope gradient. However, our results suggest that grain size was not significantly influenced by these factors. No correlation between trough relief at the shelf edge and grain-size composition is observed.

Mechanisms causing the depletion of fine-grained material in Antarctic diamictons

Winnowing by along-slope currents, or cascading flows of dense water formed during sea-ice formation through brine rejection, may influence grain-size composition on the shelf and slope of polar margins during glacial and interglacial periods. This may lead to erosion along some parts of the shelf and slope and deposition of mud in other areas. Strong bottom currents are observed on both Arctic and Antarctic margins (e.g. Camerlenghi et al., 1997; Heathershaw et al., 1998; Giorgetti et al., 2003; Foldvik et al., 2004; Ivanov & Shapiro, 2005; Bøe et al., 2009) with current velocities >0.06 m s^{-1} measured using current metres and inferred from modelling along both margins. These currents are able to erode and remove at least silt- and clay-sized particles from interglacial sediments (Young and Southard, 1978). Subglacial reworking of these interglacial sediments during subsequent glacial periods may have caused a coarser grain size of the tills deposited by the ice. However, strong bottom currents are only observed near the outer Antarctic shelf and slope (e.g. Melles et al., 1994; Hillenbrand et al., 2010) suggesting that a difference in the bottom current strength between Arctic and Antarctic margins cannot explain the grain-size differences observed between shelf diamictons. Cascading flows of cold, dense water are only known to influence the seafloor sediments in the outer Filchner Trough, on the Crary Fan, and episodically on the East Antarctic shelf (Harris et al., 2000) but not from regions surrounding the Belgica Fan, which displays similar grain-size distributions to the Crary Fan. This suggests that cascading flows of dense water do not have a significant influence on the grain-size differences observed between GDFs on Arctic and Antarctic margins.

Ice sheet drainage basin size presumably influences the abundance and volume of subglacial meltwater released from beneath an ice sheet. Meltwater may winnow fine-grained particles from shelf and slope sediments and initiate turbidity currents when released at the grounding line of an ice stream. In areas of greater meltwater, processes such as turbidity current activity would increase, which could increase the coarse fraction on the fan, depositing finer sediment further down-slope, although other processes such as slope by-pass or erosion may occur at times. Plumites, or finer material, may also be deposited by settling from meltwater and deposited close to the shelf edge (Lucchi et al., 2013). This would contribute fine-grained material to the TMF and that material may later be incorporated in GDFs. The volume and abundance of subglacial meltwater is largely controlled by strain heating and the geothermal heat flux beneath the ice sheet (Joughin et al., 2004; Pattyn, 2010). The volume of palaeo-meltwater discharge for individual ice streams is difficult to quantify although there are numerous examples of bedforms formed by subglacial meltwater erosion on the inner parts of Antarctic palaeo-ice stream troughs (Lowe & Anderson, 2003; Ó Cofaigh et al., 2005, Anderson & Oakes Fretwell, 2008; Graham et al., 2009). Studies of modern systems have shown that basal meltwater production is usually millimetres per year (e.g. Beem et al., 2010; Pattyn, 2010). Meltwater released from the generally larger Antarctic palaeo-ice sheets may have resulted in increased winnowing of fine-grained sediments, thus leading to coarser-grained deposits. However, this can explain neither the average coarse grain-size composition of an Antarctic GDF, which consists of an unsorted diamicton deposited as a cohesive unit, nor the coarse-grained composition of an Antarctic shelf diamicton. The latter could have inherited its coarser grain size only by the incorporation of meltwater-winnowed interglacial sediments into the subglacial till. Subglacial meltwater release at grounding lines on the modern Antarctic shelf, however, has been shown to result in sediment deposition rather than winnowing, with the resulting sediments being enriched in terrigenous silt (e.g. Hass et al. 2010).

Mechanisms causing the enrichment of fine-grained detritus in Arctic diamictons

The difference in the onset, duration and timing of glacial-interglacial cycles between the Arctic and Antarctic may have influenced the supply of fine-grained detritus to the margins in both regions, with the supply of such material being higher in the Arctic during interglacial or deglacial periods. The fine-grained fraction of interglacial sediments in both regions consists largely of ice rafted debris, volcanic ash particles, eolian dust, hemipelagic detritus and microfossils, with modern hemipelagic sediments commonly being characterised by <6% sand content (e.g. Laberg & Vorren, 1995; Laberg et al., 2000; Lucchi et al., 2013). A significant difference between the Antarctic and Arctic margins is the interglacial supply of fluvial detritus to the latter, which plays no role in the Antarctic. Interglacial hemipelagic sediments are more abundant, or were deposited over prolonged time periods, on Arctic margins due to the shorter duration of glaciations and more rapid deglaciations (Nielson et al., 2005). Deposition of biogenic matter, resulting in the sedimentation of foraminifera- and diatom-bearing muds and oozes, also plays a greater role for the interglacial sedimentation on Arctic margins due to more favourable conditions for primary production, although this would not have affected the GDFs, which have a negligible biogenic component (Marchal et al., 2000). Therefore, a prolonged interglacial period would enhance deposition of fine-grained material on Arctic margins. The higher amount of interglacial hemipelagic deposits probably also influenced the composition of the tills on the continental shelves that incorporated this material during subsequent glacial periods and supplied it to the slope as GDFs.

The difference in dust (<100 micron) input between Arctic and Antarctic margins may contribute to the increased input of fine-grained detritus to the former during interglacials, although determining the exact input is a major challenge (e.g. Albani et al., 2014). Estimated modern bulk dust fluxes are 0-3 mg/m^2/yr for Antarctica but ~10-2080 mg/m^2/yr for Arctic margins (Cambray et al., 1979; Steffensen, 1997; Zdanowicz et al., 1998; Albani et al., 2014). Particle size was found to decrease with distance down-wind, with sand-sized grains being deposited within 5 km from the dust source and silt-clay sized grains being deposited up to >100 km down-wind of the source (Atkins & Dunbar, 2009; Chewings et al., 2014). The potential local dust sources for Antarctica are significantly smaller compared to the Arctic, with the potential source areas covering only ~2% (4,800 km^2) of the Antarctic continent today (and likely being significantly smaller during glacial periods). However, ice core records document that dust is supplied to Antarctica also from distal sources, such as Australia and South America (Li et al., 2008), and that this supply from distal sources had increased during Late Quaternary glacial maxima by a factor of ≤25 (e.g. Lambert et al., 2008). Dust production along the Greenland, Norwegian and Barents Sea margins was likely higher during both interglacials and glacials due to smaller ice sheets and shorter glaciations that resulted in larger land areas being exposed to erosion by wind, which would have caused a higher supply of fine grained dust input to the margins.

The difference in fluvial input to the Arctic and Antarctic margins is likely to be a dominant factor controlling the composition of glacial diamictons and GDFs on both margins. This is reflected by the total suspended matter flux, which is estimated to be 227×10^6 t/year (1% of the global flux) in the Arctic Ocean (Gordeev, 2006) whereas it is probably far less in the Antarctic due to the extensive ice cover. Fjords (e.g. observed along coastal Norway, Greenland and Svalbard), however, may limit the transport of sediment to the shelf by acting as efficient sediment traps during interglacials. In contrast to the Arctic, land surface is seldom exposed in Antarctica and fluvial transport to the Antarctic margin is negligible even during interglacial periods. Thus, surface run-off and river discharge are the most likely explanation for the fine-grained shelf diamictons and slope GDFs characterising the Arctic margins.

Conclusions

Analysis of the grain-size composition of GDFs and shelf diamictons from 82 sediment cores recovered from Arctic and Antarctic TMFs and outer shelf parts of adjacent palaeo-ice stream troughs revealed a distinct coarser-grained composition for the Antarctic margin. A significant difference in grain-size composition is observed between diamictons recovered on the Arctic and Antarctic outer-shelves, indicating that the origin of the differences in grain-size distribution lies on the shelf. Palaeo-environmental conditions, such as palaeo-ice sheet drainage basin size, subglacial sediment transport distance and size of the palaeo-ice sheets, do not appear to influence grain-size distribution of the shelf diamictons and GDFs. Similarly, the hinterland geology does not influence the grain-size compositions of the TMFs on the continental slopes. The significant difference between the Arctic and Antarctic margins is attributed to the differences in environmental conditions between the two regions during interglacial periods. The duration of interglacial periods is recognized to control the supply of fine-grained detritus to the margins. The volume and composition of interglacial sediments has the greatest influence on the grain-size composition of the glacial sediments. Input of fluvial detritus, greater dust production and supply resulting from greater land exposure in combination with enhanced surface weathering, and prolonged high biological productivity in response to longer interglacial conditions, are responsible for a higher accumulation of fine-grained sediment on Northern hemisphere shelves during interglacials. This fine-grained sediment is eroded and reworked into tills by grounded ice advancing to the shelf edge during subsequent glacial periods. The till is then redeposited downslope as GDFs to form TMFs. We suggest that the observed difference in grain-size composition between Antarctic and Arctic shelf diamictons and GDFs originates from the fundamental difference in the composition of shelf sediments deposited during interglacials.

Acknowledgements

We thank Kelly Hogan and Denise Rüther for their advice and comments during the review process.

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Table 1. *Physiography of high-latitude trough mouth fans used in analysis*

Location	Area (km^2)	Slope	Trough length (km)	Trough relief at shelf edge (m)	Palaeo-ice stream drainage basin area (km^2)	Reference
Belgica Fan, Antarctica	22,000	1–2	490[1]	>250	217,000–256,000	Dowdeswell et al. (2008); Livingstone et al. (2012)
Crary Fan, Antarctica	34,300*	1	≤460	340	1,454,878	Kuvaas & Kristoffersen (1991); Melles & Kuhn (1993); Melles et al. (1994); Livingstone et al. (2012); Ó Cofaigh et al. (2003)
Prydz Channel Fan, Antarctica	9,200	0.6	220–350	>300	1,600,000	O'Brien (1994); Livingstone et al. (2012); Jamieson et al. (2005)
Vilkitsky-Khatanga	28,000	1.42	350	250	100,000	Kleiber et al. 2001; Batchelor et al. (2014)
Voronin	20,800*	1.55	450	240	130,000	Vågnes (1996); Batchelor et al. (2014)
St. Anna	48,200*	1.15	600	>440	300,000	Vågnes (1996); Batchelor et al. (2014)
Franz Victoria	21,000*	2.20	300	>420	170,000	Kleiber et al. (2000); Batchelor et al. (2014)
Kongsfjorden	2700	2.29	90	120	8000	Landvik et al. (2005); Batchelor et al. (2014)
Isfjorden	3700	3.60	180	135	14,000	Svendsen et al. (1992); Batchelor et al. (2014)
Belisund	3300	2.98	160	40	8000	Ottesen et al. (2007); Batchelor et al. (2014)
Storfjorden	11,200	1.68	250	140	60,000	Vorren et al. (1998); Batchelor et al. (2014)
Kveithola	2,600*	2.30	90	110	10,000	Rebesco et al. (2011); Batchelor et al. (2014)
Bear Island	215,000	0.74	700	>300	576,000	Vogt et al. (1993); Batchelor et al. (2014); Elverhoi et al. (1998)
North Sea Fan	142,000	0.5	800	300	x	King et al. (1996; 1998); Batchelor et al. (2014); Nygard et al. (2005)
Scoresby Sund	17,800	2.11	480	300	60,000	Mienert et al. (1992); Batchelor et al. (2014)

*Estimated from IBCSO and IBCAO dataset..

Table 2. *Cores used in sediment analysis*

Core	Location	Water depth (m)	Latitude	Longitude	Sample depth (cm)	Facies interpretation of sediments
GC357[a]	Belgica shelf	565.0	-71.7667	-80.11	30-110	Hillenbrand et al. (2010)
GC359[a]	Belgica shelf	685	-71.7183	-76.0383	70-160	Hillenbrand et al. (2010)
GC360[a]	Belgica shelf	633	-71.995	-76.5517	40-170	Hillenbrand et al. (2010)
GC362[a]	Belgica	845	-72.9833	-83.4433	140-190	Hillenbrand et al. (2010)

	shelf					
GC365[a]	Belgica shelf	1011	-72.5967	-80.83	35-150	Hillenbrand et al. (2010)
GC366[a]	Belgica shelf	617	-72.845	-82.615	34-140	Hillenbrand et al. (2010)
GC368[a]	Belgica shelf	588	-71.5783	-82.86	40-80	Hillenbrand et al. (2010)
GC370[a]	Belgica shelf	533	-71.65	-84.805	50-190	Hillenbrand et al. (2010)
GC371[a]	Belgica shelf	595	-70.6533	-84.54	30-190	Hillenbrand et al. (2010)
GC372[a]	Belgica shelf	676	-70.605	-86.2533	30-200	Hillenbrand et al. (2010)
GC374[a]	Belgica shelf	650	-70.5	-86.2367	35-195	Hillenbrand et al. (2010)
PS2533-1[a]	Belgica TMF slope	594	-71.02333	-85.89833	45-195	Hillenbrand et al. (2009)
PS2543-1[a]	Belgica TMF slope	547	-70.94666	-89.34333	50-170	Hillenbrand et al. (2009)
PS2538-2[a]	Belgica TMF slope	3238	-69.73	-88.921667	65-420	Hillenbrand et al. (2009)
PS2540-1[a]	Belgica TMF slope	1822	-70.063333	-87.931667	35-414	Hillenbrand et al. (2009)
GC352[a]	Belgica TMF slope	718	-70.2567	-86.365	30-150	Hillenbrand et al. (2009)
GC353[a]	Belgica TMF slope	1041	-70.086667	-86.188333	44-290	This study
GC354[a]	Belgica TMF slope	788	-70.005	-84.89	30-197	This study
GC375[a]	Belgica TMF slope	877	-70.271667	-86.825	19-75	This study
GC376[a]	Belgica TMF slope	1016	-70.221667	-86.905	49-260	This study
GC377[a]	Belgica TMF slope	1608	-69.956667	-86.881667	60-326	This study
GC378[a]	Belgica TMF slope	2182	-69.7667	-87.3617	51-220	This study
GC381[a]	Belgica TMF slope	1953	-69.7217	-83.6983	38-105	This study
PS1494-2/3[a]	Crary TMF slope	1942	-74.18183	-35.5005	50-340	Melles (1991)
PS1607-1/3[a]	Crary TMF slope	1610	-74.106333	-33.648833	211-367	Melles (1991)
PS1606-1/3[a]	Crary TMF slope	2933	-73.50216	-34.0335	108-426	Melles (1991)
PS1612-1/2[a]	Crary TMF slope	815	-74.404667	-37.022333	49-213	Melles (1991)
PS1016-1[a]	Weddell outer shelf	701	-77.284798	-40.832699	23-40	Melles (1987)
PS1017-1[a]	Weddell outer shelf	874	-77.284798	-39.145	25-202	Melles (1987)
PS1018-	Weddell	1165	-77.589	-37.921	100-165	Melles (1987)

1[a]	outer shelf					
PS1019-1[a]	Weddell outer shelf	1095	-77.427	-37.876	21-172	Melles (1987)
PS1216-1[a]	Weddell outer shelf	1091	-77.69	-37.065	34-36	Melles (1987)
PS1222-1[a]	Weddell outer shelf	685	-75.8583	-34.3133	17-54	Melles (1987)
PS1223-1[a]	Weddell outer shelf	772	-75.9832	-34.3133	31-52	Melles (1987)
PS1277-1[a]	Weddell outer shelf	415	-77.53	-43.661701	11-22	Melles (1987)
PS1278-1[a]	Weddell outer shelf	635	-77.540001	-42.126701	19-47	Melles (1987)
PS1279-1[a]	Weddell outer shelf	729	-77.3133	-40.1367	34-35	Melles (1987)
PS1400-1/4[a]	Weddell outer shelf	1058	-77.551	-36.403	60-306	Melles (1987)
PS1401-1/2[a]	Weddell outer shelf	689	-77.6	-35.9	44-60	Melles (1987)
ODP Site 1167[a]	Prydz TMF slope	1640	-66.400167	72.284167	80-440	Passchier et al. (2003)
92-T-2/1[b]	Bear Island Fan (slope)	905	73.638611	14.901667	65-205	Laberg & Vorren (1995)
92-T-1/1[b]	Bear Island Fan (slope)	1503	73.798333	13.927778	90-275	Laberg & Vorren (1995)
JM93-7/1[b]	Bear Island Fan (slope)	2090	74.147222	12.108333	45-290	Laberg & Vorren (1995)
JM93-6/1[b]	Bear Island Fan (slope)	2364	74.469444	10.7	90-290	Laberg & Vorren (1995)
7317/10-U-01[b]	Bear Island (shelf)	465	73.149583	17.270278	0-150	Sættem et al. (1992)
7316/06-U-01[b]	Bear Island (shelf)	428	73.554583	16.833222	0-30	Sættem et al. (1992)
7316/06-U-02[b]	Bear Island (shelf)	421	73.568806	16.833583	0-65	Sættem et al. (1992)
7317/02-U-01[b]	Bear Island(shelf)	297	73.8197	17.367925	0-45	Sættem et al. (1992)
88-01[b]	Isfjorden (inner shelf)	270	78.035556	12.984167	200-470	Svendsen et al. (1992)
88-04[b]	Isfjorden (inner shelf)	232	78.016667	11.665	120-250	Svendsen et al. (1992)
NP90-19/PC(1)[b]	Bear Island Fan (Isfjorden slope)	1427	78.236111	8.804722	20-850	Elverhøi et al. (1997)
JM95-2/1[b]	Andøya Canyon (slope)	1975	69.583333	15.5	450-472	Laberg et al. (2000)
JM99-583[b]	Kongsfjorden Trough, NW' Svalbard (shelf)	308	78.721667	9.354333	0-95	Landvik et al. (2005)

JM99-591 [b]	Kongsfjorden Trough, NW' Svalbard (shelf)	239	78.9765	9.864833	65-105	Landvik et al. (2005)
49-23 [b]	Storegga Slide (slope)	2842	64.69	1.636	30-60	Jansen et al. (1987)
49-24 [b]	Storegga Slide (slope)	2876	64.799833	1.773833	210-340	Jansen et al. (1987)
49-29 [b]	Storegga Slide (slope)	2758	64.658667	2.351	30-90	Jansen et al. (1987)
49-30 [b]	Storegga Slide (slope)	2372	64.536667	3.0585	55-220	Jansen et al. (1987)
49-31 [b]	Storegga Slide (slope)	2100	64.449833	3.685333	60-250	Jansen et al. (1987)
49-36 [b]	Storegga Slide (slope)	1581	63.922833	3.4845	70-130	Jansen et al. (1987)
49-38 [b]	Storegga Slide (slope)	1245	63.594167	3.042167	0-70	Jansen et al. (1987)
JM96-47/1 [b]	Trænadjupet Slide (slope)	945	67.333333	8.509	20-127	Laberg et al. (2002)
JM96-52/1 [b]	Trænadjupet Slide (slope)	649	67.295	8.703333	10-177	Laberg et al. (2002)
83-03 [b]	North Sea Fan (slope)	1615	62.926667	-0.8	268-290	King et al. (1998)
79-08 [b]	North Sea Fan (slope)	1327	62.873333	-0.03	225-270	King et al. (1998)
101-06 [b]	North Sea Fan (slope)	1006	62.746667	0.83	230-300	King et al. (1998)
79-20 [b]	North Sea Fan (slope)	2819	64.661667	-0.706667	90-250	King et al. (1998)
83-06 [b]	North Sea Fan (slope)	3002	64.28	-2.68	70-305	King et al. (1998)
31-38 [b]	North Sea Fan (slope)	1880	63.416667	0.383333	-	King et al. (1998)
31-41 [b]	North Sea Fan (slope)	810	62.616667	1.216667	-	King et al. (1998)
31-39 [b]	North Sea Fan (slope)	1309	63.033333	0.743333	190-520	Jansen et al. (1983); King et al. (1998)
31-37 [b]	North Sea Fan (slope)	2285	63.778333	0.0	50-510	Jansen et al. (1983); King et al. (1998)
ODP Site 987 [b]	Scoresby Sund TMF (slope)	1670	70.4966	-17.937383	560-660	Butt et al. (2001)
SV-03 [b]	Storfjorden fan	761	75.222533	14.620817	550-560	Lucchi et al. (2013)
EG-01 [b]	Storfjorden fan	1069	76.10335	13.627083	50-100	Lucchi et al. (2013)
SV-02 [b]	Storfjorden fan	743	75.22845	14.59933	400-640	Lucchi et al. (2013)

SV-05 [b]	Storfjorden fan	713	75.111716	15.221783	310-470	Lucchi et al. (2013)
SV-04 [b]	Kveithola / Storfjoden fan	1839	74.957083	13.899533	260-280	Lucchi et al. (2013)
JM09-KA11-GC [b]	Kveithola (shelf)	345	74.874667	16.484667	100-370	Ruther et al. (2012)
PS2118-2 [b]	Kongsfjorden fan	1306	79.0265	6.6165	0-630	Müller et al. (2004)
PS2121-4[b]	Kongsfjorden trough (shelf)	339	79.0265	10.74933	0-620	Müller et al. (2004)
PS2782-1[b]	Vilkitsky-Khatanga fan (shelf)	340	79.610000	103.355000	420-520	Weiel (1997)

[a]Directly measured grain size data; [b]Approximate grain size data estimated from literature.

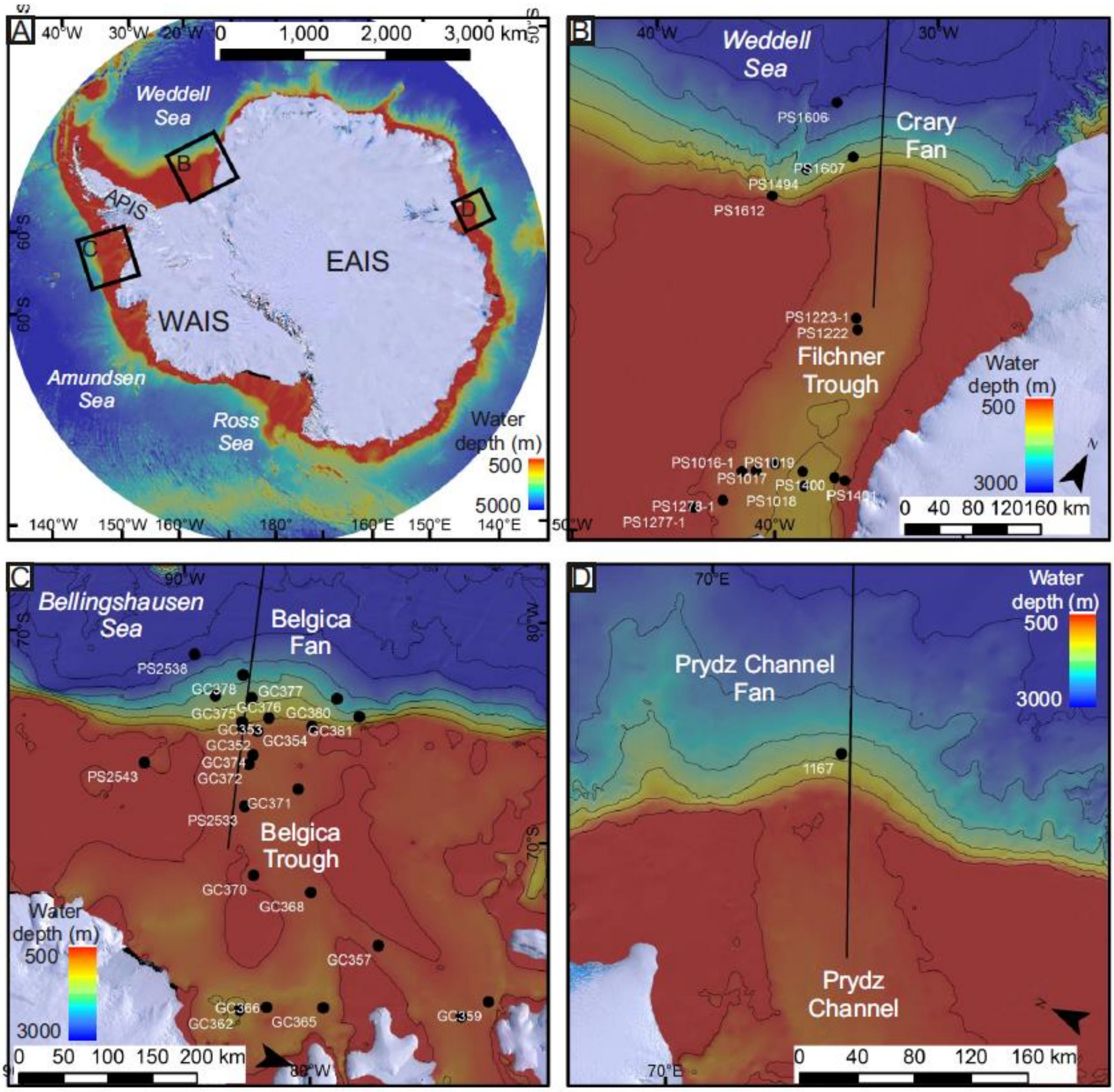
Fig. 1. (**a**) Location of Antarctic Trough Mouth Fans. Bathymetry is IBCSO v.1 Satellite data is LIDAR. (**b**) Crary Trough Mouth Fan at mouth of the Filchner Trough, Weddell Sea. (**c**) Belgica Fan at mouth of the Belgica Trough, Bellingshausen Sea. (**d**) Prydz Channel Fan at mouth of the Prydz Channel. Multibeam is IBCSO v.1 Black dots are core locations used in this paper. Black lines are long-profiles shown in Fig. 3B.

Fig. 2. (**a**) Location of Arctic Trough Mouth Fans used in analysis. (**b**)Vilkitsky-Khatanga fan; (**c**) Voronin fan. (**d**) St Anna fan. (e) Franz Victoria Fan. (**f**) Kongsfjorden Fan. (**g**) Isfjorden Fan. (**h**) Bellsund. (**i**) Scoresby Sund Fan. (**j**) Bear Island Fan. Bathymetry is IBCAO v. Bathymetry is IBCAO v.3 Black dots are sediment core locations used in this paper. Black lines are long-profiles shown in Fig. 4B.

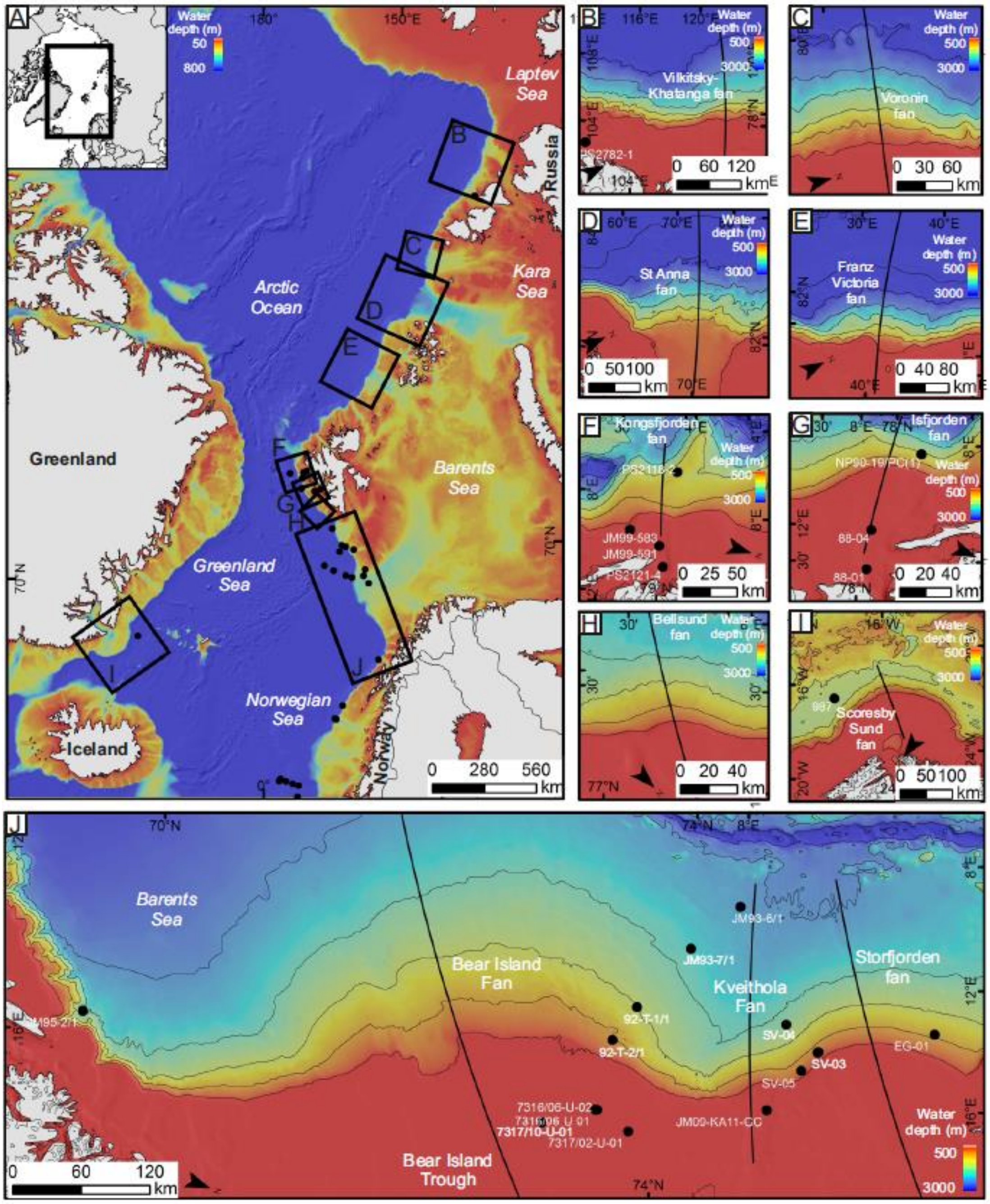
Fig. 3. (**a**). Example for the homogenous grain-size distribution within diamictons interpreted as glaciogenic debris flows (GDFs) recovered from trough-mouth fans (TMFs) on polar continental margins. Core GC376 was recovered from Belgica TMF (West Antarctica), and its GDF reveals hardly any variations in the contents of gravel, sand, silt and clay (silt +clay = mud) and of sand, silt and clay (or mud), respectively, if the contents of the individual grain-size fractions are calculated on a gravel-free basis. (**b**) Example for the estimation of published gravel, sand, silt and clay contents in diamictons interpreted as GDFs, for which the data were not available for this study in numerical form. We assume an uncertainty of ≤3 wt.% for the estimated contents of the individual grain-size fractions (estimated contents here: 4 wt.% gravel, 16 wt.% sand, 40 wt.% silt and 40 wt.% clay). Core JM93 7/1 was recovered from Bear Island TMF (Fig. 14b in Laberg & Vorren, 1995).

Fig. 4. (**a**). Arctic and Antarctic Trough Mouth Fan parameters including slope gradient, fan area, trough length and paleo-ice stream drainage basin area and regression lines. Antarctic TMF in blue; Arctic TMF in red. (**b**) Down-slope profiles for Arctic (dashed black) and Antarctic (blue) TMF from IBSCO and IBCAO bathymetric data (located in Figures 1 and 2).

Fig. 5. Grain-size composition of sediment cores collected in diamictons on the shelf and Glacial Debris Flows (GDFs) on the slope of trough mouth fans and surrounding areas. (**a**) Arctic vs Antarctic grain-size composition (sand-silt-clay%). (**b**) Arctic vs Antarctic grain-size composition (gravel-sand-mud%). (**c**) Antarctic grain-size composition (sand-silt-clay%). (**d**) Arctic grain-size composition (sand-silt-clay%).

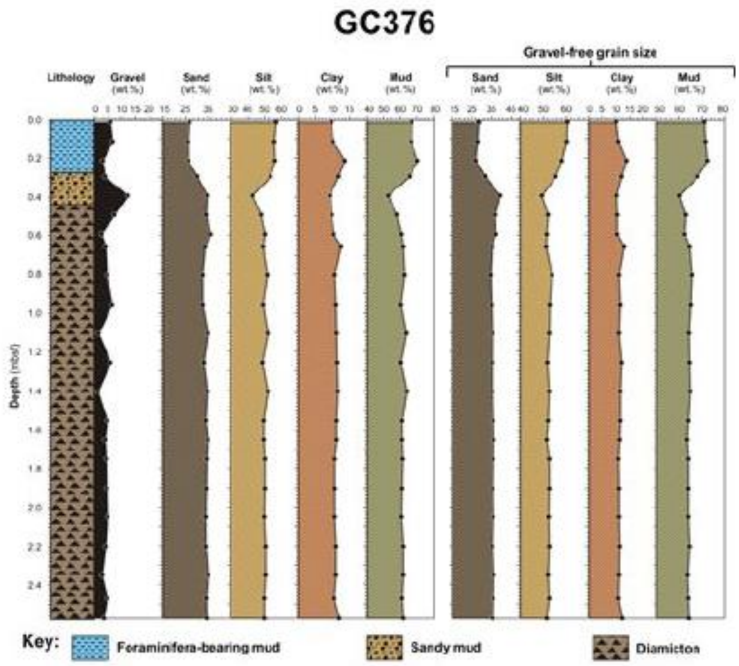

A
Weddell Sea
APIS
EAIS
WAIS
Amundsen Sea
Ross Sea
Water depth (m)
500
5000
0 1,000 2,000 3,000 km
B
Weddell Sea
Crary Fan
PS1606
PS1607
PS1494
PS1612
PS1223-1
PS1222
Filchner Trough
PS1016-1
PS1019
PS1017
PS1400
PS1018
PS1278-1
PS1277-1
Water depth (m)
500
3000
0 40 80 120160 km
C
Bellingshausen Sea
Belgica Fan
PS2538
GC378
GC377
GC375
GC376
GC380
GC353
GC381
GC352
GC354
GC374
PS2543
GC372
GC371
PS2533
Belgica Trough
GC370
GC368
GC357
GC366
GC362
GC365
Water depth (m)
500
3000
0 50 100 150 200 km
D
Prydz Channel Fan
1167
Prydz Channel
Water depth (m)
500
3000
0 40 80 120 160 km

878

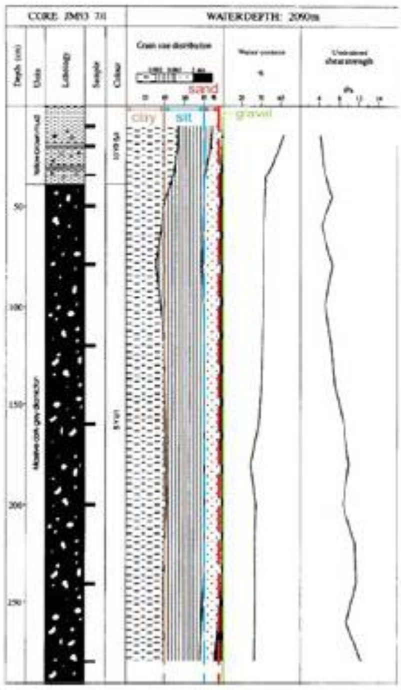

A
Water depth (m)
Laptev Sea
Russia
Kara Sea
Arctic Ocean
Greenland
Barents Sea
Greenland Sea
Norwegian Sea
Iceland
Norway
0 280 560 km
B
Vilkitsky-Khatanga fan
PS2782-1
0 60 120 km
C
Voronin fan
0 30 60 km
D
St Anna fan
0 50 100 km
E
Franz Victoria fan
0 40 80 km
F
Kongsfjorden fan
PS2118-2
JM99-583
JM99-591
PS2121-4
0 25 50 km
G
Isfjorden fan
NP90-19/PC(1)
88-04
88-01
0 20 40 km
H
Bellsund fan
0 20 40 km
I
Scoresby Sund fan
0 50 100 km
J
Barents Sea
Bear Island Fan
Kveitehola Fan
Storfjorden fan
JM93-6/1
JM93-7/1
92-T-1/1
92-T-2/1
SV-04
SV-03
SV-05
EG-01
JM95-2/1
JM09-KA11-GC
7316/06-U-02
7316/06-U-01
7317/10-U-01
7317/02-U-01
Bear Island Trough
Water depth (m)
500
3000
0 60 120 km

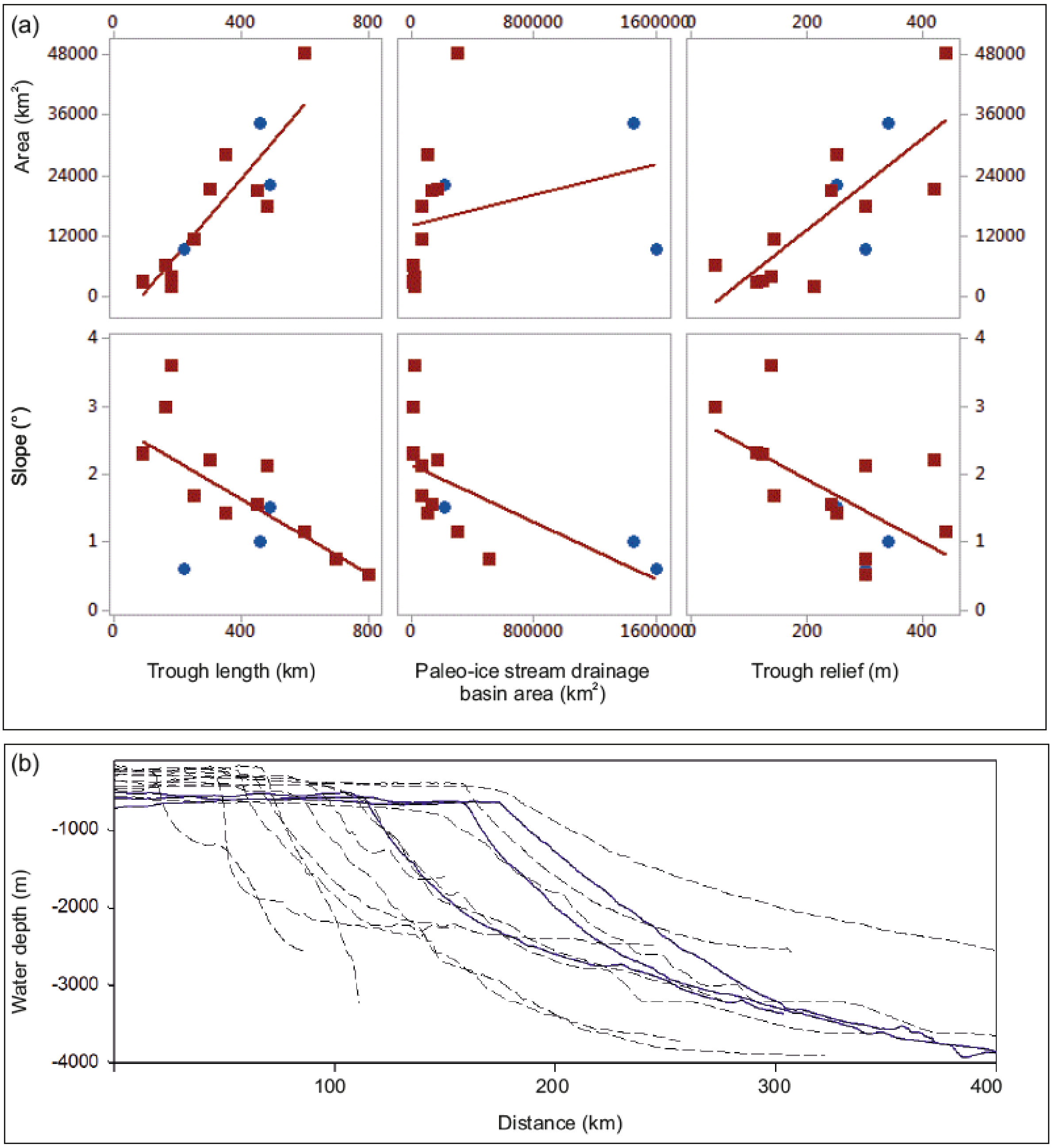
879

a)

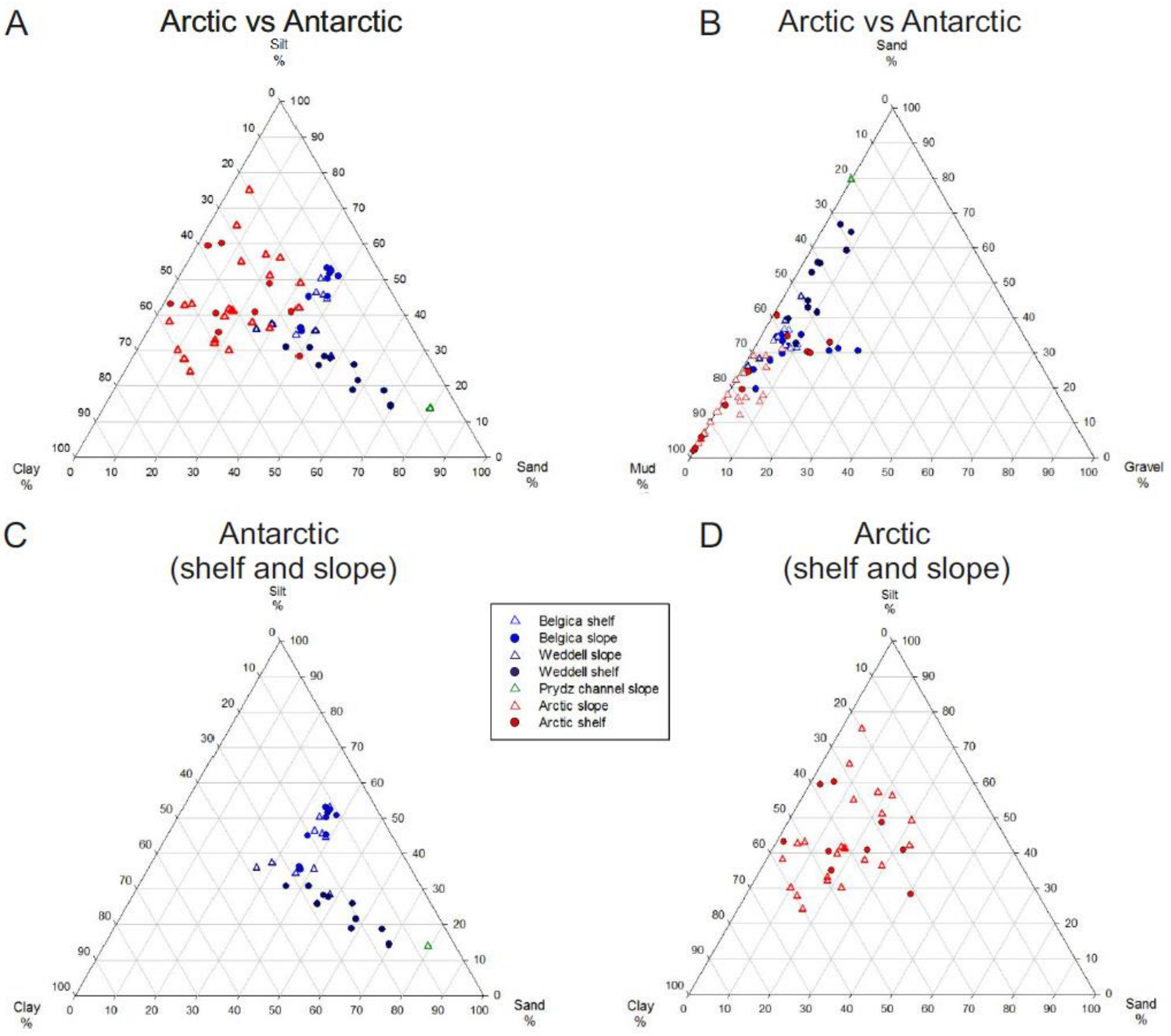

GC376
Gravel-free grain size
Lithology
Gravel (wt.%)
Sand (wt.%)
Silt (wt.%)
Clay (wt.%)
Mud (wt.%)
Depth (mbsf)
Key:
Foraminifera-bearing mud
Sandy mud
Diamicton

b)


WATERDEPTH: 2090m
clay
silt
sand
gravel


(a)
Area (km²)
Slope (°)
Trough length (km)
Paleo-ice stream drainage basin area (km²)
Trough relief (m)
(b)
Water depth (m)
Distance (km)

881


A
Arctic vs Antarctic
Silt %
Clay %
Sand %
B
Arctic vs Antarctic
Sand %
Mud %
Gravel %
C
Antarctic
(shelf and slope)
Silt %
Clay %
Sand %
D
Arctic
(shelf and slope)
Silt %
Clay %
Sand %
Belgica shelf
Belgica slope
Weddell slope
Weddell shelf
Prydz channel slope
Arctic slope
Arctic shelf