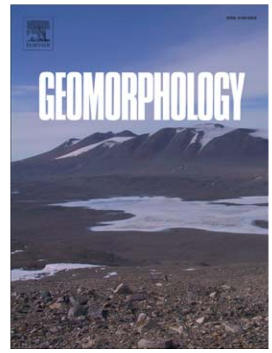

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Arctic and Antarctic submarine gullies – a comparison of high latitude continental margins

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Abstract

Submarine gullies are common features of high latitude continental slopes and, over the last decade, have been shown to play a key role in continental margin evolution, submarine erosion, downslope sediment transport, slope deposits, and the architecture of petroleum reservoirs. However, the processes that form these gullies, the timescales over which they develop, and the environmental controls influencing their morphology remain poorly constrained. We present the first systematic and comparative analysis between Arctic and Antarctic gullies with the aim of identifying differences in slope character, from which we infer differences in processes operating in these environments.

Quantitative analysis of multibeam echosounder data along 2469 km of the continental shelf and upper slope and morphometric signatures of over 1450 gullies show that six geomorphically distinct gully types exist on high latitude continental margins. We identify distinct differences between Arctic and Antarctic gully morphologies. In the Arctic data sets, deep relief (> 30 m gully incision depth at 50 m below the shelf edge) and shelf-incising gullies are lacking. These differences have implications for the timescales over which the gullies were formed and for the magnitude of the flows that formed them. We consider two hypotheses for these differences: (1) some Antarctic gullies developed through several glacial cycles; and (2) larger Antarctic gullies were formed since the Last Glacial Maximum as a result of erosive flows (i.e., sediment-laden subglacial meltwater) being more abundant on parts of the Antarctic margin over longer timescales.

A second difference is that unique gully signatures are observed on Arctic and on Antarctic margins. Environmental controls, such as the oceanographic regime and geotechnical differences, may lead to particular styles of gully erosion observed on Arctic and Antarctic margins.

Keywords: geomorphology; submarine gully; continental margin; sedimentary processes; Antarctic; Arctic

1. Introduction

Submarine gullies are small-scale, confined channels in the order of tens of meters deep and form one of the most common morphological features of high latitude continental slopes. Gullies also occur on mid- and low latitude margins and on hillslopes in the terrestrial environment (e.g., Hartmann et al., 2003; Micallef and Mountjoy, 2011; Vachtman et al., 2012; Lonergan et al., 2013). Different gully types are recognised on Arctic and Antarctic continental margins (Fig. 1) (Vorren et al., 1989; Laberg and Vorren, 1995; Laberg et al., 2007; Noormets et al., 2009; Pedrosa et al., 2011; Gales et al., 2013), but a distinct lack of knowledge remains about their formation processes and differences that exist between these regions. In Antarctica, gullies vary in length, width, incision depth, branching order, sinuosity, shelf-incision, cross-sectional shape, and mean gully spacing, with gully morphology influenced by environmental controls such as local slope character (i.e., slope gradient, geometry), large-scale spatial characteristics (i.e., drainage basin size, location of cross-shelf troughs, regional heat flow), ice sheet history and sediment yield (Gales et al., 2013). For Arctic gullies, no systematic studies have to our knowledge been undertaken. By quantitatively examining Arctic and Antarctic gully morphology, we aim to identify variations in slope character that suggest differences in processes operating in these environments, factors influencing slope instability, and the timescales over which these features evolved.

Although small-scale variations in high latitude slope morphology remain largely unknown, studies examining the large-scale morphology show important differences (Dowdeswell et al., 1998; Ó Cofaigh et al., 2003; Nielsen et al., 2005). One striking difference between some Arctic and Antarctic continental margins is a distinct lack of modern large-scale features of slope instability (i.e., submarine slides) on the latter (Barker et al., 1998; Dowdeswell and Ó Cofaigh., 2002; Nielsen et al., 2005). Large-scale submarine slides are known to have occurred in the geological past (i.e., Miocene, early Pliocene) on the Antarctic margin, but modern examples are few (Barker and Austin., 1998; Imbo et al., 2003; Diviacco et al., 2006). In contrast, slides are abundant on northern high latitude slopes (Damuth, 1978; Bugge et al., 1988; Laberg and Vorren, 1993, 2000; Dowdeswell et al., 1996; Vorren et al., 1998; Laberg et al., 2000; Evans et al., 2005; Nielsen et al., 2005). These differences have been attributed to variations in (i) the underlying geology, such as the presence of weak contouritic/hemipelagic layers present on many Arctic continental margins that are mainly controlled by the ocean circulation (Long et al., 2003; Nielsen et al., 2005; Laberg and Camerlenghi, 2008); (ii) pore pressure, with Antarctic slopes displaying a greater stability owing to ice sheet compaction (Prior and Coleman, 1984; Larter and Barker, 1991); (iii) episodic and high quantities of sediment delivered to the shelf edge (Dowdeswell and Ó Cofaigh, 2002); and (iv) the timing of particular stages of glaciation (Nielsen et al., 2005).

Currently, there is a distinct lack of knowledge of the causes behind different gully morphologies observed on high latitude continental slopes. One potential gully-forming mechanism is erosion by hyperpycnal flows initiated as a result of discharges of sediment-laden subglacial meltwater (Wellner et al., 2001, 2006; Lowe and Anderson, 2002; Ó Cofaigh et al., 2003; Dowdeswell et al., 2004, 2006; Heroy and Anderson, 2005; Noormets et al., 2009). Studies of freshwater discharge (such as rivers, jökulhaups, and lahars) and laboratory experiments show that a critical sediment concentration of 1-5 kg m^{-3} is needed to initiate a hyperpycnal flow (taking into account fine-scale convective instability) (Parsons et al., 2001; Mulder et al., 2003). If enough sediment is entrained into subglacial meltwater released from beneath an ice sheet, and a critical sediment concentration is reached, then sediment-laden subglacial meltwater may initiate a hyperpycnal flow with the potential to erode the seafloor. Extensive relict subglacial meltwater channels are present on the Antarctic inner shelf, including the Marguerite and Pine Island troughs (Lowe and Anderson, 2002; Domack et al., 2006; Anderson and Oakes-Fretwell, 2008; Graham et al., 2009; Nitsche et al., 2013), potentially the outer shelf at the Belgica trough (Noormets et al., 2009), and the inner shelf of the NW Barents Sea (Hogan et al., 2010). Studies of modern ice sheets, however, show that basal meltwater generated is in the range of millimetres per year (e.g., Beem et al., 2010; Pattyn, 2010), with larger discharges suggested to result from processes such as subglacial lake outbursts or subglacial volcanic activity (Goodwin, 1988; Wellner et al., 2001; Dowdeswell et al., 2006; Fricker et al., 2007; Bell, 2008; Nitsche et al., 2013).

Other potential gully-forming mechanisms include erosion from mass flows initiated by factors such as gas hydrate dissociation, tidal pumping beneath ice sheets, shelf and contour currents, iceberg scouring, and large accumulations of glacigenic debris deposited at, or near to, the shelf edge during glacial maxima (Larter and Cunningham, 1993; Vanneste and Larter, 1995; Shipp et al., 1999; Dowdeswell et al., 2006; Dowdeswell and Bamber, 2007). Gullies may develop by aggradation between gully thalwegs (Field et al., 1999; Chiocci and Casalbore, 2011), with deposits forming from avulsing turbidity currents or levees of debris flows arising from their nonlinear rheology. Fine sediment, such as silt and clays may be deposited during low shear stress conditions, but may become eroded (resuspended) along gully thalwegs during the passage of the flows. Evidence from subbottom acoustic data from the Antarctic margin, however, shows that in most cases gullies form in poorly stratified or acoustically impenetrable layers, contrasting good subbottom penetration that is expected on the gully interfluves formed by the aggradation (Gales et al., 2012). Gullies are suggested to be the first features to form on steeply dipping slopes in relation to mass wasting (Laberg et al., 2007), similar to terrestrial settings where gullies are known to represent the first step in the fluvial dissection of landscapes (Bloom, 1991).

The cascading of dense bottom water produced through sea-ice freezing and brine rejection may influence seafloor morphology (Vorren et al., 1988). However, recent studies find that in an area of active dense water overflow in the southern Weddell Sea, Antarctica, deeply incised gullies are absent. This suggests that this mechanism does not form the deeply incised and V-shaped gullies observed over much of the Antarctic continental margin (Gales et al., 2012).

By examining similarities and differences between high latitude gully morphologies, we aim to better understand what predisposes some slopes to particular styles of erosion, while other slopes appear relatively stable. We find that the variation in high latitude gully morphology has important implications for slope processes operating in these environments: the timing and rate of deglaciation and factors influencing slope stability.

2. Study areas

The study includes data along 1919 km of the Antarctic continental shelf and upper slope (Fig. 2), including data from the western Antarctic Peninsula, Bellingshausen, Amundsen and Weddell seas and 550 km of Arctic data from western Svalbard, the southwest Barents Sea, and the northern Norwegian continental margins (Fig. 3). The tectonic history and geology of both regions have been extensively studied (e.g., Kenyon, 1987; Hübscher et al., 1996; Livermore and Hunter, 1996; Eagles et al., 2004, 2009; Evans et al., 2005; Stoker et al., 2005; Faleide et al., 2008). The uppermost beds comprise predominantly Quaternary sediment that is glacially derived or glacially influenced (i.e., glacigenic debris flows, glacigenic muds, and ice rafted debris) (e.g., Bonn et al., 1994; Vorren and Laberg, 1997;

Vorren et al., 1998; Dahlgren et al., 2002, 2005; Dowdeswell et al., 2004, 2006; Hillenbrand et al., 2005; Cooper et al., 2008; Laberg et al., 2010). One key difference is the greater prevalence of thin hemipelagic/contouritic sediments on parts of the Arctic continental slope, which form weak interglacial layers interbedded between the glacigenic sediments (Laberg and Vorren, 1995, 2000; Laberg and Camerlenghi, 2008). Although large mounds, interpreted as sediment drifts produced by bottom currents, occur on some areas of the Antarctic continental rise (Rebesco et al., 1996, 2007; Weber et al., 2011), little evidence exists for weak geological layers on the Antarctic upper slope (Nielsen et al., 2005).

Ice has covered much of Antarctica for the last 34 Ma (Barrett, 2008), advancing across the continental shelf from the early Oligocene in east Antarctica and from the late Miocene on the west Antarctic margin (Nitsche et al., 1997). During the Last Glacial Maximum (LGM), the maximum extents of ice have been placed at, or near to, the shelf edge in areas off the western Antarctic Peninsula (Pudsey et al., 1994; Vanneste and Larter, 1995; Heroy and Anderson, 2005), Bellingshausen Sea (Ó Cofaigh et al., 2005; Hillenbrand et al., 2010b), Amundsen Sea (Lowe and Anderson, 2002; Evans et al., 2006; Graham et al., 2010), and the Weddell Sea, although this remains disputed (Hillenbrand et al., 2012; Larter et al., 2012). In the Arctic, the onset of glaciation occurred during the middle to late Miocene, with glacial-interglacial cycles along the Norwegian margin commencing from around 2.6 Ma (Thiede et al., 1998). The most extensive northern hemisphere ice sheets are suggested to have developed around 600-700 ka (Berger and Jansen, 1994; Wright and Flower, 2002), and have retreated during interglacial periods and since the LGM.

The Arctic and Antarctic have distinctive oceanographic regimes. The northern Norwegian and western Svalbard margins are influenced by the Norwegian and Barents seas. The Barents Sea is dominated by three major currents: the Arctic Current, the Norwegian Atlantic Current (NAC), and the Norwegian Coastal Current. The NAC affects the upper ~

800 m of the water column and transfers warm and saline water northeastward along the continental slope of the Norwegian Sea, with a branch entering the Barents Sea along with warm coastal waters (Orvik et al., 1995; Blindheim, 2004). The main branch becomes the West Spitsbergen Current to the west of Svalbard (Blindheim, 2004). In winter, cold, dense water forms through brine rejection during sea-ice production (Ivanov and Shapiro, 2005). Bottom current velocities of ~ 0.2 m s^{-1} have been measured by current meters along the northern Norwegian slope (Heathershaw et al., 1998), with velocities of 0.2-0.8 m s^{-1} inferred from modelling studies, reaching maximum velocities of 1 m s^{-1} on the outer continental shelf of northern Norway (Bøe et al., 2009).

Cold, dense water overflow is also produced in the southern Weddell Sea, Antarctica (Nicholls et al., 2009). The cold dense water contributes to Weddell Sea Deep Water, which flows around the northern tip of the Antarctic Peninsula (Fig. 2; Nowlin and Zenk, 1988). Maximum flow velocities of 1 m s^{-1} were recorded at 2075 m water depth in the southern Weddell Sea (Foldvik et al., 2004). Southwestward flowing bottom currents are also documented on the slope and rise off the western Antarctic Peninsula margin (between 1000 and 4000 m deep) (Camerlenghi et al., 1997; Giorgetti et al., 2003), with maximum current velocities of 0.2 m s^{-1}. As currents with velocities > 0.06 m s^{-1} are able to transport silt- and clay-sized particles (Young and Southard, 1978; Singer and Anderson, 1984), bottom currents may influence the surface morphology by resuspension and transport of fine-grained sediment (Camerlenghi et al., 1997). Episodic and high energy currents, for example, produced by the sporadic presence of barotropic eddies, will increase shear stress and may cause short-term increases in sediment resuspension (Giorgetti et al., 2003).

3. Data and methods

Multibeam echosounder data used in this study are summarised in Table 1. The data were gridded to cell sizes of 25 to 50 m using either Kongsberg Simrad NEPTUNE software or public-access MB-System software (Caress and Chayes, 1996). In this study, a gully is considered to have an incision depth > 5 m, and a gullied slope is one where gullies occur with a mean gully spacing of > 0.1 gully/km. Gully parameters were measured along transects parallel to the shelf edge at 50 m below the shelf edge. Analysis of the Trænadjupet region (Fig. 3) required measurements to be taken at 250 m below the shelf edge because of limited data availability. Measured parameters include gully width (distance between points of maximum curvature of gully flanks), incision depth (vertical distance from gully base to line defining gully width), length, branching order, sinuosity (distance measured along gully/straight line distance), mean gully spacing (gully/km), shelf-indentation (cutback), slope angle, and cross-sectional shape (U/V index). Cross-sectional shape was measured using the General Power Law ($^{G}P_{L}$) programme (Pattyn and Van Huele, 1998). $^{G}P_{L}$ approximates the cross-sectional shape of a gully according to

$$y - y_0 = a \mid x - x_0 \mid^{b} \qquad (1)$$

where *a* and *b* are constants and *x* and *y* are the horizontal and vertical coordinates taken from a cross-sectional profile of a gully. The programme automatically determines x_o and y_o as the coordinates of the point of inflection of the gully profile. The *b* value gives a measure of the cross-sectional shape of the gully and ranges from 1 (V-shape) to 2 (parabolic, commonly referred to as U-shape) on the U/V index. Branching order was calculated using the ArcGIS automated Stream Order application based on Strahler's (1957) method. Gullies were categorized according to their quantitative geomorphic signature based on the classification proposed by Gales et al. (2013). According to this classification, the following gully parameters are considered as 'high': incision depth > 30 m, sinuosity > 1.04, and length > 10 km.

The statistical significances of the results were calculated using the *T*-test that tests whether differences between Arctic and Antarctic gullies were significant. Standard deviations were calculated to test whether the variances between gully parameters were greater between Arctic and Antarctic gullies than within the data sets.

4. Results

Six geomorphically distinct gully types exist along the 2469 km of high latitude continental shelf and upper slope data analysed, with unique gully types recognised on both Arctic and Antarctic slopes. Five geomorphically distinct gully types occur on the Antarctic continental margin (Fig. 1). These are described by Gales et al. (2013) as type *I*: nonbranching with low incision depth (< 30 m), sinuosity (< 1.04), and length (< 10 km) and a V-shaped cross section; type *II*: nonbranching with low incision depth, sinuosity, and length and a U-shaped cross-section; Type *IIIa*: branching with high incision depth and length, low sinuosity and a V-shaped cross section; type *IIIb*: branching with a high incision depth, sinuosity, and length and a V-shaped cross section; and type *IV*: branching with a low incision depth, sinuosity, and length and a U-shaped cross section.

On the Arctic margins analysed, all gullies have average incision depths of < 30 m, measured at 50 m below the shelf edge. Five geomorphically distinct gully types are identified when gully incision depth is excluded from the identification criteria (Fig. 4), including type *I*, *IIIa*, *IIIb*, *IV,* and a previously unclassified gully type *V*, which is not observed in the Antarctic margin data analysed. Type *V* is characterised by a nonbranching, U-shaped, high length (> 10 km), low incision depth (< 30 m) and low sinuosity (< 1.04) signature. Gully type *I* covers 23 % of the Arctic and 21 % of the Antarctic margin data analysed; type *II* is not observed in the Arctic but covers 12 % of the Antarctic margin data analysed; type *IIIa* covers 9 % of the Arctic and 15 % of the Antarctic margin data analysed; type *IIIb* covers 31 % of the Arctic and 11 % of the Antarctic margin data analysed; type *IV* covers 6 % of the Arctic and 2 % of the Antarctic margin data analysed; and type *V* covers 12 % of the Arctic, but is not observed on Antarctic margins analysed (Antarctic values from Gales et al., 2013). Smooth continental slope, defined in this study as having a topography with gully depth incisions < 5 m, or a mean gully spacing of < 0.1 gully/km, covers 19 % of the Arctic continental margin analysed and 39 % of the Antarctic continental margin analysed. Mean gully spacing is similar between some gully types observed on the Arctic and Antarctic margin including types *I* and *IIIb*, although spacing varies for types *IIIa* and *IV* with Arctic gullies generally occurring in lower densities (Table 2).

Two distinct differences in gully morphology are recognised between the Arctic and Antarctic datasets. Firstly, deeply incised gullies within the Arctic data are absent, with mean gully depths in each area studied not exceeding 30 m, measured at 50 m below the shelf edge (Fig. 5). Mean gully incision depth from the Antarctic margin is 48 m compared to 12 m for Arctic gullies. Secondly, there is a distinct lack of gullies incising the shelf edge, with a mean shelf-indentation of 35 m on the Arctic margins, compared to 324 m on Antarctic margins. The statistical significances of these differences were tested by calculating the standard deviations of the means and by using the *T*-test. The standard deviations of the mean gully incision depths and shelf-incisions for Arctic and Antarctic gullies were less than the difference between the means. This shows that the differences between Arctic and Antarctic gullies are greater than variances within each dataset. The results of the *T*-test shows that the *P* value is < 0.05, and so lies within the 95 % significance level, suggesting that a significant difference exists between Arctic and Antarctic gully incision depth and shelf-incision.

Differences also exist in gully spatial distribution. On Antarctic margins, sinuous but long gullies (type *IIIb*) are located at the mouths of cross-shelf troughs, with less sinuous gullies (type *IIIa*) occurring in inter-trough areas (Table 3). However, on the Arctic margins analysed, sinuous gullies (type *IIIb*) are observed in inter-trough regions and at the mouths of cross-shelf troughs (Fig. 6). Additionally, type *IV* gullies, which are only observed on an isolated inter-trough region offshore from Alexander Island, western Antarctic Peninsula (Fig. 1E), are observed more widely on Arctic margins and occur at the mouths of cross-shelf troughs and in inter-trough areas (Fig. 6).

5. Discussion

Quantitative analysis of over 1450 high latitude continental slope gullies show that gullies share similar morphologies and, excluding gully depth, fit a common classification scheme. However, we identify two distinct differences between Arctic and Antarctic gullies. Firstly, there is a significant lack of deeply incised gullies within the Arctic data analysed. Secondly, there is a distinct difference in shelf-indentation with Antarctic gullies displaying greater cutback into the shelf edge. Like submarine canyons, gullies likely evolve through either downslope erosion driven by flows of turbidity currents, which may be initiated by discharges of sediment-laden subglacial meltwater, or through headward erosion by retrogressive mass failures (i.e., slides, slumps), or a combination of both (Harris and Whiteway, 2011). The differences in gully incision depth and shelf-indentation have implications for the timescales over which these features were formed and for the magnitude of the flows that potentially formed them. Questions still remain regarding the processes that form submarine gullies and whether they are formed over multiple glacial cycles by steady-state flows or develop over shorter timescales by larger episodic releases (Ó Cofaigh, 2012).

We suggest two hypotheses for the observed differences in gully incision depth and shelf-indentation: (i) some Antarctic gullies were formed over multiple glacial cycles, dating back to before the LGM; and (ii) the stages in which they were formed (i.e., glacial maximum and early deglaciation) prevailed over longer time periods in Antarctica than on Arctic margins during the last glacial cycle. Environmental controls, such as the oceanographic regime and geotechnical differences may also lead to particular styles of gully erosion on Arctic and Antarctic margins.

5.1. Long-term versus short-term gully formation

Ice sheets are known to have advanced and retreated within cross-shelf troughs over many glacial cycles, and as a result of this, gullies may have formed during earlier glacial periods when ice was previously grounded at, or near to, the shelf edge. The significant differences in gully incision depth and shelf-indentation observed between some Arctic and Antarctic gullies may therefore reflect differences in the timing of initial glaciation and the number of subsequent glacial cycles. Ice has covered much of Antarctica for over 34 M.y. (Barrett, 2008), although onset of the west Antarctic glaciation is thought to have begun after 26 Ma (Barker et al., 2007) compared to 2.6 Ma on parts of the northwest European margin (Thiede et al., 1998). The difference in gully incision depth and shelf-incision may reflect a longer period of development over multiple glacial cycles for the larger gullies on the Antarctic margin. Recent studies using three dimensional seismic data of submarine canyons on the northwest Mediterranean margin show that canyons may develop over longer timescales during continental margin construction (Amblas et al., 2012). Gullies present on mid-Pleistocene palaeocanyon flanks are maintained through to the modern canyon morphology (Amblas et al., 2012), demonstrating that the gullies can be preserved during slope progradation. If gullies on the Antarctic margin acted as conduits for glacigenic sediment, which was transported to the shelf edge during successive ice sheet readvances, and were reactivated in successive glacial stages, gully morphology may have been preserved and enhanced during slope progradation over multiple glacial cycles, leading to greater gully depths observed on parts of the Antarctic margin.

However, unlike the northwest Mediterranean margin, high latitude margins are influenced by huge quantities of glacigenic sediment transported by ice sheets to the shelf edge during glacial periods. This may have filled any shelf-edge depressions present, masking palaeogullies, and resulting in new gullies forming with each new glacial cycle. Subbottom data from some high latitude margins (e.g., Storfjorden TMF, northern Barents Sea; Belgica Fan, Bellingshausen Sea, Antarctica) show that submarine gullies incise glacial debris flow deposits, suggesting that erosion of some gullies likely post-dates the last glacial advance to the shelf edge (Vorren et al., 1989; Laberg et al., 2007; Pedrosa et al., 2011; Ó Cofaigh, 2012). As the most recent episodes of gully erosion (since LGM) may obscure previously developed gullies, it is difficult to rule out gully formation over longer timescales without high resolution three-dimensional seismic datasets from glacial margins.

5.2. Timing and rate of deglaciation

The length of time that ice was grounded at the shelf edge during the LGM and the timing of particular glacial stages may affect gully size and shelf-incision. If the dominant mechanism forming V-shaped and deeply incised high latitude gullies are erosive flows initiated by sediment-laden subglacial meltwater (Lowe and Anderson, 2002; Ó Cofaigh et al., 2003; Dowdeswell et al., 2004, 2006, 2008; Heroy and Anderson, 2005; Noormets et al., 2009; Ó Cofaigh, 2012; Gales et al., 2013), this suggests that either these processes were operating over longer time periods in Antarctica, were more frequent, or occurred in larger events, for example owing to larger drainage basin sizes or from the outer shelf morphology facilitating flow toward the shelf edge.

Gullies with the greatest incision depth and shelf-incision (types *IIIa* and *IIIb*) are located along the Bellingshausen and Amundsen Sea margin and at the mouths of the Pine Island West (PIW) and Belgica trough, Antarctica (Figs. 1C and D; Table 3). The difference between the closely spaced and smaller type *I* gullies observed on some Arctic margins and the larger, more widely spaced type *III* gullies may reflect a difference in the length of time that the gullies developed over, perhaps owing to differences in the length of time that ice was present near to the shelf edge and the effective drainage areas associated with the palaeo-ice streams. A larger drainage basin size and/or longer presence of ice near the shelf edge may increase the size and frequency of flows down the gully thalwegs.

Although only limited sediment cores are available from the outer shelf of Belgica and PIW troughs, ice streams within these troughs are suggested to have undergone slow and episodic retreat, with mean retreat rates of ~ 15 m y^{-1} for Belgica trough and 18 m y^{-1} for the Amundsen Sea Embayment outer shelf (Lowe and Anderson, 2002; Ó Cofaigh et al., 2008; Graham et al., 2010; Hillenbrand et al., 2010a; Smith et al., 2011; Kirshner et al., 2012; Livingstone et al., 2012). Conversely, some Arctic ice streams underwent significantly more rapid and later retreat. Studies suggest that deglaciation commenced around ~ 17.5 cal. ky BP on the western Barents Sea margin and Norwegian continental shelf and 20.5 $\pm$ 5 cal ky BP on the outer western Svalbard shelf (Jessen et al., 2010), with core evidence showing that deglaciation was relatively rapid, occurring over a period of ~ 2000 years, with retreat rates of 60 m y^{-1}, increasing to 275 m y^{-1} for the Bjørnøyrenna ice stream (Vorren and Plassen, 2002; Landvik et al., 2005, 2012; Winsborrow et al., 2012). A longer duration of grounded ice at the shelf edge and/or slower initial ice sheet retreat history would have exposed the shelf edge to more continuous turbidity-current or subglacial meltwater activity for longer time periods, facilitating the development of larger features over time.

Belgica and PIW troughs are characterised by large drainage basin sizes, with areas of 417,000 km^2 for Pine Island trough (Rignot et al., 2008) and 217,000-256,000 km^2 for Belgica trough (Livingstone et al., 2012). Although Bjørnøyrenna Ice Stream is also associated with a large drainage basin (576,000 km^2; Elverhøi et al., 1998), other Arctic margins analysed are characterised by significantly smaller drainage basin sizes, e.g., Kongsfjorden trough (1426 km^2; Elverhøi et al., 1998) and by narrow continental shelves along the northern Norwegian margin. Ice streams within larger drainage basins are associated with slower or more episodic retreat rates in Antarctica (Livingstone et al., 2012) and greater sediment yields (Elverhøi et al., 1998). The difference in drainage basin size may therefore influence the rate of ice retreat as well as potentially influencing the abundance or frequency of subglacial meltwater discharged from beneath an ice sheet. Mechanisms for the production of subglacial meltwater include strain heating and geothermal heat flux at the base of the ice sheet (Joughin et al., 2004). The generally longer ice stream flow paths in larger drainage basins may have resulted in warmer basal ice and therefore higher abundances of subglacial meltwater, although studies of modern systems have shown that basal meltwater generated is in the range of millimetres per year (e.g., Beem et al., 2010; Pattyn, 2010).

The PIW and Belgica troughs have relatively unique outer shelf morphologies (Figs. 7A and B). The PIW trough is characterised by a re-entrant feature where the outer shelf is slightly seaward-sloping compared to most other Antarctic outer shelves that slope landward because of erosional over-deepening of the inner shelves by palaeo-ice sheets and lithospheric flexture caused by ice sheet loading (ten Brink and Cooper, 1992; Bart and Iwai, 2012). This may encourage the gravity-driven flow of subglacial meltwater toward the shelf edge, leading to larger and more deeply incised gullies located at the mouths of these troughs. The outer shelf of Belgica trough is also slightly seaward sloping and asymmetric, with a subtrough to the west of the trough axis (Graham et al., 2011). The unusual trough bathymetry may have enabled slower rates of glacial retreat and may have funnelled flows of subglacial meltwater toward the shelf edge during early stages of glacial retreat.

5.3. Environmental controls

Although large-scale variations in high latitude gully morphology may result from varied glacial histories, local differences in gully morphology may result from different environmental controls, including slope gradient, oceanographic, and geotechnical differences. Within the data analysed, the most deeply incised gullies (type *IIIa*; mean incision depth of 81 m at 50 m below the shelf edge) occur on relatively low slope gradients of ~ 4-5.5° in Antarctica. The deepest gullies on Arctic margins (type *IIIb*; mean incision depth of 21.5 m at 50 m below the shelf edge) occur on higher slope gradients of ~ 7.5º (Fig. 8). No relationship is observed between mean gully incision depth or shelf-indentation and slope gradient, suggesting that gradient is unlikely to be influencing the differences observed between high latitude margins.

The occurrence of a previously uncharacterised gully type identified on the Arctic margin (type *V;* Baeten et al., 2013) suggests that different processes are operating in this region that are absent from the Antarctic margin. Type *V* covers 61 km of the northern Norwegian continental shelf and upper slope and is found on relatively low slope gradients (~ 2°). Although no shelf edge data is available for this region at present, backscatter data show that the gullies are filled with sediments that are characterised by high backscatter (Baeten et al., 2013), suggesting that sediment within the gullies is coarser grained than the surrounding sediment. Seismic data from this region show that a glacigenic wedge formed of debris flow deposits is present on the upper slope, with gullies initiating within, or at the boundary of the wedge (Baeten et al., in prep.). The type *V* gullies may therefore have been formed by deposition on to the wedge during past glaciations that initiated sediment gravity flows. The local oceanographic regime may also influence the unique gully morphology, for example, by strong contour current activity activating sediment flows over the shelf edge and potentially allowing sediment gravity flows to develop. More detailed oceanographic data is needed from this region to confirm this.

Along the northern Norwegian margin, variation in along-slope sedimentation may influence differences in local sedimentation rates (Laberg et al., 2002). This may affect gully infilling leading to a reduction in the apparent incision depths on Arctic margins and may be one factor influencing the large discrepancy in high latitude gully incision depths. On the outer shelf offshore from Vesterålen (Fig. 3), bottom current velocities of 0.7-0.8 m s^{-1} have been suggested from modelling studies, reaching maximum velocities of 1 m s^{-1} (Bøe et al., 2009). The presence of strong bottom currents influences local sedimentation, with erosion occurring in high-energy environments and fine-grained sediment accumulating within sheltered environments (Bøe et al., 2009). However, even if some Arctic gullies did undergo significant infilling, this would not explain the distinct difference in shelf-incision. Subbottom acoustic data from the Arctic and Antarctic margins show that gullies are not significantly influenced by sediment infilling and largely maintain their original gully morphologies (Vorren et al., 1989, 1998; Gales et al., 2012, 2013). Additional subbottom data from Arctic margins are needed to rule out this possibility.

5.3.4. Continental slope instability

Type *IV* gullies are relatively rare on high latitude continental margins, covering 6 % of the shelf edge of Arctic margins analysed and 2 % of Antarctic margins analysed. In Antarctica, type *IV* gullies are only observed in an inter-trough region and are absent from the mouths of cross-shelf troughs. New data from the Arctic show that similar gully morphologies occur on inter-trough margins and at the mouths of a cross-shelf trough (i.e., Rebbenesdjupet trough;

Fig. 6). Here, type *IV* gullies occur adjacent to an area of deeply incised and dendritic type *IIIb* gullies. Type *IV* gullies may indicate a continental slope that has undergone subsequent gradual modification through mass-wasting processes (Gales et al., 2013) and show characteristics similar to small-scale slides, demonstrating small-scale escarpments and an absence of a well-defined gully thalweg (Kenyon, 1987). The greater occurrence of type *IV* gullies on the Arctic margins may indicate a higher susceptibility to mass-wasting processes, for example, owing to the presence of weak geological layers on parts of the Arctic upper slope.

6. Conclusion

The mechanisms involved in gully formation and the factors that influence this are highly complex and poorly constrained. This study identifies key differences between high latitude submarine gullies and provides insight into the causes behind the different morphologies observed and the processes operating in these environments. The major findings of this study are as follows:

- Quantitative analysis of over 1450 gullies from multibeam bathymetric data along 2469 km of high latitude continental shelf and upper slope identifies six gully types from a common gully classification scheme.

- Two distinct differences exist between some Arctic and Antarctic continental slopes. There is a lack of deeply incised (> 30 m gully incision depth at 50 m below the shelf edge) and shelf-incising gullies in the Arctic continental margin datasets that we examined. Secondly, unique gully signatures are observed on Arctic and Antarctic margins, with type *II* gullies absent from Arctic margins and type *V* gullies absent from Antarctic margins analysed.

- We suggest two hypotheses for the distinct differences in gully incision depth and shelf-incision: (i) some Antarctic gullies were formed over multiple glacial cycles, dating back to before the LGM; and (ii) the stages in which gullies were formed prevailed over longer time periods in Antarctica than on Arctic margins, during and since the LGM. A longer period of grounded ice at the shelf edge and/or slower and more episodic retreat history of ice streams within Belgica and PIW troughs may have allowed the deeply incised type *IIIb* gullies to develop over longer timescales. Environmental controls, such as the oceanographic regime and geotechnical differences, likely influenced particular styles of gully erosion (i.e., type *IV* and *V*).

- The unique outer shelf morphology of both the Belgica and Pine Island West troughs may have encouraged the gravity-driven flow of subglacial meltwater toward the shelf edge as the ice sheet retreated. Further research is needed in reconstructing detailed ice sheet history, as flow switching within ice streams and glacial readvance may also have influenced gully morphology.

- Our study highlights the need for three-dimensional seismic datasets from the Antarctic continental margin, in particular for the outer shelf and upper slope regions. These data would constrain the evolutionary stages of high latitude gullies and the timescales they develop over, as well as providing insight into the mechanisms influencing submarine erosion and slope instability on high latitude continental margins.

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Figures

Fig. 1. Antarctic slope geomorphology. Different morphological gully styles observed across the Antarctic continental margin. **(A)** Gully type *I*; **(B)** gully type *II*; **(C)** gully type *IIIa*; **(D)** gully type *IIIb*; **(E)** gully type *IV*; **(F)** cross-shelf profiles at 50 m below the shelf edge for gullies A-E. Profile locations are marked by black dashed lines and lower case letters on each figure above. For location of (A)-(E), see Fig. 2. Colour scale is the same for (A)-(E). For colour bar, see (D). Adapted from Gales et al. (2012).

Fig. 2. **(A)** Study areas from the western Antarctic Peninsula, Bellingshausen, Amundsen and Weddell Seas. **(B)** Inset showing location of (A) in relation to the Antarctic continent. Thick black lines mark extent of multibeam bathymetric data along the continental shelf edge. Regional bathymetry is from Bedmap2 (Fretwell et al., 2013). The Antarctic continent is Landsat Image Mosaic of Antarctica (LIMA) (U.S Geological Survey, 2007). Black squares mark location of Figs. 7A and 7B. Red squares mark location of Figs. 1A-E. Arrows mark general direction of bottom currents including: Weddell Sea bottom water (WSBW), Weddell Sea deep water (WSDW), and Ice Shelf water (ISW; black) and modified Weddell Sea deep water (MWSDW; red). The Antarctic Circumpolar Current (ACC) is marked by a white arrow.

Fig. 3. Study areas from western Svalbard, southwest Barents Sea and northern Norwegian continental margins. Inset (upper right) locates the map within the Arctic. Solid black lines mark extent of multibeam bathymetric data along continental shelf edge. Regional bathymetry is from IBCAO (Jakobsson et al., 2012). Dashed black lines mark boundaries of cross-shelf troughs analysed. Red squares mark locations of Figs. 4A-E.

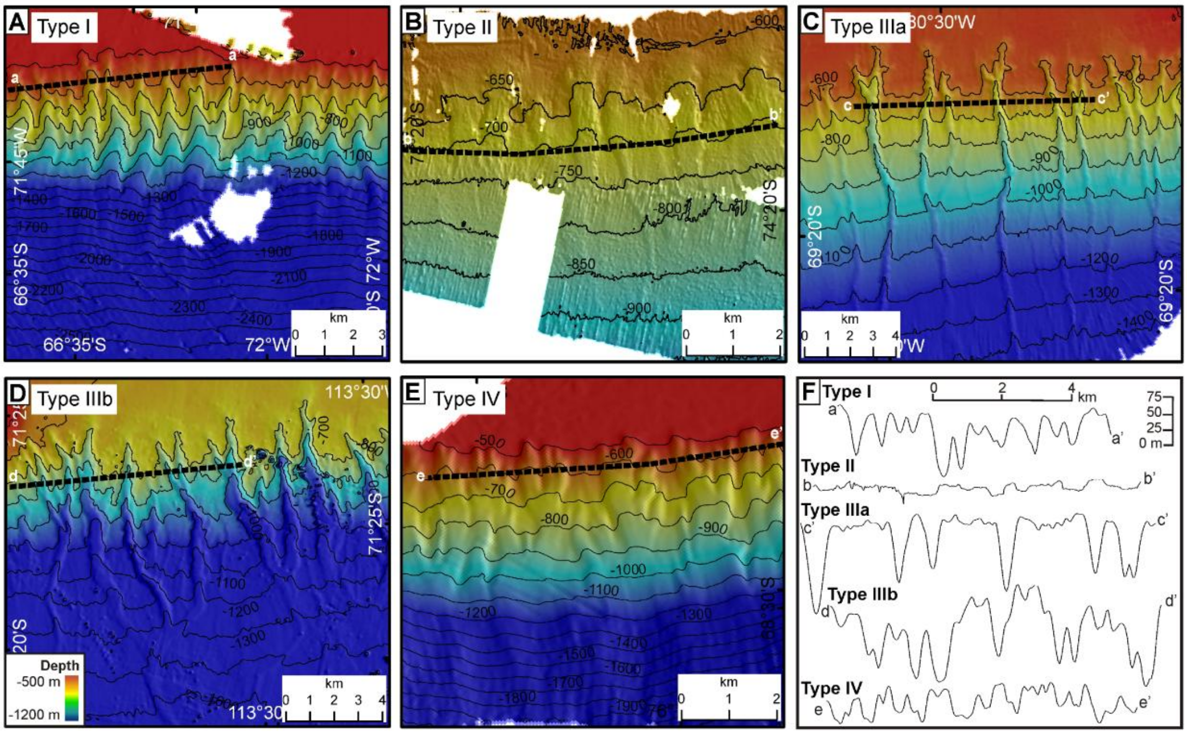
Fig. 4. (A)-(E). Arctic gully morphologies from the northern Norwegian, Barents Sea, and western Svalbard margin. (**F**) Cross-shelf profiles taken at 50 m* below the shelf edge (*E is taken at 250 m below shelf edge because of data limitations). Profile locations are marked by black dashed lines and lower case letters on each figure above. For location of (A)-(E), see Fig. 3. Colour scale is the same for (A)-(E). For colour bar, see (A).

Fig. 5. Arctic and Antarctic gully parameters: length (km), width (m), incision depth (m), sinuosity, U/V, and cutback (m). Red circles = Arctic gullies; black circles = Antarctic gullies.

Fig. 6. Spatial distribution of Arctic gully types. Solid black lines indicate segments of shelf edge included in analysis. Pie charts represent percentage of sea floor covered by different slope types. Numbers within chart segments represent kilometres of seafloor each gully type covers. Dashed lines mark cross-shelf troughs reaching the shelf edge in the areas analysed. Regional bathymetry is from IBCAO (Jakobsson et al., 2012).

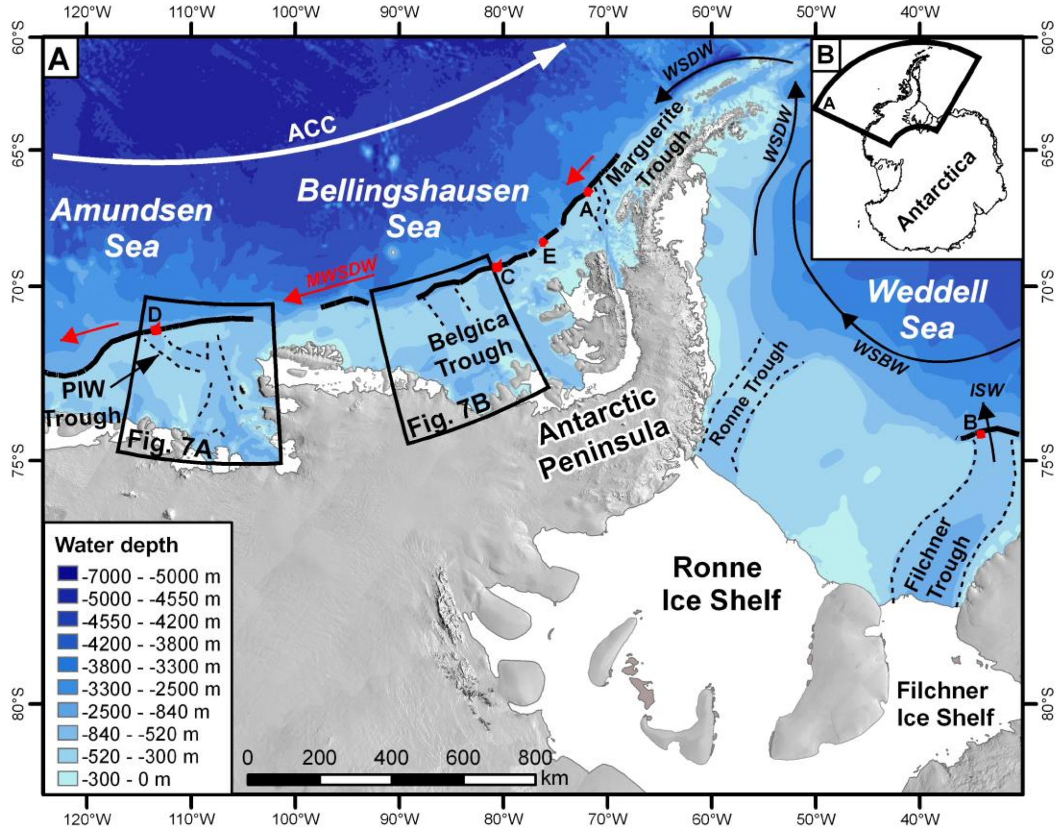
Fig. 7. (A) Pine Island West (PIW) trough, Amundsen Sea. (**B**) Belgica trough, Bellingshausen Sea. Bathymetry data is from Bedmap2 (Fretwell et al., 2013). Antarctic continent is shaded Landsat Image Mosaic of Antarctica (LIMA) data (U.S Geological Survey, 2007). WAIS is West Antarctic Ice Sheet. Dashed lines mark boundaries of cross-shelf troughs.

Fig. 8. Mean cutback (m) and gully incision depth (m) versus slope gradient (º) for Arctic (hollow circles) and Antarctic (filled circles) gully types (*I*, *II*, *IIIa*, *IIIb*, *IV*, *V*).



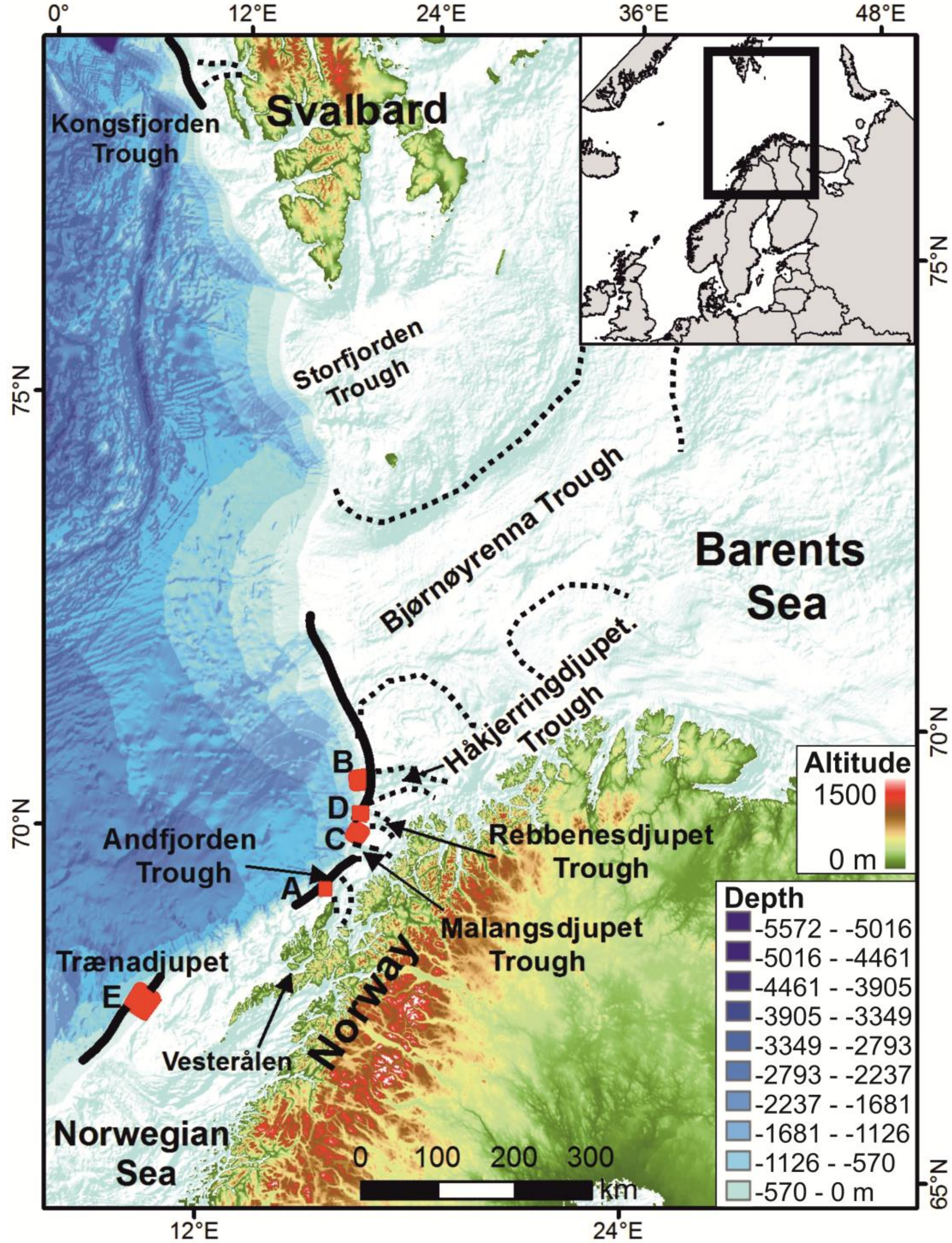
A Type I
B Type II
C Type IIIa
D Type IIIb
E Type IV
F Type I
Type II
Type IIIa
Type IIIb
Type IV
km
Depth
-500 m
-1200 m

Fig. 1



120°W
110°W
100°W
90°W
80°W
70°W
60°W
50°W
40°W
60°S
65°S
70°S
75°S
80°S
A
B
ACC
WSDW
Marguerite Trough
WSDW
Amundsen Sea
Bellingshausen Sea
Antarctica
A
E
C
MWSDW
Weddell Sea
D
Belgica Trough
WSBW
PIW Trough
Fig. 7B
Fig. 7A
Antarctic Peninsula
Ronne Trough
ISW
B
Ronne Ice Shelf
Filchner Trough
Filchner Ice Shelf
Water depth
-7000 - -5000 m
-5000 - -4550 m
-4550 - -4200 m
-4200 - -3800 m
-3800 - -3300 m
-3300 - -2500 m
-2500 - -840 m
-840 - -520 m
-520 - -300 m
-300 - 0 m
0 200 400 600 800 km

Fig. 2



0°
12°E
24°E
36°E
48°E
Svalbard
Kongsfjorden Trough
Storfjorden Trough
Bjørnøyrenna Trough
Barents Sea
Håkjerringdjupet. Trough
B
D
C
A
E
Andfjorden Trough
Rebbenesdjupet Trough
Malangsdjupet Trough
Trænadjupet
Vesterålen
Norway
Norwegian Sea
0 100 200 300 km
Altitude
1500
0 m
Depth
-5572 - -5016
-5016 - -4461
-4461 - -3905
-3905 - -3349
-3349 - -2793
-2793 - -2237
-2237 - -1681
-1681 - -1126
-1126 - -570
-570 - 0 m
75°N
70°N
65°N

Fig. 3

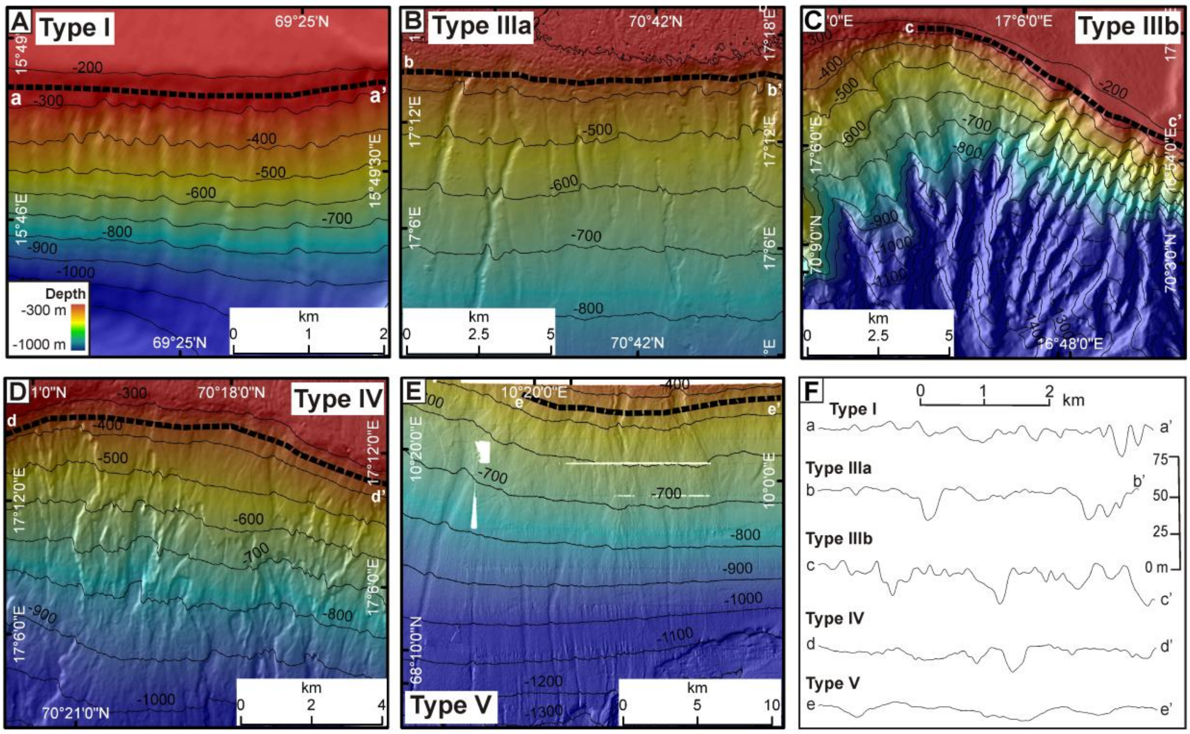
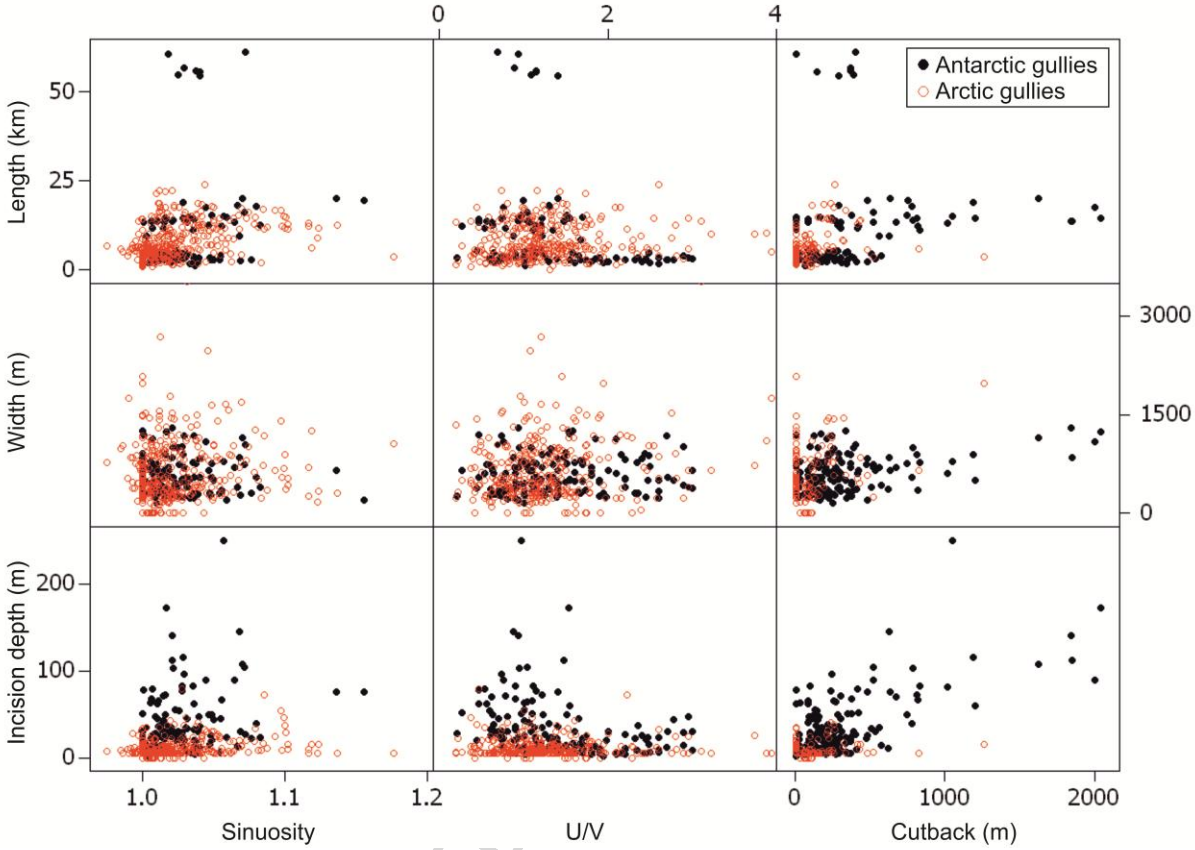

A Type I
B Type IIIa
C Type IIIb
D Type IV
E Type V
F
Depth
-300 m
-1000 m
km
Type I
Type IIIa
Type IIIb
Type IV
Type V
75
50
25
0 m

Fig. 4



0
2
4
Antarctic gullies
Arctic gullies
Length (km)
50
25
0
Width (m)
3000
1500
0
Incision depth (m)
200
100
0
1.0
1.1
1.2
Sinuosity
U/V
0
1000
2000
Cutback (m)

Fig. 5

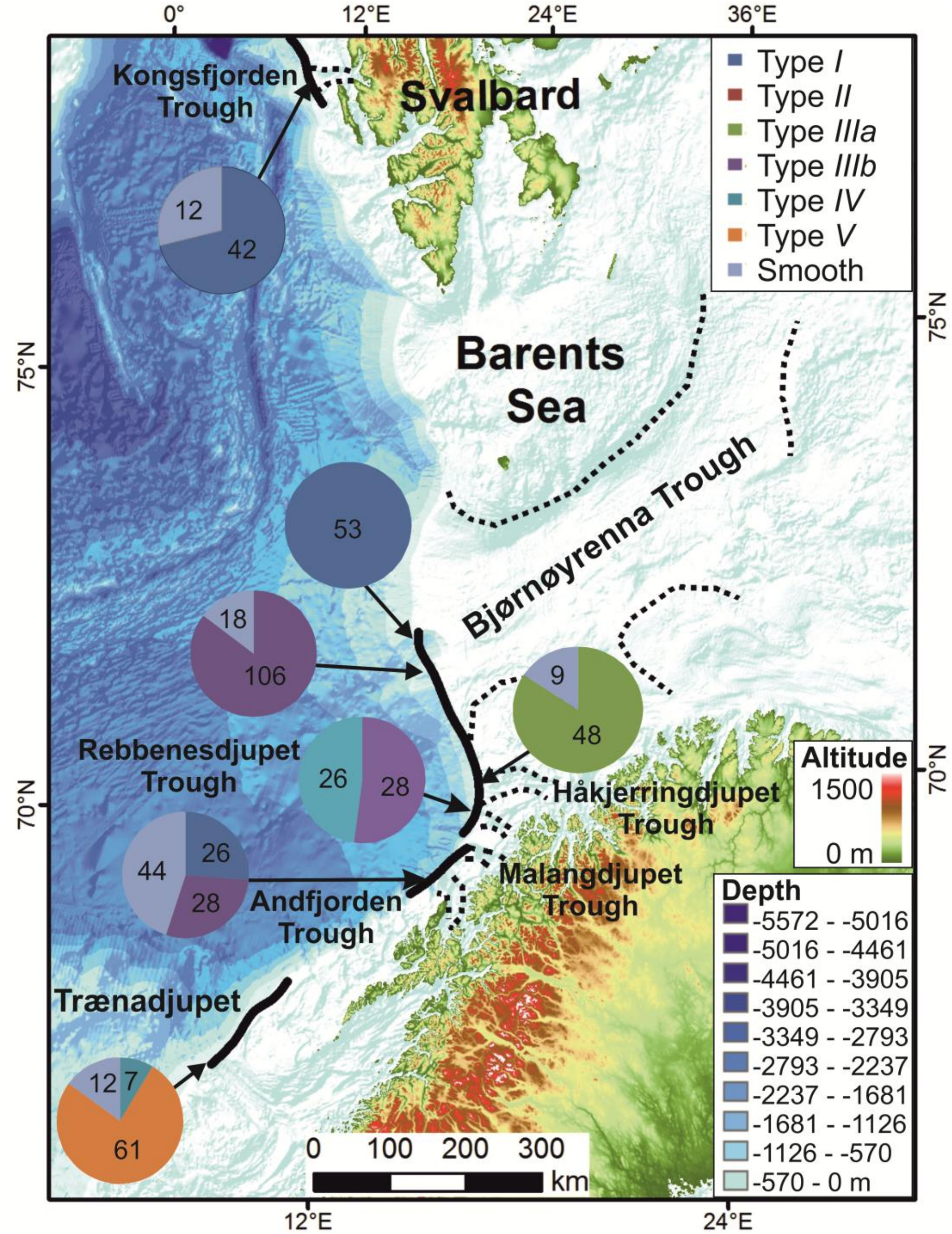
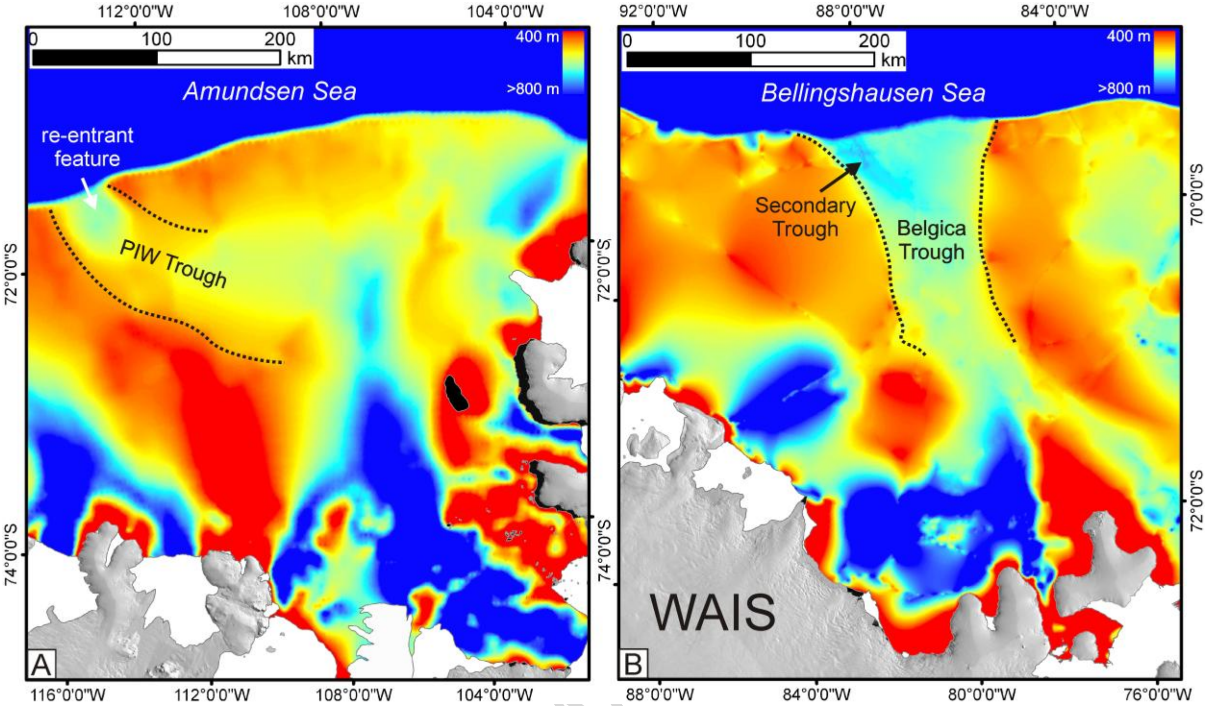
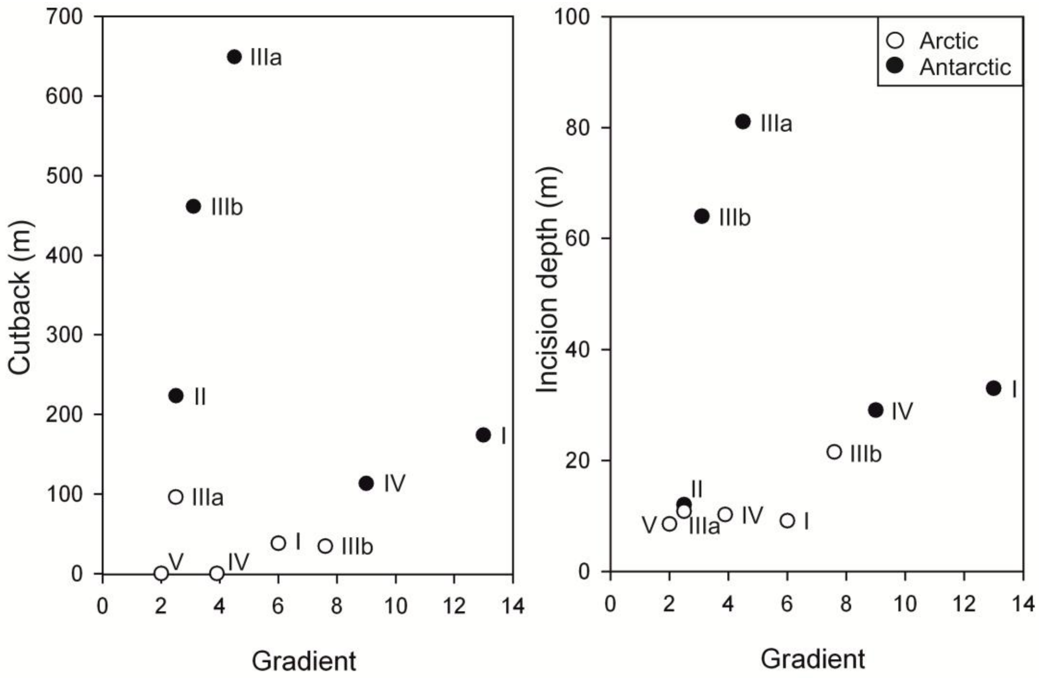

0°
12°E
24°E
36°E
Kongsfjorden Trough
Svalbard
Type I
Type II
Type IIIa
Type IIIb
Type IV
Type V
Smooth
12
42
75°N
Barents Sea
Bjørnøyrenna Trough
53
18
106
9
48
Rebbenesdjupet Trough
26
28
Håkjerringdjupet Trough
Altitude
1500
0 m
70°N
44
26
28
Andfjorden Trough
Malangdjupet Trough
Depth
-5572 - -5016
-5016 - -4461
-4461 - -3905
-3905 - -3349
-3349 - -2793
-2793 - -2237
-2237 - -1681
-1681 - -1126
-1126 - -570
-570 - 0 m
Trænadjupet
12
7
61
0 100 200 300
km
12°E
24°E

Fig. 6



112°0'0"W
108°0'0"W
104°0'0"W
0
100
200
km
400 m
>800 m
Amundsen Sea
re-entrant
feature
PIW Trough
72°0'0"S
74°0'0"S
A
116°0'0"W
112°0'0"W
108°0'0"W
104°0'0"W
92°0'0"W
88°0'0"W
84°0'0"W
Bellingshausen Sea
Secondary
Trough
Belgica
Trough
70°0'0"S
72°0'0"S
74°0'0"S
WAIS
B
88°0'0"W
84°0'0"W
80°0'0"W
76°0'0"W

Fig. 7



700
600
500
400
300
200
100
0
Cutback (m)
IIIa
IIIb
II
I
IV
IIIa
I
IIIb
V
IV
0 2 4 6 8 10 12 14
Gradient
100
80
60
40
20
0
Incision depth (m)
Arctic
Antarctic
IIIa
IIIb
I
IV
IIIb
II
V
IIIa
IV
I
0 2 4 6 8 10 12 14
Gradient

Fig. 8

Table 1

Multibeam data analysed

Data set		Reference	System
Cruise / ID	**Year**		
ANT23-4	2006	Gohl (2006); Nitsche et al. (2007)	Atlas Hydrosweep DS-2[a]
JR59	2001	Dowdeswell et al. (2004)	Kongsberg EM120[b]
JR71	2002	Ó Cofaigh et al. (2005); Dowdeswell et al. (2004)	Kongsberg EM120[b]
JR84	2003	Evans et al. (2006)	Kongsberg EM120[b]
JR97	2005	Gales et al. (2012); Larter et al. (2012)	Kongsberg EM120[b]
JR104	2004	Ó Cofaigh et al. (2005); Dowdeswell et al. (2008)	Kongsberg EM120[b]
JR141	2006	Noormets et al. (2009); Graham et al. (2010)	Kongsberg EM120[b]
JR157	2007	Noormets et al. (2009)	Kongsberg EM120[b]
JR179	2008	Graham et al. (2010)	Kongsberg EM120[b]
JR244	2011	Gales et al. (2012); Larter et al. (2012)	Kongsberg EM120[b]
NBP9902	1999	Wellner et al. (2001, 2006); Lowe and Anderson (2002)	Seabeam 2112[c]
NBP0001	2000	Nitsche et al. (2007)	Seabeam 2112[c]
NBP0103	2001	Bolmer (2008)	Seabeam 2112[c]

NBP0104	2001	Bolmer (2008)	Seabeam 2112[c]
NBP0201	2002	Wellner et al. (2006)	Kongsberg EM120[b]
NBP0202	2002	Bolmer (2008)	Kongsberg EM120[b]
NBP0702	2007	Graham et al. (2010)	Kongsberg EM120[b]
MAREANO		www.mareano.no	
R/V Jan Mayen	2004/5	Laberg et al. (2007)	Kongsberg EM300[d]
R/V Jan Mayen	2010	Baeten et al. (2013)	Kongsberg EM300[d]
R/V Jan Mayen	2006/7	Hustoft et al. (2009)	Kongsberg EM300[d]
	2008/9	Forwick (2009a,b)	Kongsberg EM300[d]

[a]Frequency of 15.5 KHz and swath width of up to 120°.

[b]Frequency range of 11.75-12.75 kHz and beam width up to 150°.

[c]Frequency of 12 kHz and swath width of up to 120°.

[d]Frequency of 30 kHz and swath width of up to 150°.

Table 2

Mean gully spacing (gully/km) from parts of the Arctic and Antarctic continental shelf and upper slopes

Gully type	Mean gully spacing (gully/km)	
	Arctic	Antarctic
I	1.56	1.54
II	-	0.74
IIIa	0.74	1.37
IIIb	1.07	1.16
IV	0.7	1.32
V	0.5	-

Table 3

Comparison of submarine gully coverage (km) from high latitude continental margins

	Western Antarctic Peninsula		Bellingshausen Sea		Amundsen Sea		Filchner trough (Weddell Sea)	Kongsfjorden trough (western Svalbard)		Southwest Barents Sea		Northern Norway		
	a	*b*	*c*	*d*	*e*	*f*			*g*	*h*	*i*	*j*	*k*	*m*
Type *I*	75	281		8		35		42	53				26	
Type *II*				98	3	64	68							
Type *IIIa*				127		163					48			
Type *IIIb*			152	6	52					106		28	28	
Type *IV*		31										26		7
Type *V*														61
Smooth	11	68		145		467	63	12		18	9		44	12
Inside trough	X	-	-	X	-	X	X	X	X	-	-	-	X	-
Inter-trough	X	X	X	-	X	-	-	-	-	-	-	-	-	X
Slide scars present	-	-	-	-	-	-	-	X	X	-	-	-	X	X

Canyon present	-	-	-	-	-	-		-	-	-	-	-	X	-
Gradient >5°	X	X	-	-	-	-	-	-	-	-	-	-	X	-
Density (gully/km) >1.3	X	X	-	X	-	X	-	X	-	-	-	X	X	-

a = Marguerite trough; b = west Antarctic Peninsula inter-trough; c = Belgica trough; d = Bellingshausen Sea margin; e = Pine Island West trough; f = Amundsen Sea margin; g = Bjørnøyrenna trough; h = SW Barents Sea margin; i = Håkjerringdjupet Trough; j = Rebbenesdjupet Trough; k = Andfjorden (Andøya) Trough; l = Trænadjupet. Values for Antarctic gully coverage taken from Gales et al. (2013).

Highlights

- We provide a quantitative comparison of Arctic and Antarctic submarine gullies
- Six quantitatively distinct gully types occur on high latitude continental slopes
- Distinct differences exist between Arctic and Antarctic gullies
- Unique gully types are observed on Arctic and Antarctic margins