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# Geomorphic signature of Antarctic submarine gullies: Implications for continental slope processes

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ABSTRACT

Five quantitatively distinct gully types are identified on the Antarctic continental margin from swath bathymetric data of over 1100 individual features. The gullies differ in terms of length, width, depth, width/depth ratio, cross-sectional shape, branching order, sinuosity and spatial density. Quantitative analysis suggests that Antarctic gully morphology varies with local slope character (i.e. slope geometry, gradient), regional factors (i.e. location of cross-shelf troughs, trough mouth fans, subglacial meltwater production rates, drainage basin size), sediment yield and ice-sheet history. In keeping with interpretations of previous researchers, most gullies are probably formed by hyperpycnal flows of sediment-laden subglacial meltwater released from beneath ice-sheets grounded at the continental shelf edge during glacial maxima. The limited down-slope extent of gullies on the western Antarctic Peninsula is explained by the steep gradient and slope geometry at the mouth of Marguerite Trough, which cause flows to accelerate and entrain seawater more quickly, resulting in a reduction of the negative buoyancy effect of the sediment load. Due to pressure gradients at the ice-sheet bed caused by variations in ice thickness inside and outside palaeo-ice stream troughs, subglacial meltwater flow was generally focussed towards trough margins. This has resulted in gullies with larger cross-sectional areas and higher sinuosities at the trough margins. A unique style of gullying is observed off one part of the western Antarctic Peninsula, corresponding to an area in which the ice-sheet grounding line is not thought to have reached the shelf edge during the Last Glacial Maximum. We interpret the features in this area as the cumulative result of slope processes that operated over a long period of time in the absence of hyperpycnal meltwater flows.

## 1. Introduction

Understanding the processes operating on continental margins is essential for interpreting seafloor erosion patterns, continental margin evolution, canyon development and sediment core records from the continental slope and rise. Submarine gullies are the most common morphological features observed on the Antarctic continental margin, and the processes which form these gullies remain a key research question, with important implications for continental slope research.

Submarine gullies are becoming increasingly important in the field of geomorphology, with some studies documenting different gully morphologies on Antarctic continental margins (i.e. Noormets et al., 2009; Gales et al., 2012) and on mid-latitude margins (i.e. Micallef and Mountjoy, 2011; Vachtman et al., 2012). In Antarctica, gullies incise the upper slope over much of the continental margin, in places eroding back into the continental shelf (Noormets et al., 2009). Gullies are present along the western Antarctic Peninsula continental margin and along the shelf edge and upper slopes of the Weddell, Bellingshausen, Amundsen and Ross seas (Vanneste and Larter, 1995; Shipp et al., 1999; Lowe and Anderson, 2002; Dowdeswell et al., 2004a, 2006, 2008; Heroy and Anderson, 2005; Noormets et al., 2009; Gales et al., 2012).

Variation in gully morphology is likely to reflect differences in the underlying substrate, the spatial characteristics of the slope and slope processes. The continental slopes considered in this paper are all underlain by thick Quaternary sediments, most of which are glacially derived (e.g. glacigenic debris flows) or glacially influenced (e.g. glacimarine muds with ice rafted debris) (Wright and Anderson, 1982; Melles and Kuhn, 1993; Bonn et al., 1994; Dowdeswell et al., 2004a, 2004b, 2006; Hillenbrand et al., 2005). Seismic reflection and coring studies from the Antarctic continental slope show that sediments present along the slope exhibit a limited range of characteristics, with similar lithology, physical properties and grain-size composition (e.g. Vanneste and Larter, 1995; Anderson and Andrews, 1999; Michels et al., 2002;

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Dowdeswell et al., 2004a, 2006, 2008; Hillenbrand et al., 2005, 2009). As the outer-shelf and upper-slope sediments are relatively homogenous, variation in substrate is therefore not likely to be a factor influencing differences in gully morphology. Although variation in geotechnical properties cannot be dismissed unequivocally, and are in some cases influenced by processes themselves, correlations suggest a strong effect of process rather than substrate in influencing gully morphology.

In this study, we quantitatively analyse Antarctic gully morphologies and show that several different gully types are present. Based on characteristics of the different gully types, we infer slope processes that are operating, or have operated in the past, on Antarctic continental margins. The study aims to reduce large uncertainties regarding Antarctic slope processes and to provide a diagnostic tool in which gully types may be identified and used, alongside other indicators, in assessing the processes operating in these high-latitude environments.

## 2. Slope processes

There are large uncertainties regarding processes operating on different parts of the Antarctic continental margin, with the influence of slope processes and slope character difficult to separate. Suggested processes include mass flows, subglacial meltwater discharge and dense bottom water overflow.

Mass flows, including sediment slides, slumps, debris flows and turbidity currents may be initiated by a range of mechanisms such as gas hydrate dissociation, tidal pumping beneath large icebergs and near ice shelf grounding lines, resuspension by shelf and contour currents, tectonic disturbances, iceberg scouring and rapid accumulations of glacigenic debris at the shelf edge during glacial maxima (Larter and Cunningham, 1993; Vanneste and Larter, 1995; Shipp et al., 1999; Michels et al., 2002; Dowdeswell et al., 2006, 2008; Dowdeswell and Bamber, 2007).

Subglacial meltwater is thought to have been discharged from ice-sheet grounding lines during glacial maxima, through either of two processes. (1) A continuous supply, where basal water is generated predominantly through geothermal and strain heating, as there was little or no ice-surface melting during full-glacial times to supply the basal drainage system. Typical yields for geothermal heating are, however, in the range of mm/yr of basal melt (e.g. Beem et al., 2010; Pattyn, 2010), making it difficult to sustain continuous discharges over long periods. (2) Episodic water release such as subglacial lake discharges ('glacial outburst floods' or 'jökulhlaups') (Goodwin, 1988; Wellner et al., 2001; Dowdeswell et al., 2006, 2008; Fricker et al., 2007; Bell, 2008; Noormets et al., 2009; Piper et al., 2012). Subglacial meltwater is able to entrain sediment at the base of glaciers and may produce hyperpycnal flows when discharged at the grounding line (Russell and Knudsen, 1999a, b, 2002). The critical sediment concentration needed for meltwater to initiate hyperpycnal flows in seawater is 1–5 kg $m^{-3}$ (Parsons et al., 2001; Mulder et al., 2003). This value is considerably lower than previous estimates of sediment concentrations (e.g. 33 kg $m^{-3}$; Syvitski, 1989) which are based on buoyancy considerations and do not take into account the effects of fine-scale convective instability (Parsons et al., 2001; Mulder et al., 2003). Large palaeo-subglacial drainage systems have been documented on the inner Antarctic continental shelf and in onshore areas that are presently ice free (Sugden et al., 1991; Lowe and Anderson, 2002; Ó Cofaigh et al., 2002; Denton and Sugden, 2005; Domack et al., 2006; Anderson and Oakes-Fretwell, 2008; Larter et al., 2009). However, very few channel systems have been observed on well-preserved outer shelf sediments in cross-shelf troughs.

Dense bottom water formed from sea-ice freezing and brine rejection, and the cascading of this bottom water down-slope may also influence slope morphology (Kuvaas and Kristoffersen, 1991; Dowdeswell et al., 2006, 2008; Noormets et al., 2009). The Weddell Sea is the largest source of Antarctic Bottom Water (AABW), which is exported from the Southern Ocean and forms a major component of the global thermohaline circulation (Nicholls et al., 2009). High Salinity Shelf Water (HSSW), produced in the Weddell Sea through brine rejection during sea-ice production, is supercooled and freshened by circulation beneath the ice shelves, producing cold and dense Ice Shelf Water (ISW). HSSW and ISW contribute to the production of Weddell Sea Bottom Water (WSBW) and Weddell Sea Deep Water (WSDW), which are components of AABW (Nicholls et al., 2009). Temperature profiles of the water column west of the Antarctic Peninsula and in the Bellingshausen and Amundsen seas preclude bottom water production at the present day in those regions (Hoffman and Klinck, 1998; Smith et al., 1999; Smith and Klinck, 2002; Dinniman and Klinck, 2004). Gales et al. (2012) showed that deeply incised and V-shaped gullies, as observed on other parts of the Antarctic continental margins, were absent from the mouth of the Filchner Trough, in a region of active and highly energetic cascading dense water overflow. This absence makes it unlikely that V-shaped and deeply eroded gullies found elsewhere along the Antarctic continental margin were formed by erosion caused by cascading dense water (Gales et al., 2012).

## 3. Regional setting

The study areas on the Antarctic margin encompass 1919 km of continental shelf edge and upper slope to the west of the Antarctic Peninsula (WAP), in the Bellingshausen and Amundsen seas, and at the mouth of the Filchner Trough, Weddell Sea (Fig. 1). The continental shelves of the WAP, Bellingshausen, Amundsen and Weddell seas show characteristic landward-sloping gradients, formed as a result of erosional overdeepening of the inner shelves, and to a lesser extent lithospheric flexture due to ice sheet loading (ten Brink and Cooper, 1992; ten Brink and Schneider, 1995; Bart and Iwai, 2012). The continental shelves are dissected by broad cross-shelf troughs which extend to the shelf edge in places. The troughs were eroded by fast-flowing ice streams which transported sediment towards the shelf edge during glacial maxima (e.g. Vanneste and Larter, 1995; Dowdeswell and Siegert, 1999; Ó Cofaigh et al., 2003; Dowdeswell et al., 2004a, 2004b) and deposited prograding sedimentary sequences along the continental margin and upper slope (e.g. Kuvaas and Kristoffersen, 1991; Larter and Cunningham, 1993; Larter et al., 1997; Cooper et al., 2008). Modal depths of the Antarctic continental shelves are in the range of 400–600 m.

Although the study areas have varying tectonic histories (e.g. Hübscher et al., 1996; Livermore and Hunter, 1996; Eagles et al., 2004, 2009), the underlying Quaternary geology along these high-latitude continental margins is fundamentally similar. The continental slopes are constructed largely of prograded sequences (e.g. Anderson, 1999; Cooper et al., 2008) that reflect cycles of growth and retreat of grounded ice from the West Antarctic Ice Sheet (WAIS), East Antarctic Ice Sheet (EAIS) and Antarctic Peninsula Ice Sheet (APIS). At the mouth of the Belgica and Filchner Trough, sediment progradation has resulted in the formation of trough mouth fans which comprise mainly of glacigenic debris-flow deposits (Ó Cofaigh et al., 2003). The EAIS grew rapidly at the Eocene–Oligocene boundary (34 Ma), reaching the coast in Prydz Bay and the Ross Sea (Barron et al., 1988; Barrett, 1989; Barrett et al., 1995; Cooper and O'Brien, 2004). Early history of the WAIS is less clear; however, it is likely that a major step in its development was associated with the shift in oxygen isotope ratios in open ocean foraminifera about 14 Ma ago (Zachos et al., 2001). Compelling evidence from the morphology of volcanoes in Marie Byrd Land, West Antarctica, shows that the climate in the interior of the region has not been warm enough to permit significant runoff since the Middle Miocene (Rocchi et al., 2006). During the Last Glacial Maximum (LGM), ice extended across the continental shelf of the WAP and Bellingshausen, Amundsen and Weddell seas, reaching the shelf edge in most areas (e.g. Anderson et al., 2002; Ó Cofaigh et al., 2005a, 2005b; Hillenbrand et al., 2012).