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Large-scale submarine landslides, channel and gully systems on the southern Weddell Sea margin, Antarctica

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ABSTRACT

New multibeam bathymetric data from the southeastern Weddell Sea show significant differences in surface morphology of the outer continental shelf and slope between two adjacent cross-shelf troughs. These are the Filchner Trough and a smaller trough to the east which we refer to as the 'Halley Trough'. Multibeam bathymetric data, acoustic sub-bottom profiler and seismic data show major differences in the incidence and morphologies of submarine gullies, channel systems, submarine slides and iceberg scours, and in sediment deposition. These large-scale differences suggest significant variation in slope and sedimentary processes and in the environmental setting between the two troughs, leading to much greater deposition at the mouth of the Filchner Trough. Bedforms, including a terminal moraine and scalloped embayments on the outer shelf of the Halley Trough, provide insight into the relative timing and extent of past ice-sheet grounding and point to grounded ice near to the shelf edge during the Late Quaternary.

The new data reveal two large-scale submarine slides on the upper slope of the eastern Crary Fan, a trough mouth fan offshore from the Filchner Trough. Both slides head at the shelf edge (~500 m water depth), with the largest slide measuring 20 km wide and with an incision depth of 60 m. Multibeam and seismic data show elongate slabs on the seafloor surface of the mid-slope. The lack of a discernible sedimentary cover suggests that they were generated after the Last Glacial Maximum (LGM). This is unusual because post-LGM submarine slides are very rare on the Antarctic continental margin, and to our knowledge, no other post-LGM slides have been documented on an Antarctic trough mouth fan. Because the slides occur on a part of the continental slope where the deposition of glacial debris was greatest, we speculate that weaker, unconsolidated sedimentary layers within the subsurface are important for slide initiation here.

1. Introduction

The Antarctic continental margin has been influenced by the advance and retreat of grounded ice since 34 Ma (Barrett, 2008), which has led to a diverse range of continental slope morphologies. These include trough mouth fans, formed at the mouths of some glacially carved cross-shelf troughs; iceberg keel marks, gullies, channels, mass wasting features (slides, slumps), ridges, furrows and mounds (e.g. Ó Cofaigh et al., 2003; Dowdeswell et al., 2004, 2006, 2008; Noormets et al., 2009; Gales et al., 2013a). Bedforms, such as gullies, vary in size (width, incision depth and length), shelf incision, sinuosity, branching order, density and cross-sectional shape (Noormets et al., 2009; Gales et al., 2012).

Palaeo-morphologies influenced by past glacial activity are difficult to decipher from more recent slope processes due to the latter overprinting the expression of past glacial processes (i.e. iceberg scouring). Therefore, processes forming the complex continental slope morphologies and the factors influencing these processes are not well constrained. Processes which have been suggested to influence slope morphology include: (1) oceanographic processes such as geostrophic currents, tides and cascading dense water, formed during sea-ice formation through brine rejection (Kuvaas and Kristoffersen, 1991; Dowdeswell et al., 2006; Muench et al., 2009; Noormets et al., 2009); (2) sedimentary processes, such as mass flows (slides, slumps, debris flows and turbidity currents) influenced by a range of triggering mechanisms, including tectonic influences, gas hydrate dissociation, sediment loading, presence of weak sedimentary layers within the seabed, re-suspension by iceberg scouring, currents, tidal activity and changes in sea level; and (3) glacigenic processes, such as subglacial meltwater discharged from beneath an ice-sheet (e.g. released by

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sub-glacial lake discharge, basal melting, strain heating or subglacial volcanic eruptions), iceberg grounding, and high accumulations of glacigenic debris due to rapid transport by ice-streams to the shelf edge (Goodwin, 1988; Larter and Cunningham, 1993; Vanneste and Larter, 1995; Imbo et al., 2003; Long et al., 2003; Hillenbrand et al., 2005; Wellner et al., 2006; Dowdeswell et al., 2006; Dowdeswell and Bamber, 2007; Fricker et al., 2007; Dowdeswell et al., 2008; Piper et al., 2012b). These processes may be influenced by environmental controls, such as local slope character (slope geometry, gradient), debris content of ice, large-scale spatial characteristics (e.g. size of drainage basins, location of cross-shelf troughs) and ice-sheet history (Noormets et al., 2009; Peakall et al., 2012; Gales et al., 2013a). Deciphering the extent to which these processes and environmental controls influence slope morphology and the time-scales over which they occur remains a major challenge.

Post-Last Glacial Maximum (Post-LGM) submarine mass wasting is rare on the Antarctic continental margin (Barker et al., 1998; Dowdeswell and Ó Cofaigh, 2002; Nielsen et al., 2005), with no major slides documented on Antarctic trough mouth fans during the Quaternary. One of the few Quaternary slide examples from the Antarctic margin is the Gebra Slide, located on the lower continental slope of the Trinity Peninsula, Antarctica, in water depths of 1500–2000 m (Imbo et al., 2003; Casas et al., 2013). Early Pliocene slides and major erosional channels with chaotic infills have been documented on the Crary Trough Mouth Fan and in its distal part in the Weddell Sea basin (Bart et al., 1999), while Late Pliocene mega-scale debris flow deposits were observed on the western Antarctic Peninsula continental margin (Diviacco et al., 2006). Widespread Miocene mass wasting events have been documented off Western Wilkes Land (East Antarctica) (Donda et al., 2008). Submarine slides are common on other northern hemisphere high-latitude continental margins e.g. Storegga Slide (Bugge et al., 1987; Evans et al., 1996; Bryn et al., 2003), Trænadjuptet Slide (Laberg and Vorren, 2000; Laberg et al., 2002), Andøya Slide (Kenyon, 1987; Dowdeswell et al., 1996) and the Bjørnøyrenna Slide (Laberg and Vorren, 1993), located on the Norwegian and southwest Barents Sea margins. Knowledge of the dimensions and locations of large-scale mass wasting features, and the properties of the sediments in which they occur, may provide insight into the controls influencing slide initiation and slope instability. This is particularly important for better understanding submarine slide mechanisms and for predicting future risks associated with slope instability.

In this paper we present a quantitative analysis of the outer continental shelf and slope morphology of the southern and southeastern Weddell Sea. We examine differences in slope morphology observed between a trough mouth fan and the neighbouring part of the continental slope and discuss factors influencing the observed large-scale differences and the implications for past ice-sheet history and dynamics. We describe the morphology of two relatively young, large-scale submarine slides on the eastern flank of the Crary Fan and discuss possible slide initiation mechanisms.

2. Study area

2.1. Physiographic setting

The study area includes the shelf edge and upper slope of the southern Weddell Sea and the outer shelf and slope of the southeastern Weddell Sea, Antarctica, covering an area of ~56,300 km^2 (Fig. 1). The morphology of parts of the southern and southeastern Weddell Sea has been described previously (Kuvaas and Kristoffersen, 1991; Kuhn and Weber, 1993; Melles and Kuhn, 1993; Weber et al., 1994; Melles et al., 1995; Michels et al., 2002; Weber et al., 2011; Gales et al., 2012; Larter et al., 2012). Within the study area, the southern Weddell Sea shelf is dissected by the glacially-carved Filchner Trough which extends to the shelf edge and is associated with a fan offshore from its trough mouth (Crary Fan). The fan is characterised by convex-outward contours, thought to have been formed by repeated advances of grounded ice to the shelf edge causing the shelf to prograde 70–80 km from its pre-glacial location (Kuvaas and Kristoffersen, 1991). At the mouth of the Filchner Trough, small-scale and U-shaped gullies occur which are interpreted as small slide scars (Gales et al., 2012). Further down slope (below ~2400 m water depth) and to the east, large asymmetric channels are present, orientated southwest–northeast (Kuvaas and Kristoffersen, 1991; Kuhn and Weber, 1993; Weber et al., 1994). The channels feed into a large channel-ridge system at around 3400 m depth (Michels et al., 2002).

Helmert Bank forms the eastern margin of the Filchner Trough and the western boundary of a smaller trough to the east which we refer to as 'Halley Trough'. The Filchner Trough extends ~450 km from the Filchner Ice Shelf and has a width of 125 km and an axial depth of 630 m at the shelf edge. The Halley Trough is considerably smaller, with a width of 62 km, measured at the 400 m contour and a maximum depth of ~540 m at the shelf edge. International Bathymetric Chart of the Southern Ocean data (IBCSO; Arndt et al., 2013) shows that the Halley Trough extends >200 km inshore. The Brunt Basin, a depression seaward of the Brunt Ice Shelf, lies to the east of the Halley Trough (Fig. 1).

2.2. Glaciological, oceanographic and geological setting

The history of grounded ice extent on the southern and southeastern Weddell Sea has been widely debated, with disparities between marine and onshore ice-sheet reconstructions (Hillenbrand et al., 2012; Hillenbrand et al., 2013). Marine geological and geophysical data suggest that ice advanced across the southern Weddell Sea shelf, grounding at, or near to, the shelf edge of the Filchner and Ronne Troughs during the LGM (Elverhøi, 1981; Bentley and Anderson, 1998; Hillenbrand et al., 2012; Larter et al., 2012; Stolldorf et al., 2012). Hillenbrand et al. (2012) concluded that ice was grounded even within the deepest sections of the Filchner and Ronne Troughs during the LGM. However, available onshore cosmogenic exposure ages (Bentley et al., 2010; Hein et al., 2011) and glaciological modelling studies (Le Brocq et al., 2010) as well as some radiocarbon dates of pre-LGM age obtained from foraminifera in shelf sediment cores (Stolldorf et al., 2012) suggest that ice may not have been thick enough to ground at the shelf edge during the LGM.

The clockwise-flowing Weddell Gyre dominates the Weddell Sea's oceanographic circulation. The gyre transports Circumpolar Deep Water southward where it becomes Warm Deep Water (WDW) and, after further modification in the southern Weddell Sea, it becomes Modified Warm Deep Water (MWDW) (Orsi et al., 1993). High Salinity Shelf Water (HSSW) is produced during sea ice formation through brine rejection. Cold and dense Ice Shelf Water (ISW) forms when HSSW is super-cooled and freshened beneath ice-shelves (Nicholls et al., 2009). Measurements from current meters installed 10 m above the seafloor show that ISW flows towards the shelf edge within the Filchner Trough and cascades down the continental slope with a mean flow velocity of 0.38 m s^{-1} and a maximum velocity of 1 m s^{-1} (Foldvik et al., 2004). ISW mixes with MWDW to form a major component of Weddell Sea Deep Water and Weddell Sea Bottom Water, which in turn contributes to Antarctic Bottom Water (Foldvik et al., 2004). The latter is exported from the Southern Ocean and forms the deep southern branch of the global thermohaline circulation (Orsi et al., 1993; Naveira Garabato et al., 2002; Nicholls et al., 2009).

The near-surface sedimentary architecture of the southern and southeastern Weddell Sea shelf and slope has been well documented (e.g. Elverhøi and Roaldset, 1983; Haase, 1986; Ehrmann et al., 1992; Kuhn et al., 1993; Melles et al., 1994; Weber et al., 2011; Hillenbrand et al., 2012). Within the Filchner Trough, the seafloor surface sediments on the inner shelf are predominantly gravelly and sandy mud, with the trough floor on the mid-shelf largely covered by muds and sandy muds (Melles et al., 1994). The surface sediments on the outer shelf and shelf edge consist of sand and gravelly sand, while the underlying sediments