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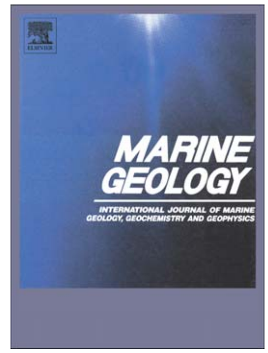

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Abstract

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 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.

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Key words: Slope processes; Antarctica; Continental slope; Slide; Mass wasting; Trough mouth fan.

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; Noormets et al., 2009; Muench 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

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subglacial meltwater discharged from beneath an ice-sheet (e.g. released by 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; Wellner et al., 2006; Long et al., 2003; Imbo et al., 2003; Hillenbrand et al., 2005; Dowdeswell et al., 2006, 2008; Dowdeswell and Bamber, 2007; Fricker et al., 2007; Piper et al., 2012). 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

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(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; Melles and Kuhn., 1993; Kuhn and Weber, 1993; Weber et al., 1994; Melles et al., 1995; Michels et al., 2002; Weber et al., 2011; Larter et al., 2012; Gales et al., 2012). Within the study area, the southern Weddell Sea shelf is dissected by the glacially-carved Filchner Trough which extends to the

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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).

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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 (LeBrocq 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, 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 toward 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

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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 recovered in cores were interpreted as glaciomarine and subglacial deposits (Elverhøi, 1984; Melles and Kuhn, 1993; Melles et al., 1994; Hillenbrand et al., 2012).

3. Data and methodology

We use multibeam bathymetric data collected on RRS *James Clark Ross* during cruises JR259 in 2012, JR244 in 2011 and JR97 in 2005 and bathymetric data collected on ten RV *Polarstern* cruises during expeditions ANT-IV/3, V/4, VI/3, VIII/5, IX/3, X/2, XII/3, XIV/3, XV/3 and XVI/2 in the 1990s. The extent of the datasets is shown in Fig. 2. Data were collected on RRS *James Clark Ross* using a hull-mounted Kongsberg EM120 (JR244 and JR97) and EM122 (JR259) multibeam bathymetric system with a maximum swath width of up to 132º (for the EM120 system) and 134° (for the EM122 system), with maximum angle variation depending on water depth, sea state (i.e. swell, sea-ice cover) and bathymetry. Both systems have a 191 beam array with real-time beam steering and active pitch and roll compensation and a frequency range of 11.25-12.75 kHz. The data aboard RV *Polarstern* were collected using a Hydrosweep DS1/2 with a frequency of 15 kHz. A Kongsberg TOPAS PS 018 acoustic subbottom profiler was used during cruise JR244. The TOPAS system transmits two primary frequencies at around 18 kHz from which secondary frequencies are generated ranging from 1300 to 5000 Hz by the parametric effect. The system is able to resolve sedimentary layers to <1 m and can penetrate ≥50 m below the seafloor in fine-grained sediment. The seismic line AWI 90060 was collected by RV *Polarstern* on cruise ANT-VIII/5 (1989-1990) using an 8-litre array of PRAKLA-SEISMOS airguns which

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operated at 140 bars and with an active hydrophone streamer length of 600 m and a shot spacing of 30 m recorded with a 2 ms sample interval.

The cleaned multibeam data were processed using public access MB-system software (Caress and Chayes, 1996) and grids with cell sizes of 20 m and 50 m were produced. Vertical resolution for the multibeam data is <1 m at 500 m water depth (for soundings between nadir and ±60°), increasing to >10 m for soundings at ±70° (de Moustier, 2001). Horizontal resolution varies with ship speed, water depth, beam angle, track spacing and seabed topography, with typical values of 10-20 m at 1000 m water depth. Cleaned hydrosweep data, also used for the IBCSO-map (Arndt et al., 2013), were gridded to a cell size of 50 m due to lower data resolution. The reflection seismic data were processed on R/V *Polarstern* and at the Alfred Wegener Institute, Bremerhaven, and displayed using a Landmark Promax system. The data were processed to a Common-Mid-Point (CMP) stack using standard procedures, with a CMP spacing of 25 m. A Stolt f-k migration was carried out on the data with a constant velocity of 1480 ms^{-1}. Backscatter maps were produced using FM Geocoder (Fonseca and Calder, 2005), the strength of backscattering being dependent upon sediment type, grain size, survey conditions, bed roughness, compaction and slope (Blondel and Murton, 1997).

The surface morphology was analysed quantitatively by extracting profiles parallel to the shelf edge along which bedform parameters were measured. We identify a gully as a small channel with a depth of >5 m that initiates from the upper slope or shelf edge. In this study, we define the point where a gully becomes a channel as the region where channel interfluve growth begins (in this study typically at 1600 m water depth). Measured parameters include bedform width, incision depth, length, sinuosity, branching order, cross-sectional shape, mean spacing and slope gradient.

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Cross-sectional shape was calculated using the General Power Law ($^{G}P_{L}$) programme (Pattyn and Van Huele, 1998) which provides a measure ranging from V-shape (1) to parabolic or U-shape (2) (*b* value; referred to as U/V index). The calculation is based on the power law equation (1), and the programme calculates a measure of cross-sectional shape (*b* value) by finding the minimum RMS misfit between the observed cross-section and a large set of symmetrical shapes defined by the equation. In equation (1), *a* and *b* are constants, χ and *y* are the horizontal and vertical coordinates taken from the cross-sectional bedform profile and χ_0 and y_0 are automatically determined coordinates of minimum elevation on the modelled profile.

$$y - y_0 = a\,|\chi - \chi_0|^b \qquad (1)$$

4. Results

4.1. Southeastern Weddell Sea morphology

4.1.1. Outer continental shelf (Halley Trough)

From new multibeam bathymetric data and IBCSO data (Arndt et al., 2013) we have identified the 'Halley Trough', located to the east of the Filchner Trough (Fig. 1). The Halley Trough mouth is 62 km wide at the 400 m bathymetric contour with the following asymmetric trough floor morphology (Fig. 3A; Table 1): water depths to the west of the trough axis reach 540 m at the shelf edge, compared to ~515 m to the east. The difference in depth is associated with an abrupt west facing scarp boundary to the east of the trough axis (near the 500 m bathymetric contour; Fig. 3, inset profile B-B'). The eastern flank of the Halley Trough is scalloped, with six concave NW-facing embayments (Fig. 3C; Fig. 4A). The individual arcuate embayments have a mean length (measured along the NW-SE axis) of 2.1 km, a mean width (measured along the NE-SW axis) of 2.3 km and a mean height of 20 m. Directly to the south of the scalloped features, a ridge runs parallel to the shelf edge, ~22.5

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km landward of it (Fig. 4B). From the available data, the ridge is 45 m high, 2.9 km wide with a minimum length of 4.5 km. The ridge has an asymmetric shape measured along profile C-C' (Fig. 4) with a slightly steeper landward flank (1.1°) compared to its seaward flank (0.5°).

The outer shelf is characterised by intense iceberg scouring, and the uppermost slope is dissected by iceberg keel marks to water depths of ~720 m (Fig. 3B, 5, 8B). In some instances, the keel marks on the uppermost slope incise the seabed by up to 24 m, with small arcuate ridges observed around the landward terminations of the scours.

4.1.2. Shelf edge and upper slope

Eastward of 30º41'W (eastern flank of the Crary Fan), the shelf edge and uppermost slope are characterised by small elongate iceberg grounding pits (Fig. 3B). The pits give the shelf edge a rough morphology and continue to a water depth of ~720 m. The grounding pits are 5-22 m deep and become less pronounced at the mouth of the Halley Trough and further eastward. Between ~74º41'S, 27º19'W and 74°39'S, 27°04'W, furrows that are ~9 km long and orientated parallel to the shelf break are observed 150 m below the shelf edge (Fig. 8B).

To the west of the Halley Trough, the mean gradient of the continental slope decreases from 3.9º to 0.5º at 1400 m water depth, with a concave upward lower slope profile (Fig. 6, Profile E). East of the trough mouth, the mean upper slope gradient is 3.7º, with the lower slope displaying a concave profile (Fig. 6, profile D). A change in acoustic backscattering and texture is observed across this region (Fig. 7), with higher backscatter on the upper slope at the mouth of the Halley Trough, decreasing down slope and to the west of the trough mouth.

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4.1.3. Gully systems

Forty eight gullies occur at the mouth of the Halley Trough (Fig. 3A, transect C-C’). The gullies do not incise the shelf edge and initiate ~150 m below the shelf edge (Fig. 8; Fig. 9). The gullies have a mean length of 12.9 km, an average width of 560 m and a mean incision depth of 11.8 m with low sinuosities and V-shaped cross-sections (Table 2). At ~1300 m water depth, a boundary occurs where small-scale mass wasting features are observed, similar to ‘type *IV*’ gullies observed on other high-latitude continental margins (Gales et al., 2013a; 2013b). The small-scale mass wasting features cross-cut the submarine gullies (Fig. 8C).

East of the Halley Trough mouth (i.e. eastward of 26°59’W), 70 small-scale and low sinuosity gullies occur on the upper slope offshore from the Brunt Basin. The gullies do not significantly incise the shelf edge and have a mean length of 3.2 km, a mean width of 303 m and a mean incision depth of 13.8 m. The gullies become progressively deeper and wider towards the Brunt Basin. A relatively smooth upper slope (depressions <5 m) occurs eastward of 25º58’W and also along the continental margin spanning the 15 km distance between the Halley Trough mouth and the Brunt Basin.

4.1.4. Channel systems

Down slope of the Halley Trough, gullies merge with branching and sinuous channels at ~1600 m depth (Fig. 8). The channels are V-shaped (U/V = 0.93), with a mean width of 1.2 km and a relief of 46 m taken along a profile at 1800 m water depth. Two sub-systems are identified. The first, between 28º42’W and 27º36’W, merges down slope into a large channel-ridge system trending north-eastward (Fig. 8). This previously documented ‘mega-scale channel’ (e.g. Kuvaas and Kristoffersen, 1991; Michels et al., 2002) is 18 km wide and 190 m deep at the 2800 m bathymetric contour.

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The second sub-system occurs eastward of 27º36'W. The channels merge with a ~2 km wide larger channel at 2600 m water depth that joins the mega-scale channel at ~3200 m water depth (Fig. 8) and proceeds as the Polarstern Canyon (Arndt et al., 2013). Within the sub-system, some channels display a braided morphology (Fig. 8D). Acoustic backscattering is higher within the channels than on the adjacent channel interfluves (Fig. 7). Further channel-ridge systems are observed down slope of the Brunt Basin (Fig. 8) (cf. Michels et al., 2002).

4.1.5. Mass wasting features

Two large submarine slides occur on the upper slope of the eastern flank of the Crary Fan, with the headwall of the largest slide (Slide *I*) between 74º33'S, 30º06'W and 74°27'S, 30°41'W (Figs. 10, 11; Table 3). This headwall has a width of 19.6 km and a relief of 60 m near the shelf edge. The slide can be traced for >20 km down slope. At the shelf edge, the relief of the slide is symmetric (Fig. 10, profile A-A'), with depressions at the margins and a shallow relief toward the centre. The headwall of the slide scar has a scalloped and stepped appearance to the west (Figs. 10B, 10E; Fig. 11) with smaller scarps along the headwall to the east, creating an irregular shelf edge (Fig. 10). Small depressions are observed on the multibeam data of the headwall of Slide *I* down to a water depth of 570 m (Fig. 10E). Seismic data show small scarps in the upper slope surface at 700, 725 and 800 ms TWT (Fig. 12). Smaller scarps also occur along the margins of Slide *I* (i.e. 30º1'W; 74º31S; Fig.10). These are ~500 m wide with a mean incision depth of <20 m (Fig. 10). TOPAS data show semi-transparent subsurface bodies within the scar of Slide *I* that appear lens-shaped in down-slope profiles (Fig. 10C). In some areas, stacks of lens-shaped bodies occur (Fig. 10D). Mean slope gradient within the slide scar is 2º.

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At least four elongate slabs occur down slope and to the east of Slide *I* (Fig. 10; 12A), at 1350 m, 1500 m, 1600 m and 1700 m water depth. Here, the gradient is reduced to 1.4º. The slabs have widths of <1.8 km, heights of <25 m and lengths of <12 km. Seismic data across the largest slab at ~2200 ms TWT (Fig. 12A) show reflectors downlapping onto a surface that is continuous with the surrounding seafloor. Below the slab, reflectors are generally sub-parallel and continuous.

The head of Slide *II* is located between 74º24'S, 31º1'W and 74º25'S, 30º58'W, and it increases in width with distance down slope, reaching a maximum width of 3 km and incision depth of 25 m at 1240 m water depth. It has a steep, nearly vertical scarp of 45 m which initiates at, but does not cut back significantly into, the shelf edge (Fig. 11). Slide *II* can be traced for 21 km down slope with a mean slope gradient of 2.3º.

Small-scale slide scars are also observed along the SE-ridge side of the western bank of the mega-scale channel down slope of the Halley Trough (Fig. 8), initiating at ~2350 m water depth. The small-scale slides have a mean width (measured along SW-NE axis) of 2.5 km, a mean incision depth of 39 m and a mean length (measured along NW-SE axis) of 2.2 km.

5. Interpretation and discussion

5.1. Weddell Sea slope morphology

A strong contrast in the morphology of the seafloor surface is observed on the continental slope directly offshore from the mouths of the Filcher Trough and the Halley Trough, with the former being characterised by deposition and the latter by erosion. The Halley Trough is smaller, shallower and shorter than the Filchner Trough, and its adjacent continental slope is characterised by a simple slope ramp. In contrast, convex-outward

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contours at the mouth of the Filchner Trough which remain evenly spaced down the slope, indicate the presence of a trough mouth fan and probably reflect a greater volume of sediment deposition. Slope gradient is on average ~2.5º in front of the Filchner Trough, whereas at the Halley Trough mouth, the slope is steeper, with a mean upper slope gradient of 3.7º (Fig. 6). A progression of bedforms is observed down slope of the Halley Trough, with the bedforms increasing in both relief and width down slope (Fig. 9) and ranging from small-scale iceberg scours on the upper slope to large-scale channels on the lower slope. The differences in slope geometry and gradient and in bedforms present, suggest that dominant slope processes vary across this region, probably due to differences in the glacial histories, ice-sheet drainage basin sizes, ice dynamic processes, geology of the sediment source areas and/or the time when these systems were active.

5.1.1. Iceberg scours

The upper slope seaward of the Halley Trough is significantly affected by small grounding pits and scours, interpreted to result from scouring by the keels of impacting icebergs. Iceberg keel marks incise the seabed up to 200 m below the shelf edge (~720 m water depth) (Fig. 8B; 9). Although the uppermost slope on the Crary Fan is also influenced by iceberg scouring, scours are less continuous there and the seafloor is less deeply incised. The maximum water depth of 630 m within the outermost Filchner Trough and the landward sloping shelf, imply that the icebergs that ploughed the deepest scours (~720 m water depth) did not originate from this region. This is because the icebergs only pass beyond the shelf break when they have shallower drafts than the depths on the trough axis. The icebergs may have originated from farther along the East Antarctic margin, which is consistent with observations that show icebergs drifting within the southern limb of the Weddell Gyre, i.e. from NE to SW (Weber et al., 1994; Stuart and Long, 2011). The icebergs were probably

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injected via the westward flowing Antarctic Coastal Current into the Weddell Gyre in this area (Gladstone et al., 2001).

Small arcuate sediment ridges are present at the landward terminations of some iceberg scours (Fig. 3B). These ridges are formed by sediment pushed by icebergs, suggesting that the shelf edge has been subjected to icebergs impacting from offshore. In the modern environment, Antarctic iceberg scouring in water depths >500 m are rare. This is because most icebergs calve from ice shelves, whose thickness decreases downstream of the grounding line due to the landward dipping continental shelf profile, creep thinning and basal melt (e.g. Dowdeswell and Bamber, 2007; Livingstone et al., 2012; Arndt et al., 2013). The wide extent of iceberg scours below 500 m may therefore reflect thicker icebergs detaching from a thicker ice shelf further east probably at the LGM when global sea level was ca. 120-130 m shallower than today.

5.1.2. Gullies

Forty-eight gullies occur along the upper slope offshore from the Halley Trough and eastward towards the Brunt Basin with a relatively high mean spacing (average 0.8 gully/km). Although gully widths and depths are similar to those at the mouth of the Filchner Trough (Table 2), the Halley Trough gullies have distinct V-shaped cross-sections, whereas the Filchner Trough gullies are predominantly U-shaped. Down slope, the gullies merge with a large channel system. The gullies initiate below the region of intense iceberg scouring at 720 m water depth (Fig. 9), and do not incise the shelf-edge. This contrasts with the surface morphology offshore from the Filchner Trough, where gullies incise the shelf edge by ~220 m (Gales et al., 2012). The gullies on the slope offshore from the Filchner Trough have short lengths, a shallow mean depth of 12.5 m and U-shaped cross-sections and are characteristic of small-scale slide scars (Gales et al., 2012).

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The gullies offshore from the Halley Trough mouth are characteristic of 'type *I*' gullies, displaying a non-branching, V-shaped and low sinuosity morphology (Gales et al., 2013a). Such gullies may have formed by suspended sediment flows, such as turbidity currents. Iceberg scouring is one mechanism which can initiate turbidity currents, as intense scouring may resuspend sediment deposited at the mouth of the trough, thus initiating dense turbid flows. This may explain why a large gully-channel system is present at the Halley Trough mouth, while sediment at the mouth of the Filchner Trough remains largely unaffected by intense iceberg scouring, with only small-scale gullies incising the shelf edge. These morphological differences suggest that during the period of intense iceberg ploughing at the mouth of the Halley Trough, ice was discharged through the mouth of the Filchner Trough, either as an ice shelf protruding over the uppermost slope, or in the form of a continuous flux of icebergs, and thus protected the upper slope from impacting icebergs. Even if no ice shelf protruded over the shelf break during this time, a steady supply of icebergs calved from the Filchner palaeo-ice stream front would have prevented large incoming icebergs from impacting the upper slope. Alternatively, grounding-line advance to the shelf break of the Filchner Trough may have occurred significantly later than in the Halley Trough, so that any deep iceberg scours on the slope offshore from the Filchner Trough were subsequently buried by glacigenic sediment supplied from the shelf edge. However, available subbottom data from the outer shelf and upper slope show a predominantly flat surface beneath sediments assumed to be of post-LGM age, with no evidence for buried iceberg scours (Fig. 5; Fig. 10B). .

The significant iceberg scouring within the Halley Trough suggests that ice derived from the Halley palaeo-ice stream must have been absent from the shelf edge at the time when large icebergs were arriving from offshore, or there was only a small local flux of icebergs calved from the Halley palaeo-ice stream. The intense iceberg activity therefore

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occurred either after or during retreat of the Halley palaeo-ice stream. This is consistent with increased iceberg activity during interglacial periods documented by high contents of iceberg rafted debris in interglacial sediments on the continental rise of the southeastern Weddell Sea (Weber et al., 1994).

Another initiator of turbidity currents is meltwater released at the grounding line of an ice stream. Such flows require a sediment concentration of 1-5 kg m-3, taking into account the effects of fine-scale convective instability, to overcome the buoyancy effects associated with freshwater in seawater (Parsons et al., 2001; Mulder et al., 2003). A freshwater flow with such a low sediment load would not be dense enough to remain at the seafloor, however Parsons et al., (2001) argued on the basis of their observations that some of the sediment load can be transferred from a meltwater plume to the underlying seawater, thus increasing the seawater density enough to trigger a turbidity current. Cascading flows of cold, dense water, produced during sea ice formation through brine rejection, may also influence continental slope morphology and energetic flows of cold, dense water have been documented at the mouth of the Filchner Trough flowing down slope with maximum velocities of 1 m s-1 (Foldvik et al., 2004). However, the gullies at the mouth of the Filchner Trough have a distinct U-shaped morphology with shallow depths and crescentic shelf-incising heads indicating that the gullies are more likely produced by small-scale slope failures (Gales et al., 2012). Bottom water production is limited on the southeastern Weddell Sea shelf due to a narrower continental shelf and narrower ice shelves (Fahrbach et al., 1994), therefore it is unlikely that gullies at the mouth of the Halley Trough were formed by cold, dense water overflow.

5.1.3. Small-scale mass wasting features

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Small-scale mass wasting features are observed along a boundary at ~1300 m depth on the slope in front of the Halley Trough (Fig. 8C) but are not observed on the Crary Fan, for which data coverage is more limited (Fig. 2). The mass wasting features incise the gullies, suggesting that they formed later. The features are similar to 'type *IV*' gullies observed on other high-latitude margins (Gales et al., 2013a; 2013b), which are characteristic of small-scale mass wasting. The fact that all the small-scale mass wasting features initiate along a common boundary at ~1300 m water depth, suggests their formation is due to a change in substrate strength within the shallow subsurface, for example due to failure within weak interglacial substrate sediments. A sediment core recovered from a channel-levee down slope of the mass-wasting features (PS1789, see location in Fig. 13), retrieved 1.5 m of post-glacial bioturbated muds deposited during the last 16 ka overlying a sequence of siliciclastic laminated and bioturbated biogenic-bearing sediments deposited from ~24 cal. ka BP to 16 cal. ka BP (Weber et al., 1994; 2011). It is likely that the small-scale slides are caused by failure within weak interglacial substrate sediments.

5.1.4. Channels

A large channel system is present down slope of the Halley Trough, between 28º42'W and 27º16'W (Fig. 8). The channels display a sinuous and branching morphology and merge with smaller and shallower gullies further up slope and a larger mega-scale channel down slope (Fig. 8). There is a clear down-slope increase in both relief and channel spacing. The relief development may originate from increased erosion by the convergence of flows from adjacent tributaries, which is expected to result in increasing flow discharge and bed shear stress (Mitchell, 2004). Alternatively, the increase in relief may reflect the deposition of fine-grained detritus on the channel levees and interfluves. The channels are likely formed by turbidity currents initiated on the upper-mid slope (cf. Kuhn and Weber, 1993; Weber et al.,

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1994; Michels et al., 2002). At the Halley Trough mouth, the slope gradient is higher than at the mouth of the Filchner Trough which may have allowed sediment transport to largely bypass the slope, with flows becoming confined within the erosional channels (Wynn et al., 2012). No channels systems are observed on the mid-slope offshore from the Filchner Trough. Large channel systems do however occur on the lower slope (Michels et al., 2002).

In some areas, channels have a braided morphology (e.g. 74º33'S, 27º15'W) (Fig. 8D). The presence of this braided network suggests a change in flow power, associated with changes in sediment or flow discharge (Ercilla et al., 1998; Hesse et al., 2001). As the slope gradient increases slightly down slope of the Halley Trough (Fig. 6, Profile D), the existence of the braided channel network suggests that suspended load must also increase for sediment to be deposited, as flow velocity otherwise increases with increasing slope gradient. The braided channel network may be associated with mass wasting features further up slope which may have supplied large amounts of detritus when small-scale slope failures occurred.

5.1.5. Submarine slides

Two large submarine slides occur on the eastern flank of the Crary Fan. Both slides have complex headwalls at the shelf edge. Down-slope bathymetric profiles and seismic data show a stepped appearance from the shelf edge down to ca. 600 m water depth (Figs. 10B; 11; 12B) indicating that sediment has been evacuated by retrogressive erosion. Several smaller scarps are present on the headwall of Slide *I*, which is characteristic of retrogressive erosion (Piper et al., 2012). The seismic data show that sub-parallel and continuous reflectors occur below the stepped shelf edge and below one of the elongate slabs observed further down slope. The slabs on the slope below Slide *I*, which are visible on both seismic and bathymetry data (Fig. 10; 12A), are either slide blocks rafted from further up slope or are remnant blocks.

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Recent submarine slides are rare on the Antarctic continental margin, with few other documented examples (e.g. Barker et al., 1998; Imbo et al., 2003). Although the relief is not as large as the 175 m deep Gebra Slide on the Trinity Peninsula margin (Imbo et al., 2003), Slide *I* has a greater width and can be traced for a similar length down slope. Seismic data from the axis of Slide *I* show its location in a region of the Crary Trough Mouth Fan, where large-scale mass wasting affected the upper continental slope during the Early Pliocene (Bart et al., 1999). This Early Pliocene collapse led to the erosion of major channels by sediment gravity flows, which were later infilled, and may have resulted from isostatic rebound and sea-level rise associated with a major reduction in Antarctic ice-sheet volume (Bart et al., 1999).

Other factors which influence slope instability on high-latitude continental margins include: (1) gas hydrate dissociation or methane-gas generation; (2) tectonic influences (earthquakes, tsunamis); (3) rapid accumulation of sediment at the shelf edge and uppermost slope resulting in under-compaction and excess pore water pressure and/or slope over steepening; (4) loading or unloading of ice at the shelf break; and (5) presence of 'weak' sediment layers within the seabed (Prior and Coleman, 1984; Bugge et al., 1987; Larter and Barker, 1991; Dowdeswell and Ó Cofaigh., 2002; Long et al., 2003; Nielsen et al., 2005; Laberg and Camerlenghi, 2008). The Weddell Sea is a passive margin, with no evidence for methane gas or gas-hydrates (e.g. Bart et al., 1999). The low slope gradients (~2º) suggest that slope over-steepening is not likely to have triggered the slides as previous studies have shown that high-latitude margins are able to maintain high slope gradients due to the generally poor sorting of glacially-transported sediments (Larter and Barker, 1989).

One mechanism which may influence the occurrence of slides on the Crary Fan is the presence of weak sediment layers interbedded with unsorted glacigenic detritus at the seafloor and within the seabed. Weak layers (i.e. fine grained, saturated, high clay content

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and/or underconsolidated) are common on Arctic continental margins and may have been essential in the initiation of the Storegga, Trænadjupet and Afen Slides (Bugge et al., 1983; Wilson et al., 2003; Canals et al., 2004). On the Antarctic upper slope, weak layers are generally thought to be less common, with contouritic layers mainly controlled by ocean circulation, and hemipelagic layers formed during interglacial or deglacial periods (Melles and Kuhn, 1993; Kuhn and Weber, 1993; Weber et al., 1994; Long et al., 2003;). However, the southern Weddell Sea shelf is one of the most important regions for dense bottom water formation and cascading flows may winnow fine particles from the shelf, depositing finer sediments further down slope (Melles and Kuhn, 1993; Weber et al., 2011). These sediments may become mixed with glaciomarine contouritic, hemipelagic and glacigenic sediments on the slope to form porous layers with a high-water content, low density, low strength and higher susceptibility to liquefaction under loading (Kuhn and Weber, 1993; Long et al., 2003). Compaction of the substrate with loading may expel water along the more permeable and weaker layers (Dugan and Flemings, 2000) reducing the stability of the slope. This may explain why recent slides occur on the Crary Fan, in a region of energetic and cascading dense water overflow, but are largely absent from many other Antarctic slope areas, where the oceanographic setting precludes cold, dense water formation. Another cause of weak layers on the Antarctic margin is the deposition of diatomaceous ooze during warm interglacial stages, which may lead to slope instability (Volpi et al., 2003). However, if this was the case, a wider occurrence of submarine landslides would be expected on the Antarctic margin.

TOPAS data from the axis of Slide *I* show lenticular bodies of semi-transparent sediment, interpreted to be debris flow deposits. Stacked debris flow deposits occur down slope (Fig. 10C; 10D), indicating that the debris flows post-date the slide event and possibly originate from retrogressive failures of the slide headwall. Rapid sediment transfer to the

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slope may be a further mechanism influencing the instability of the Crary Fan, especially if sediment is deposited rapidly on top of weaker layers, increasing pore pressures within the seabed and thus slope instability. Additional sediment cores from this region are needed to constrain both the timing of the events and the nature of the underlying sediment, which may shed light on slide initiation mechanisms.

5.2. Past glacial history

The glacial history of the Filchner Trough is widely debated (Hillenbrand et al., 2013). In contrast, there is little knowledge about the glacial history of the Halley Trough; however, our new bathymetric data show arcuate escarpments, which may mark the limit of a till sheet, and a terminal moraine suggests that ice was grounded near to the shelf edge during previous glaciations.

5.2.1. Evidence for grounded ice

Geomorphic features and sediment core data from the mid to outer shelf suggest that ice was present near the shelf edge during previous glacial periods in the Filchner Trough (Larter et al., 2012; Hillenbrand et al., 2012). We observe a terminal moraine (Fig. 4) within the Halley Trough (22 km landward of the shelf edge), documenting that ice advanced to the outermost shelf here as well. The moraine has a 45 m high lee side, displaying a characteristic asymmetric shape with a steep landward and a more gentle seaward flank. The presence of this terminal moraine probably marks the maximum extent of a grounding line advance. Mega-scale glacial lineations are not observed landward of the terminal moraine, but these may have been eradicated by subsequent iceberg scouring.

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A NE-SW trending escarpment is characterised by six scalloped embayments (Fig. 3C), which incise the outer shelf between the shelf-edge and the terminal moraine. The features are characteristic of small-scale slope failures, with mounds at the mouths of the scars that are probably slump or debris flow deposits. This unique morphology has not been observed along other cross-shelf troughs in Antarctica, and the formation process for the embayments is unclear. We suggest that they formed as a result of slope failures in unconsolidated mud deposits which were overridden by a till sheet. As the region is also heavily iceberg scoured, prolonged iceberg furrowing may also have eroded the margin of the till sheet. A tentative explanation is that ice extended towards the outer shelf from the southeast during the last glacial period, but did not ground on the deeper western side of the trough. The embayments may therefore have formed on the western boundary of the till sheet deposited along the eastern side of the trough and may mark the westernmost extent of grounded ice during the last ice advance. A more detailed study of the inner and mid-shelf morphology and information from sediment cores are needed to further constrain the past glacial history of the Halley Trough.

5.2.2. Drainage basin size and source area

The significant differences in sedimentation and surface morphology along the continental margin from the Filchner Trough to the Halley Trough are likely to reflect differences in drainage basin size and basal conditions of the ice streams draining through them and probably also differences in the timing of their advance and retreat. Regional bathymetry data (IBCSO; Arndt et al., 2013) and subglacial topographic data (Fretwell et al., 2013) suggest that the Filchner and Halley Troughs were fed from different sources, with the Filchner Trough fed by a palaeo-ice stream with a drainage basin extent into the interior of both West

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and East Antarctica (Larter et al., 2012) and the Halley Trough fed by glaciers draining a smaller basin along the Caird Coast in East Antarctica.

A clear boundary is observed in the backscatter data between the eastern Crary Fan flank and the slope west of the Halley Trough (Fig. 7). Coincidentally, the slope gradient on the eastern Crary Fan (Fig. 6, profile E) is lower than further west (Fig. 6, profile A-B). The lower backscatter on the Crary Fan probably indicates deposition of finer grained sediments than on the upper slope offshore from the Halley Trough and suggests a predominantly depositional environment. This variation in sediment texture may reflect differences in the source rock areas and composition, glacial transport distances, oceanographic circulation (e.g. fine-grained sediment transport along the pathways of cold, dense water flow) or the size of drainage basins. The extent and size of the ice-sheet and drainage basins may have also influenced the volume of meltwater discharged down slope. The Filchner palaeo-ice stream would have drained a large area in the interior of the Antarctic Ice Sheet. In the vicinity of the drainage basin of this palaeo-ice stream, snow would have accumulated at higher elevations and in colder temperatures, resulting in colder ice, compared to the palaeo-ice stream that drained over a relatively short distance through the Halley Trough (cf. Dixon, 2008;). Conversely, high elongation ratios of glacial lineations mapped on the shelf within the Filchner Trough indicate that there the palaeo-ice stream flowed relatively fast (Larter et al., 2012). Therefore, strain heating at the base of the Filchner palaeo-ice stream may alternatively have resulted in warmer basal ice. The balance between these effects has implications for the amount of subglacial meltwater produced, and numerical ice sheet modelling may provide insight into which effect dominates.

6. Conclusions

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We observe significant differences in continental slope morphology and sediment depositional and erosional features at the mouths of two geographically close cross-shelf troughs in the southern Weddell Sea, Antarctica.

- Large-scale differences between the Filchner Trough and the Halley Trough are observed in the outer shelf and upper slope morphology. Offshore from the mouth of the Filchner Trough, a large trough mouth fan (Crary Fan) is present, with small-scale and U-shaped gullies incising the shelf edge and two large submarine slides observed on the slope. On the slope directly offshore from the mouth of the Halley Trough, deeply entrenched and sometimes braided channel systems occur and small-scale and V-shaped gullies incise the upper slope. Bedforms (gullies, mass wasting features, channels and mega-scale channels) all increase in size down slope below an iceberg-scoured zone immediately seaward of the shelf break.
- Two large-scale submarine slides are observed on the eastern flank of the Crary Fan. Slide initiation here may have involved weak sedimentary layers formed by cascading flows of cold, dense water through the Filchner Trough. This is the first example of a relatively young slide on an Antarctic trough mouth fan and provides evidence for large-scale mass wasting processes on the Antarctic margin during the Late Quaternary.
- The Halley Trough mouth is significantly affected by iceberg ploughmarks with the icebergs originating from the shelf further east. The Filchner Trough is less affected by intense iceberg impacts, which suggests that during the time when large icebergs scoured the Halley Trough mouth, the mouth of the Filchner Trough was covered by an ice shelf protruding over the shelf break, the trough was protected from the impacting icebergs by icebergs being discharged from the front of the Filchner palaeo-ice stream, or that the grounding line of this ice-stream was located further

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inshore and advanced to the shelf break much later than the Halley palaeo-ice stream, resulting in the burial of deep iceberg scours by glacigenic debris.

- The differences in slope morphology observed between the Filchner Trough and the Halley Trough may reflect variations in the drainage basin size, basal ice conditions and in the histories of advance and retreat of the palaeo-ice-streams that drained through them. Backscatter data suggest that the sediment offshore from the mouth of the Halley Trough is coarser grained than offshore from the mouth of the Filchner Trough, potentially indicating differences in the sediment source areas, source rock compositions and degree of communition during glacial transport.
- This study highlights the need for a more detailed study of the inner and mid-shelf of the southern and southeastern Weddell Sea in order to better constrain the chronology and behaviour of past ice-sheet history, and the need for further marine geological, geotechnical and geophysical investigations to improve understanding of how differences in ice-stream systems are manifested in slope processes and morphology.

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Tables and Figures.

Table 1. Geomorphic features of the Filchner Trough and the Halley Trough mouths.

Table 2. Mean gully parameters from the Filchner Trough and the Halley Trough.

Table 3. Dimensions of the slides observed on the eastern Crary Fan, southern Weddell Sea.

Figure 1. Study area. Bathymetric data is from IBCSO (Arndt et al., 2013). Antarctic Ice Sheet is shaded Landsat Image Mosaic of Antarctica (LIMA) data (U.S Geological Survey, 2007). Dashed lines mark cross-shelf trough margins. Black box marks study area and locates Fig. 2 and Fig. 8A.

Figure 2. Data extent for southern Weddell Sea. **A**. Data collected by Alfred Wegener Institute on expeditions ANT-IV/3, V/4, VI/3, VIII/5, IX/3, X/2, XII/3, XIV/3, XV/3 and XVI/2. **B**. Data collected by the British Antarctic Survey on cruises JR244, JR97 and JR259. Grey profiles (A-E) locate down-slope profiles in Fig. 6. Grey square locates Fig. 7. **C**. Combined multibeam datasets. Grey squares locate Fig. 3A and Fig. 10.

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Figure 3. A. Outer shelf and upper slope morphology of the Halley Trough, southeastern Weddell Sea. Profile A-A' highlights location of cross-shelf profile in Fig. 9. Solid line B-B' is cross-shelf profile in bottom left. Dashed line C-C' highlights transect that 48 gullies were measured along. **B**. Iceberg keel marks, sediment ridges and grounding pits on the outer shelf of the flank of Halley Trough. **C**. Scalloped embayments within the Halley Trough. Location of Fig. 3A is shown in Fig. 2C.

Figure 4.A. Terminal moraine. Location of Fig. 4A is marked in Fig. 3A. **B.** C-C' profile marked on part A. **C.** D-D' is TOPAS profile marked on part A.

Figure 5. Iceberg scour on the southern Weddell Sea outer shelf. **A.** TOPAS Profile through profile A-A' on C. **B.** Shelf profile through A-A' on C. **C.** Hillshaded bathymetry data of the southern Weddell Sea outer shelf. Location of 5C is shown in Fig. 10.

Figure 6. Slope profiles from the Filchner Trough (FT) and the Halley Trough (HT), Weddell Sea. The locations of profiles A-E are highlighted in Fig. 2B.

Figure 7. Backscatter data of the slope seaward of the Halley Trough. Darker shading indicates lower backscatter.

Figure 8. Hillshaded bathymetry data with sun illumination from NW. **A**. Southeastern Weddell Sea continental shelf edge and upper slope. **B**. Iceberg scouring and shelf-parallel furrows (location marked by black arrows). **C.** Small-scale mass wasting features (locations marked by black arrows). **D**. Braided channel system. Lines B-B', C-C', D-D', E-E' and F-F'

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mark location of cross-shelf profiles in Fig. 9. Black down-slope line (G-G') marks down-slope profile in Fig. 9. Location of 8A is shown in Fig. 1.

Figure 9. Down slope bedform progression at the Halley Trough mouth. Cross-shelf profile A-A' is marked by black profile A-A' parallel to the shelf in Fig. 3A. Cross-shelf profiles B-B', C-C', D-D', E-E' and F-F' are marked by black profiles parallel to the shelf edge in Fig. 8. The down-slope profile is marked by the black down-slope profile (G-G') in Fig. 8.

Figure 10. A. Submarine slides and mounds on the eastern Crary Fan flank, southern Weddell Sea. White dotted line is along-slope profile A-A' in upper right inset. Grey solid line highlights TOPAS profile (JR244) with white solid lines locating TOPAS profile sections shown in Fig. 10B, 10C and 10D. Bold, black dots highlight seismic profile AWI90060 (ANT VIII/5) with white dots locating sections displayed in Fig. 12A (eastern section) and Fig. 12B (western section). Thin black dashed lines illustrate extent of Slide *I* and *II* and scarps. Letters 'S' indicate scarps of slide scars. Location of Fig. 10 is shown in Fig. 2C. White square locates Fig. 5C. **B.** TOPAS profile section through shelf edge and upper slope. **C.** TOPAS profile section through upper slope. **D.** TOPAS profile section through mid-slope. **E.** Hillshaded perspective view of multibeam bathymetry of shelf edge and upper slope.

Figure 11. Down-slope profiles within Slide I (solid black line) and Slide II (dashed line). **B.** Inset figure showing down-slope profile of shelf edge and upper slope.

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Figure 12. Seismic data from seismic profile AWI90060 (Cruise ANT VIII/5) located in Figure 10. **A.** Slab on the lower slope. **B**. Scarps within slide *I* on the upper slope.

Figure 13. Interpretation of geomorphological features in the southeastern Weddell Sea. Dashed line marks shelf edge. Dotted line marks boundary of deeper section of seafloor within Halley Trough. Black arrow marks direction of palaeo-ice flow. Red point marks location of sediment core PS1789 (Weber et al., 1994, 2011).

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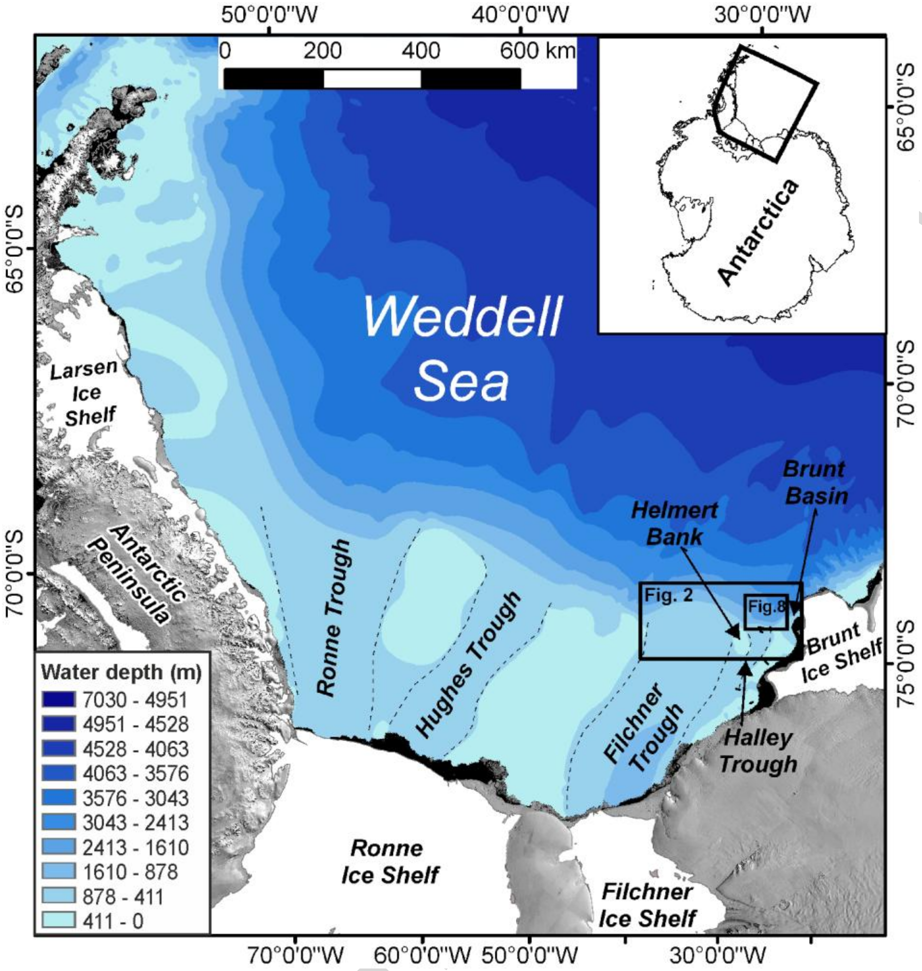
50°0'0"W
40°0'0"W
30°0'0"W
0 200 400 600 km
65°0'0"S
70°0'0"S
75°0'0"S
Antarctica
Weddell Sea
Larsen Ice Shelf
Antarctic Peninsula
Ronne Trough
Hughes Trough
Filchner Trough
Helmert Bank
Brunt Basin
Fig. 2
Fig.8
Brunt Ice Shelf
Halley Trough
Ronne Ice Shelf
Filchner Ice Shelf
Water depth (m)
7030 - 4951
4951 - 4528
4528 - 4063
4063 - 3576
3576 - 3043
3043 - 2413
2413 - 1610
1610 - 878
878 - 411
411 - 0
70°0'0"W
60°0'0"W
50°0'0"W
30°0'0"W

Figure 1

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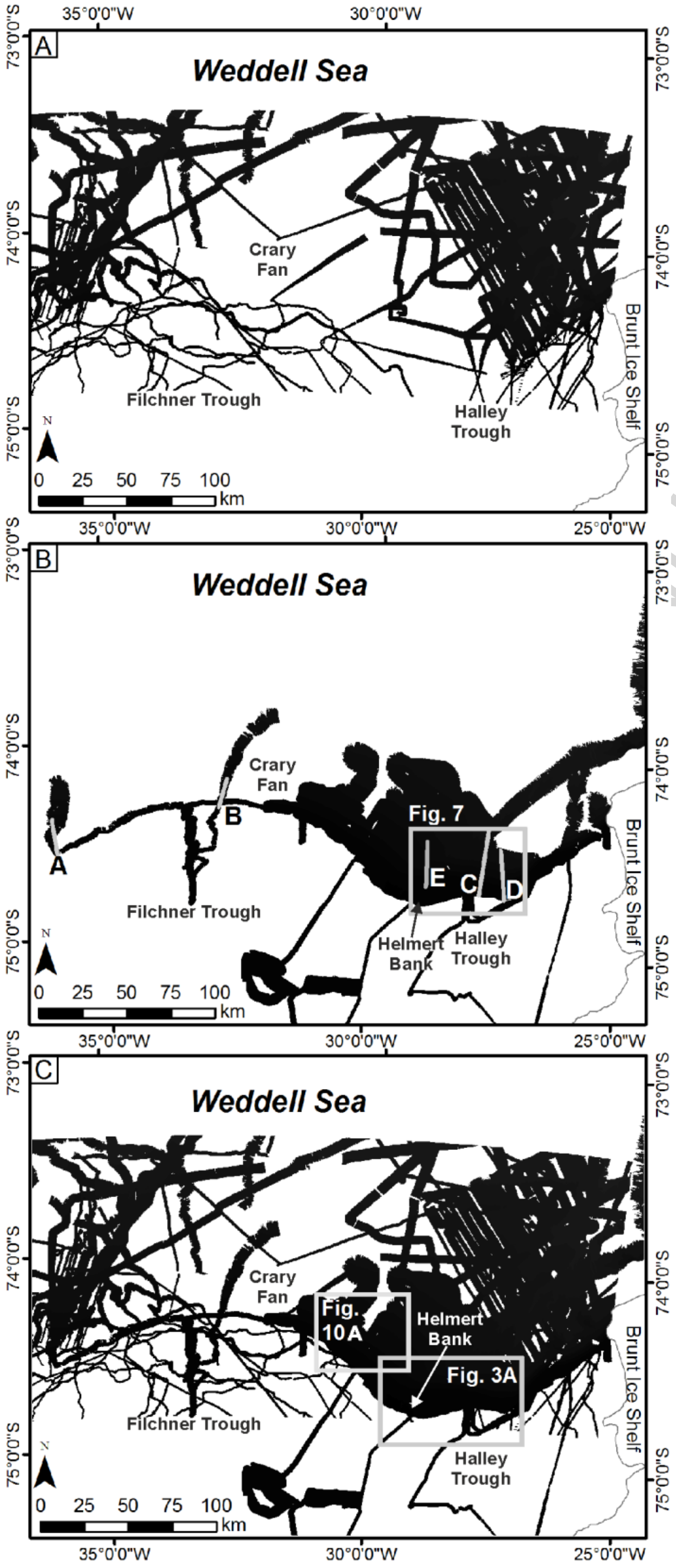
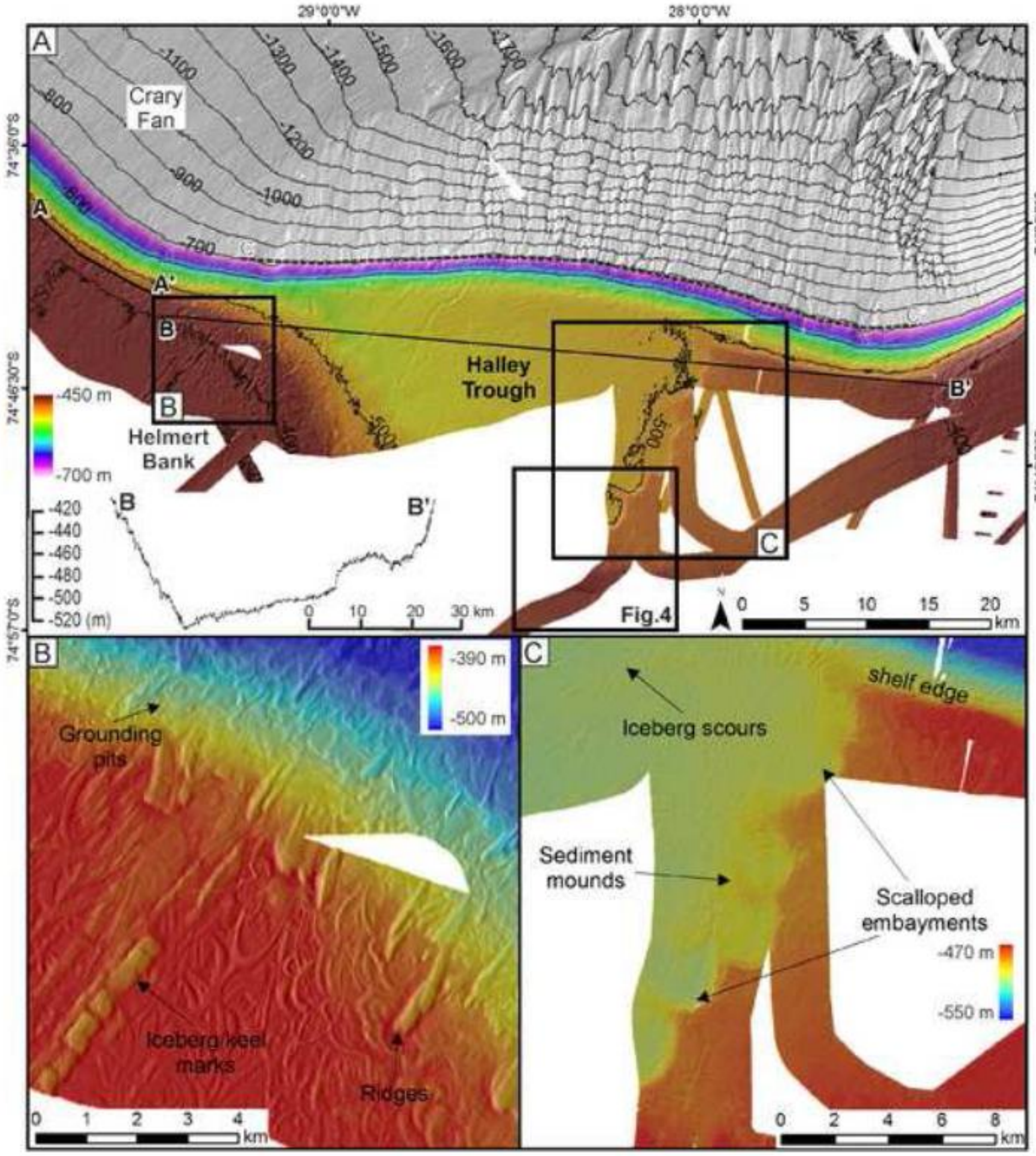


Figure 2



29°0'0"W
28°0'0"W
A
Crary Fan
Halley Trough
Helmert Bank
-450 m
-700 m
A
A'
B
B'
C
Fig.4
-420
-440
-460
-480
-500
-520 (m)
0 10 20 30 km
0 5 10 15 20 km
74°35'0"S
74°46'30"S
74°57'0"S
-390 m
-500 m
Grounding pits
Iceberg keel marks
Ridges
0 1 2 3 4 km
shelf edge
Iceberg scours
Sediment mounds
Scalloped embayments
-470 m
-550 m
0 2 4 6 8 km

Figure 3

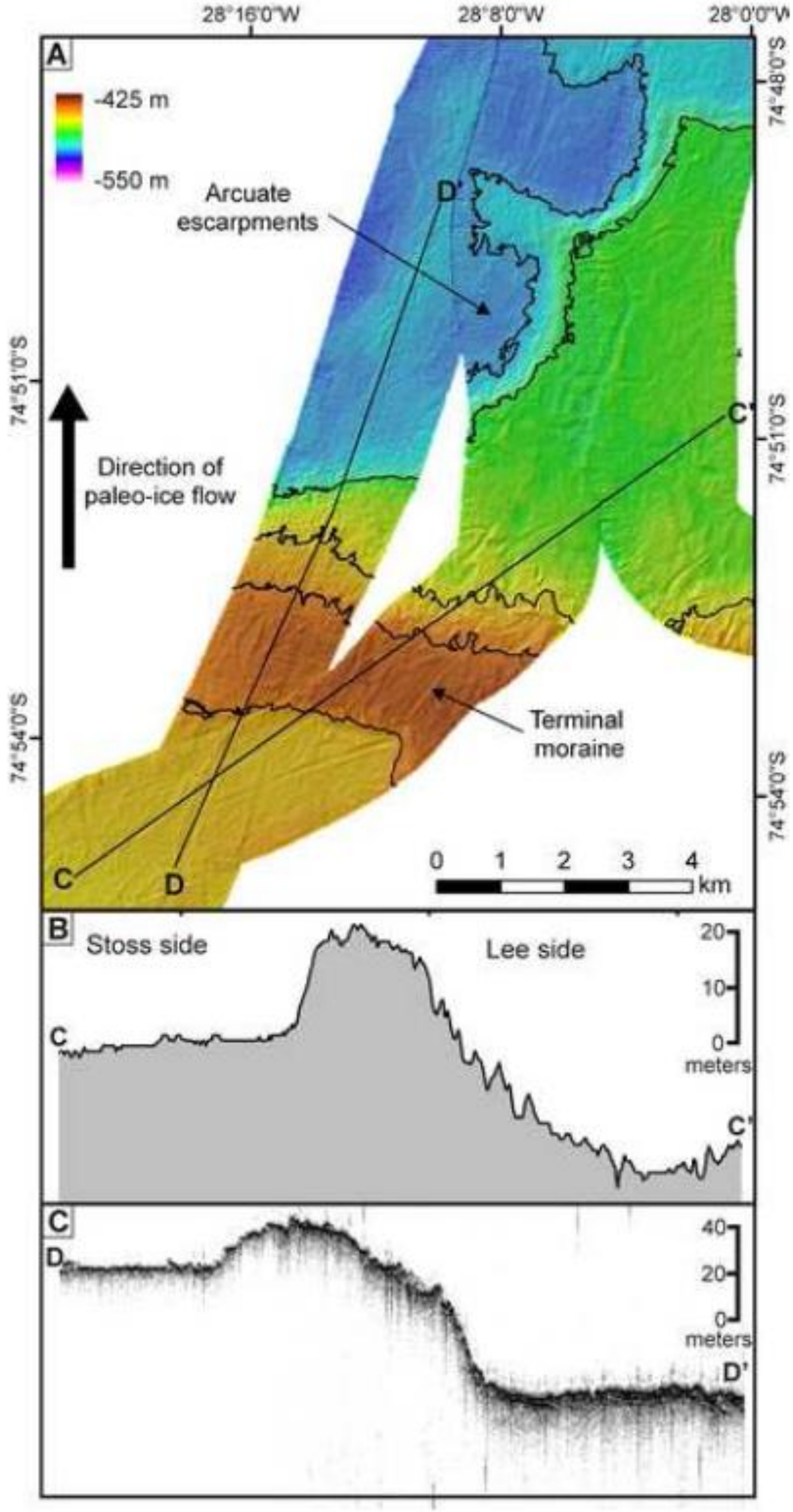

28°16'0"W
28°8'0"W
28°0'0"W
74°48'0"S
74°51'0"S
74°54'0"S
A
-425 m
-550 m
Arcuate
escarpments
D'
Direction of
paleo-ice flow
C'
Terminal
moraine
C
D
0 1 2 3 4 km
B
Stoss side
Lee side
20
10
0
meters
C
C'
C
D
40
20
0
meters
D'

Figure 4

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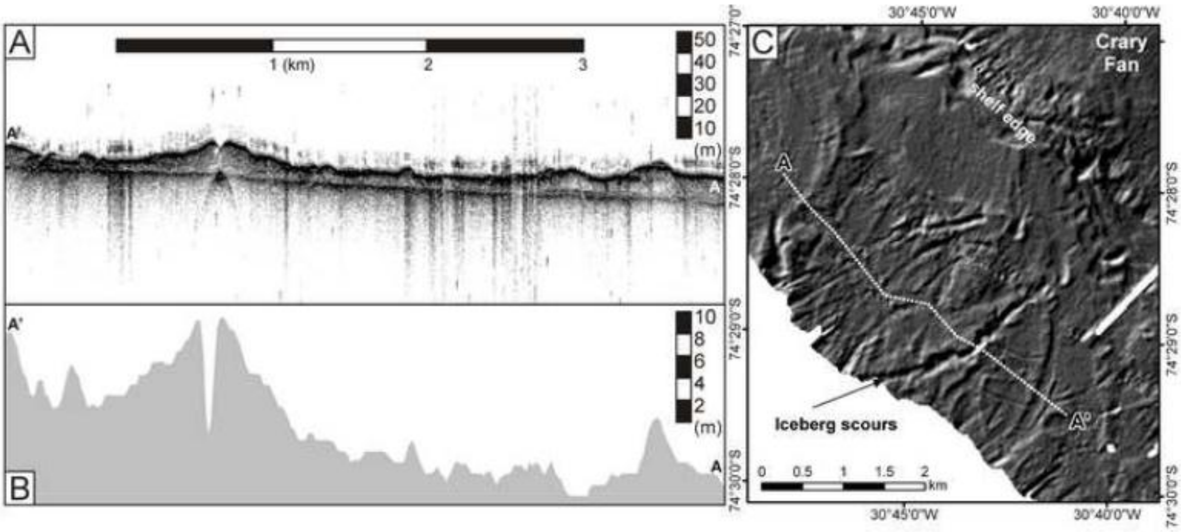

Figure 5

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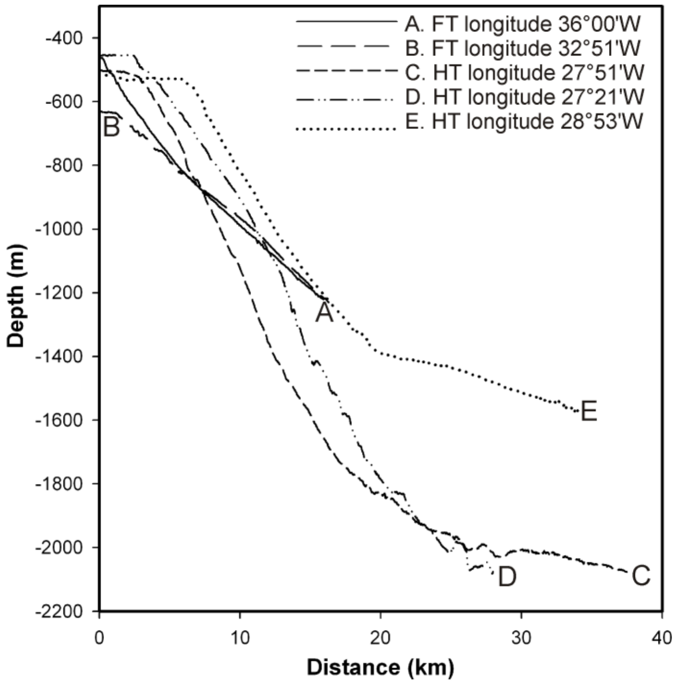

Figure 6

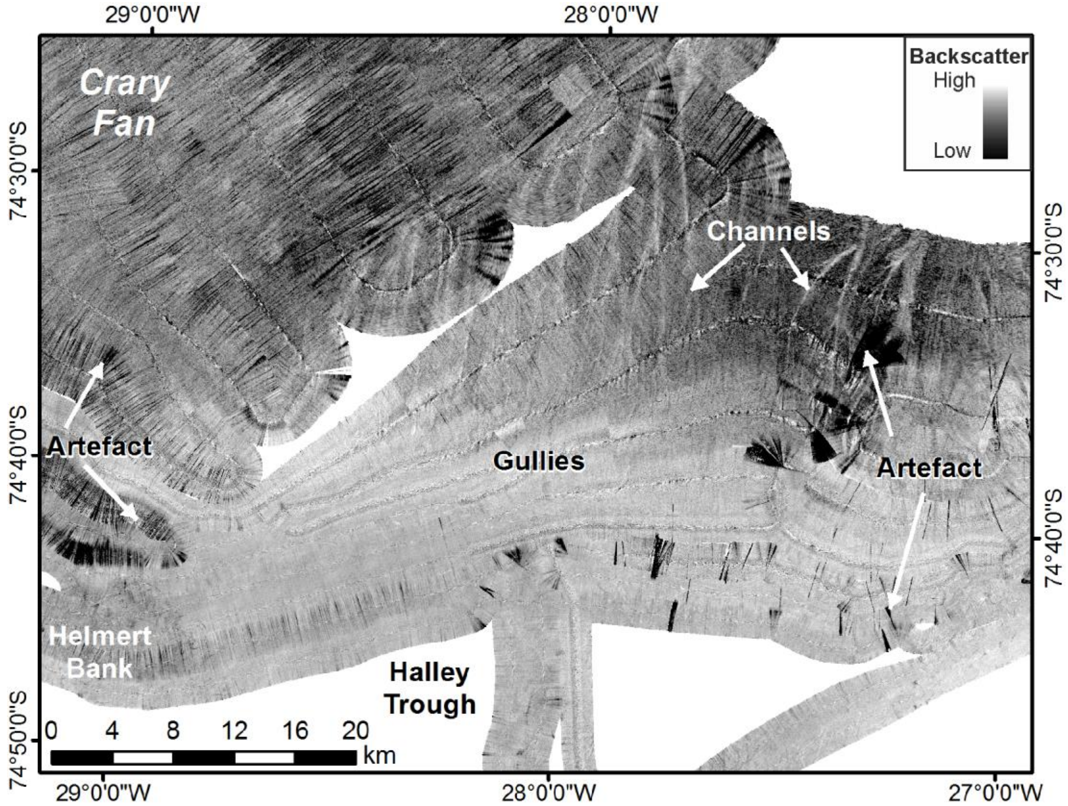

Figure 7

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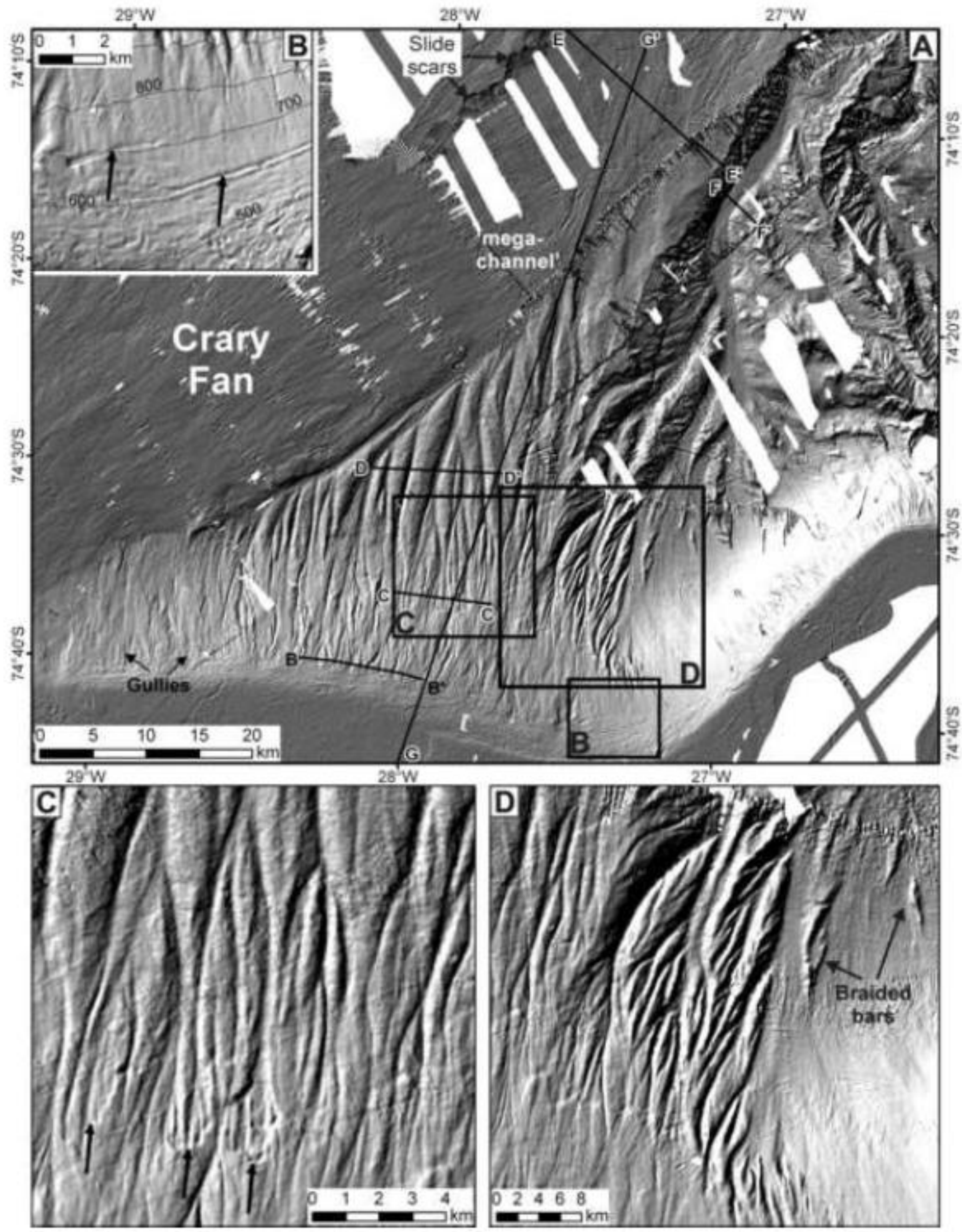
29°W
28°W
27°W
74°10'S
74°20'S
74°30'S
74°40'S
A
B
C
D
Slide scars
'mega-channel'
Crary Fan
Gullies
Braided bars
0 5 10 15 20 km
0 1 2 km
0 1 2 3 4 km
0 2 4 6 8 km
800
700
600
500

Figure 8

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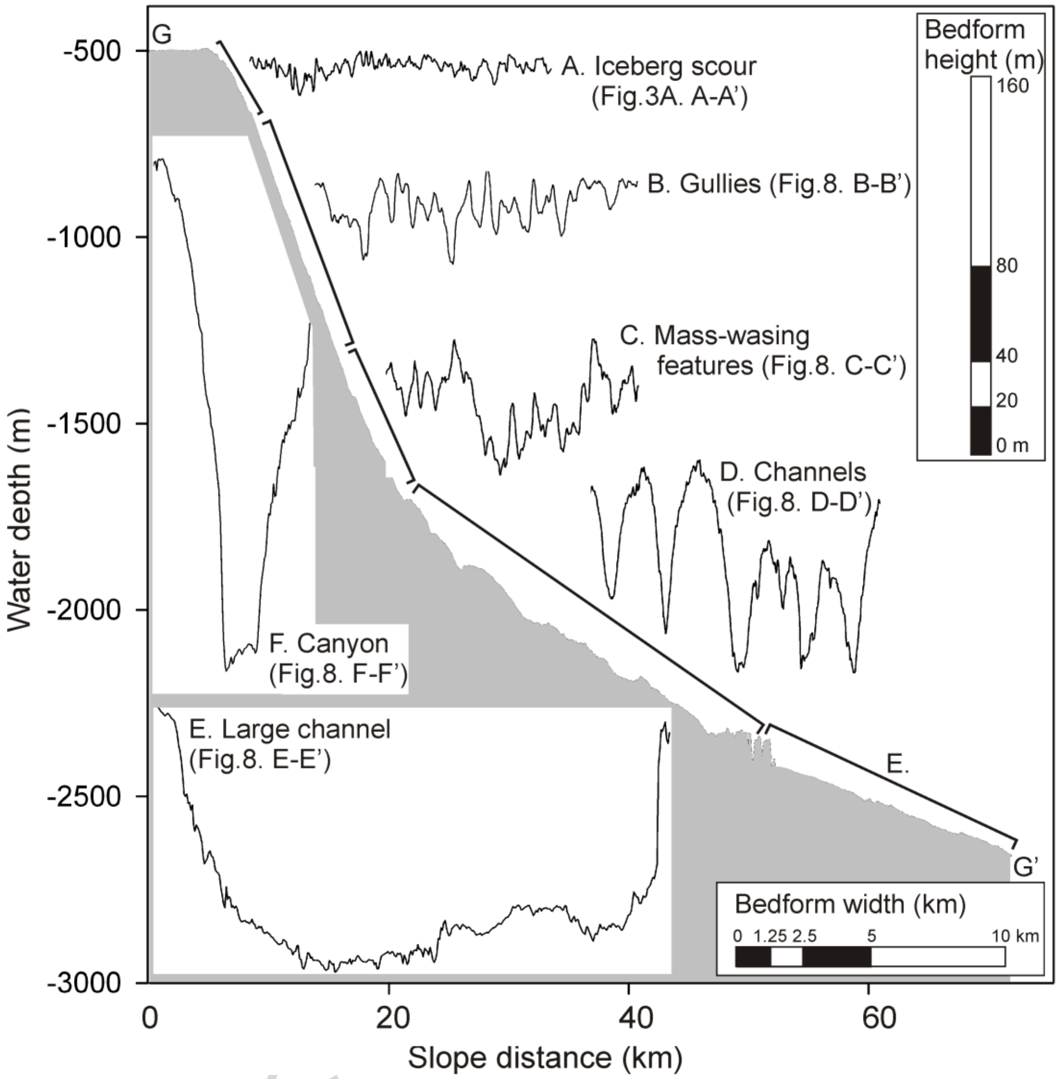

Figure 9

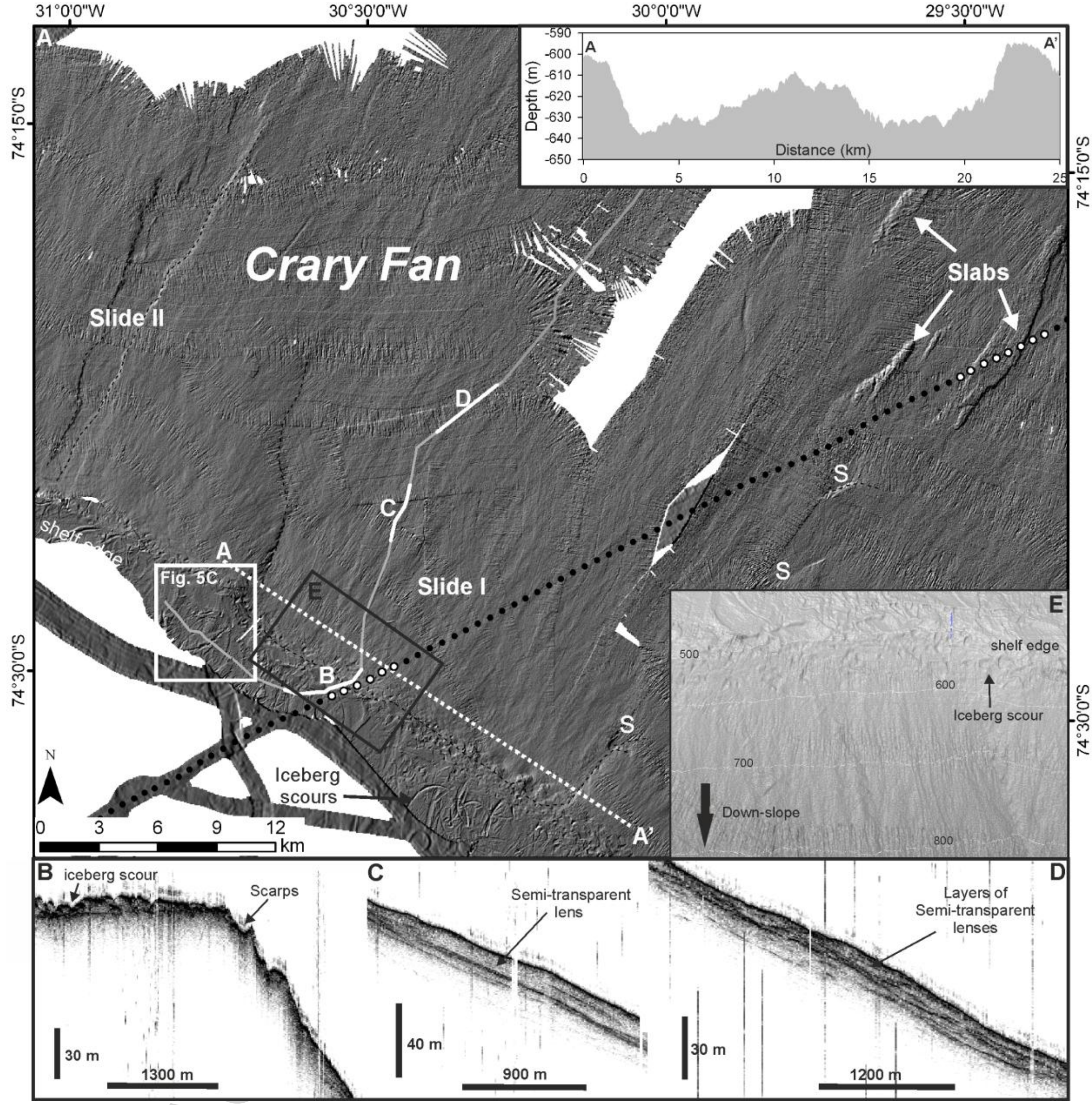
31°0'0"W
30°30'0"W
30°0'0"W
29°30'0"W
74°15'0"S
74°30'0"S
A
Depth (m)
Distance (km)
A'
Crary Fan
Slide II
Slide I
Slabs
D
C
B
E
S
shelf edge
Fig. 5C
Iceberg scours
km
0 3 6 9 12
shelf edge
Iceberg scour
Down-slope
500
600
700
800
iceberg scour
Scarps
30 m
1300 m
Semi-transparent lens
40 m
900 m
Layers of Semi-transparent lenses
30 m
1200 m

Figure 10

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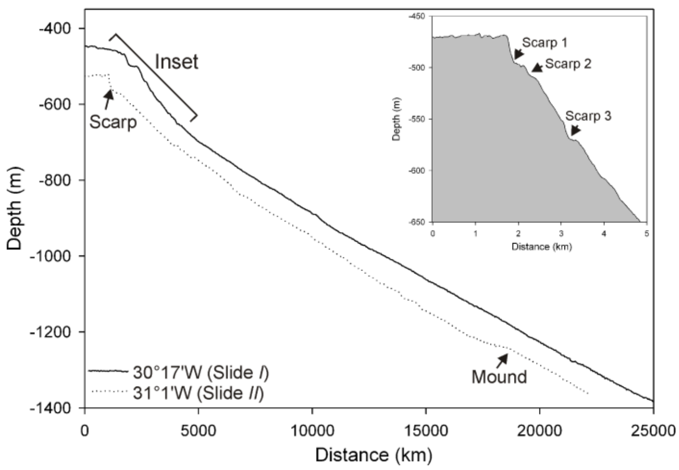

Figure 11

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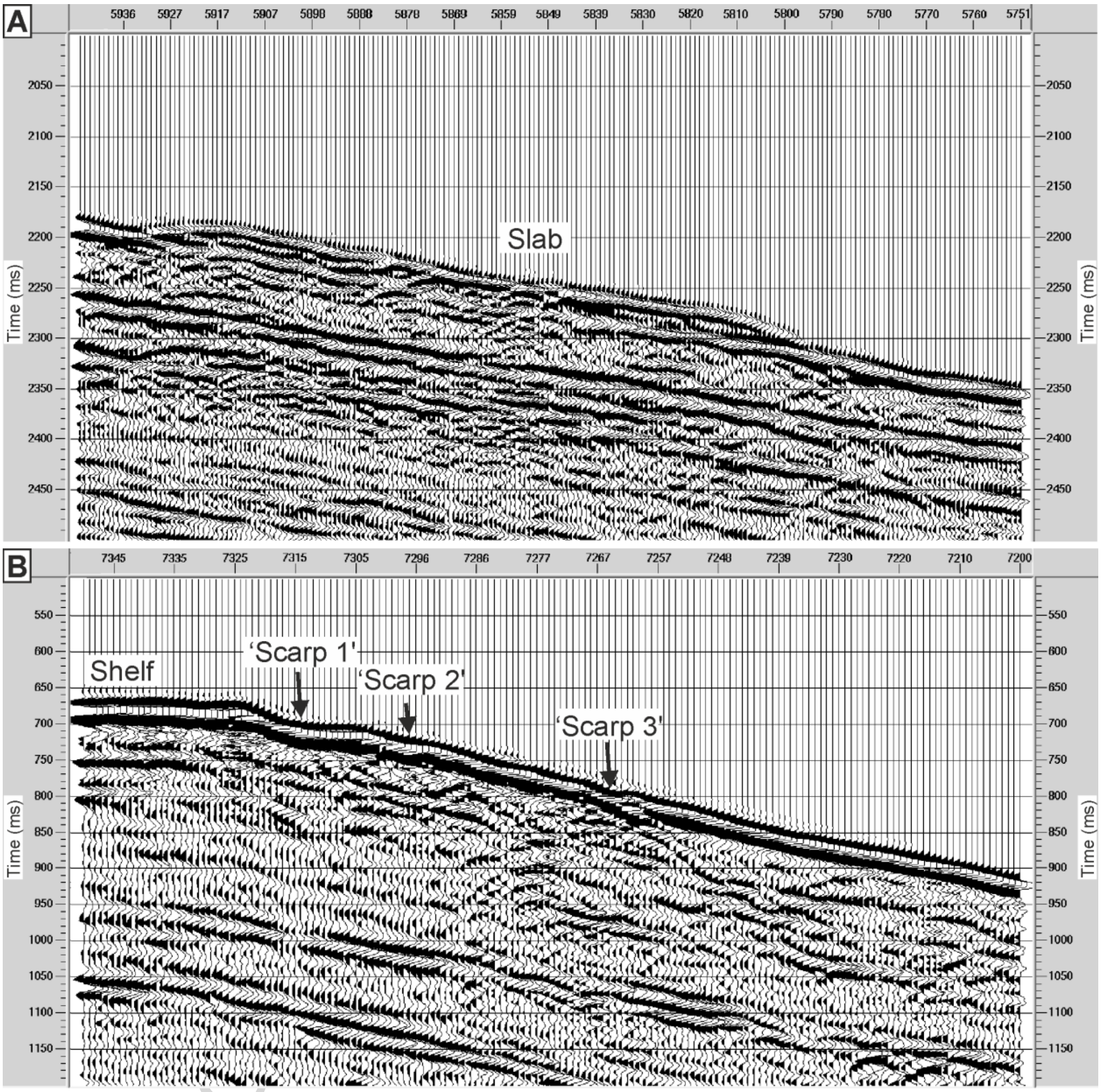

Figure 12

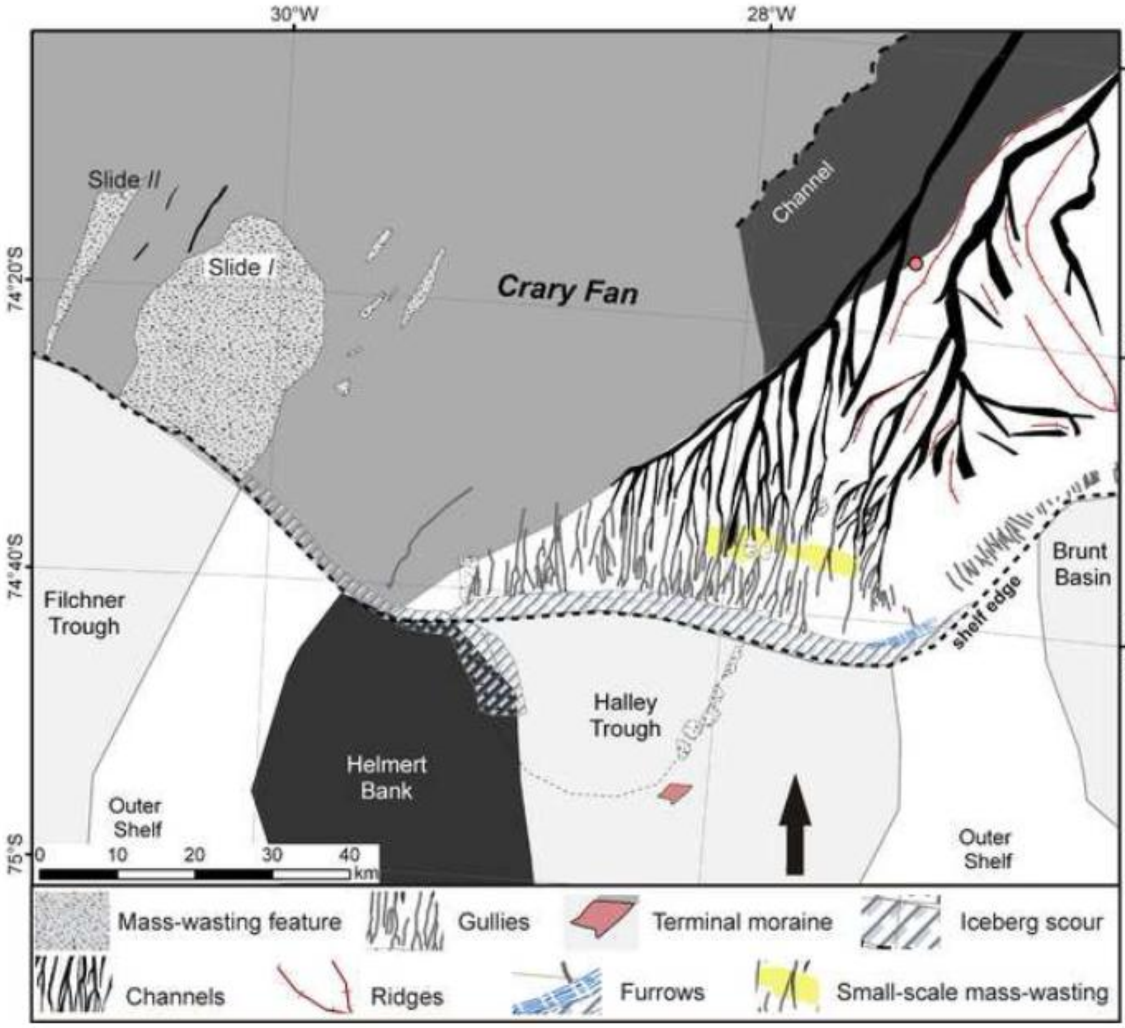
30°W
28°W
74°S
74°20'S
74°20'S
74°40'S
74°40'S
75°S
Slide II
Slide I
Crary Fan
Channel
Filchner Trough
Brunt Basin
shelf edge
Halley Trough
Helmert Bank
Outer Shelf
Outer Shelf
0 10 20 30 40 km
Mass-wasting feature
Gullies
Terminal moraine
Iceberg scour
Channels
Ridges
Furrows
Small-scale mass-wasting

Figure 13

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Table 1. Geomorphic features of Filchner Trough and Halley Trough mouths.

Geomorphic feature	Filchner Trough	Halley Trough
Upper slope gradient (º)	2.5	3.7
Width (km)[a]	125	62
Maximum depth (m)	630	540[b]/515[c]
Length (km)	>450	>200
No. of Gullies	76	48
Gullies/km	0.61	0.8

[a]Measured at shelf edge; [b]West of trough axis; [c]East of trough axis;

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Table 2. Mean gully parameters from Filchner Trough and Halley Trough.

Location	Gully parameters					
	Length (km)	Width (m)	Depth (m)	Sinuosity	U/V	Branching
Filchner Trough[a]	2.7	630	12.5	1.01	1.88	No
Halley Trough[b]	12.9	560	11.8	1.02	1.13	No

[a]Measurements taken at 50 m below the shelf edge; [b]Measurements taken at 200 m below the shelf edge.

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Table 3. Dimensions of the slides observed on the eastern Crary Fan, southern Weddell Sea.

Slide	Slope gradient (º)	Length (km)	Width[b] (km)	Incision depth[c] (m)	Direction of movement	Headwall	Segments within deposit
I 30º41'W, 74º27'S - 30º6'W, 74º33'S	2.0	>20	19.6	60	SW to NE	Complex, multiple small steps down-slope of larger scar. Small scars within larger scar.	Elongate rafted slide blocks (>4).
II 31º1'W, 74º24'S - 30º58'W, 74º25'S	2.3	21[a]	3	20	SW to NE	Small, vertical headwall.	No slide blocks observed.

[a]Limited by data extent; [b]Maximum width; [c]Maximum incision depth.

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Highlights

- Geomorphology shows different slope processes at two cross-shelf trough mouths.
- Two large and relatively young submarine slides occur on the Antarctic margin.
- Outer shelf morphology suggests ice extent near shelf edge during Late Quaternary.

ACCEPTED MANUSCRIPT