Southern Weddell Sea shelf edge geomorphology: Implications for gully formation by the overflow of high-salinity water

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Received 27 January 2012; revised 10 September 2012; accepted 21 September 2012; published 9 November 2012.

[1] Submarine gullies are the most common morphological features observed on Antarctic continental slopes. The processes forming these gullies, however, remain poorly constrained. In some areas, gully heads incise the continental shelf edge, and one hypothesis proposed is erosion by overflow of cold, dense water masses formed on the continental shelf. We examined new multibeam echo sounder bathymetric data from the Weddell Sea continental slope, the region that has the highest rate of cold, dense water overflow in Antarctica. Ice Shelf Water (ISW) cascades downslope with an average transport rate of 1.6 Sverdrups (Sv) in the southern Weddell Sea. Our new data show that within this region, ISW overflow does not deeply incise the shelf edge. The absence of gullies extending deeply into the glacial sediments at the shelf edge implies that cold, high salinity water overflow is unlikely to have caused the extensive shelf edge erosion observed on other parts of the Antarctic continental margin. Instead, the gullies observed in the southern Weddell Sea are relatively small and their characteristics indicative of small-scale slides, probably resulting from the rapid accumulation and subsequent failure of proglacial sediment during glacial maxima.

Citation: Gales, J. A., R. D. Larter, N. C. Mitchell, C.-D. Hillenbrand, S. Østerhus, and D. R. Shoosmith (2012), Southern Weddell Sea shelf edge geomorphology: Implications for gully formation by the overflow of high-salinity water, *J. Geophys. Res.*, *117*, F04021, doi:10.1029/2012JF002357.

1. Introduction

[2] Submarine gullies are distinct, small-scale, confined channels, forming the most common morphological features observed on the Antarctic continental slope. Gullies exist along the shelf edge and upper continental slope to the west and northeast of the Antarctic Peninsula, and in the Bellingshausen, Amundsen, Ross, and Weddell seas [*Vanneste and Larter*, 1995; *Shipp et al.*, 1999; *Lowe and Anderson*, 2002; *Michels et al.*, 2002; *Dowdeswell et al.*, 2004, 2006, 2008; *Heroy and Anderson*, 2005; *Noormets et al.*, 2009]. Along most of the length of these margins, seismic reflection and coring studies show that the gullies form in sediments deposited in glacially influenced environments [e.g., *Cooper et al.*, 2008]. Many authors have described the lithology, physical properties, grain-size composition, and mineralogical composition of continental slope sediments incised by gullies [e.g., *Anderson and Andrews*, 1999; *Michels et al.*, 2002; *Dowdeswell et al.*, 2004, 2006, 2008]. These properties are often homogenous and show a similar range of characteristics to glaciomarine and subglacial diamictons on the adjacent shelf [*Hillenbrand et al.*, 2005, 2009]. Variation in substrate type is therefore unlikely to be an important factor controlling gully geomorphological expression. The abrupt and angular shape of the gully interfluves in cross-section suggests that they are formed by erosion of the channels, rather than by aggradation of the interfluves [*Dowdeswell et al.*, 2008]. Numerous morphological gully styles are observed on Antarctic continental slopes (Figure 1), varying in gully size (length, width, and depth), branching order, sinuosity, extension into the shelf edge, cross-sectional shape, and spatial density.

[3] The variability in gully morphologies reflects the complexity of erosional processes occurring on high-latitude continental margins where it is likely that different processes or a different balance of processes have resulted in different morphological styles. By constraining these gully forming mechanisms, we increase our understanding of continental slope processes, seafloor erosion patterns, and continental margin evolution, which will help to interpret sediment core records from the continental slope and rise. This will also enable us to gain a better understanding of how gullies develop as precursors to the more major features of continental slopes, such as canyons.

[4] Antarctic gully formation has been attributed to erosion by (1) mass flows, such as sediment slides, slumps, debris flows, and turbidity currents, with triggering mechanisms including resuspension by shelf and contour currents, gas

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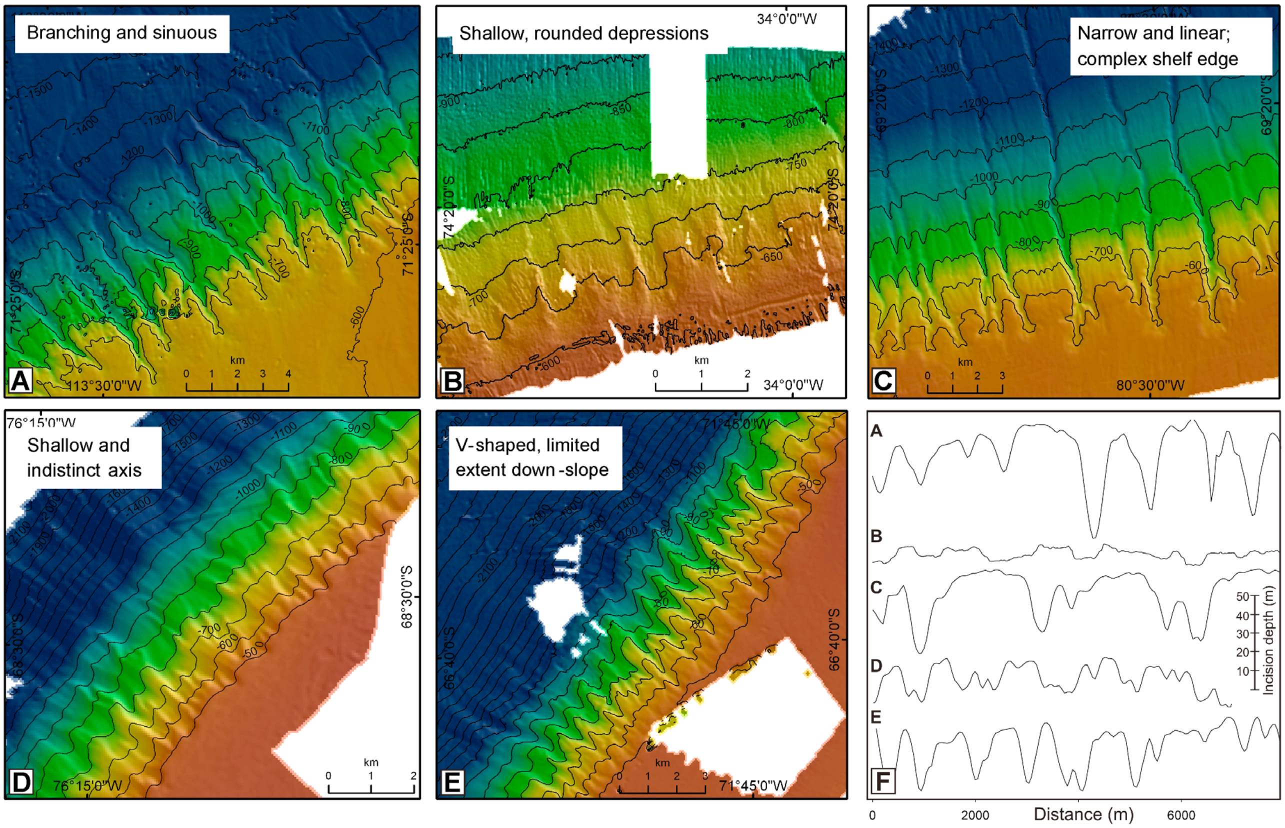

Figure 1. Antarctic slope geomorphology. Different morphological gully styles observed across Antarctic continental margins. (a) Branching and sinuous gullies in the Amundsen Sea. (b) Shallow, rounded depressions in the southern Weddell Sea. (c) Narrow and linear gullies with complex shelf edge in the Bellingshausen Sea. (d) Shallow gullies with indistinct gully axes on the western Antarctic Peninsula margin. (e) V-shaped gully with limited expression downslope on the western Antarctic Peninsula margin. (f) Cross shelf profiles at 50 m below shelf edge for gullies A–E. See Table 1 for data sources.

hydrate dissociation, tidal pumping beneath large icebergs and near ice shelf grounding lines, iceberg scouring, tectonic disturbances, and rapid accumulations of glaciogenic 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]; (2) subglacial meltwater discharge from ice sheet grounding lines during glacial maxima or deglaciations, whether by constant release [*Wellner et al.*, 2001; *Dowdeswell et al.*, 2006, 2008, *Noormets et al.*, 2009] or more episodic and large-scale release [*Wellner et al.*, 2006] possibly by meltwater evacuation from subglacial lakes [*Goodwin*, 1988; *Bell*, 2008]; and (3) dense water overflow [*Kuvaas and Kristoffersen*, 1991; *Dowdeswell et al.*, 2006, 2008; *Noormets et al.*, 2009].

[5] The potential for cascading, dense bottom water to erode gullies is not well documented or understood; however, such dense water overflow has been proposed as one potential mechanism for gully erosion in the Bellingshausen, Amundsen, and Weddell seas [*Kuvaas and Kristoffersen*, 1991; *Dowdeswell et al.*, 2006; *Noormets et al.*, 2009]. Most authors, however, favor the hypothesis of ice sheet derived basal meltwater and related mass wasting on the upper slope [*Wellner et al.*, 2001; *Lowe and Anderson*, 2002; *Dowdeswell et al.*, 2006, 2008; *Noormets et al.*, 2009]. Although dense water overflow is not an active process off the West Antarctic Peninsula or in the Bellingshausen and Amundsen Sea today, the possibility that it may have been active during previous stages of glaciation cannot be dismissed. This mechanism for gully erosion is also suggested on Norwegian margins, such as Bear Island Trough [*Vorren et al.*, 1989; *Laberg and Vorren*, 1995, 1996] and at midlatitude margins [*Micallef and Mountjoy*, 2011].

[6] In the terrestrial environment, fluvial erosion typically produces V-shaped incisions [*Simons and Sentürk*, 1992], and submarine fluid flow is widely thought to generate similarly shaped gullies [e.g., *Micallef and Mountjoy*, 2011] and channels [e.g., *Lonsdale*, 1977]. If dense water overflow was the mechanism responsible for forming the highly incisional and V-shaped gullies found on other Antarctic continental margins (Figure 1), we would expect a similar seafloor signature on the southern Weddell Sea margin, where dense bottom water overflow is well documented [e.g., *Nicholls et al.*, 2009].

[7] In this paper, we present new morphological data from the shelf edge and continental slope in the southern Weddell Sea. We present a quantitative analysis of the gully morphology

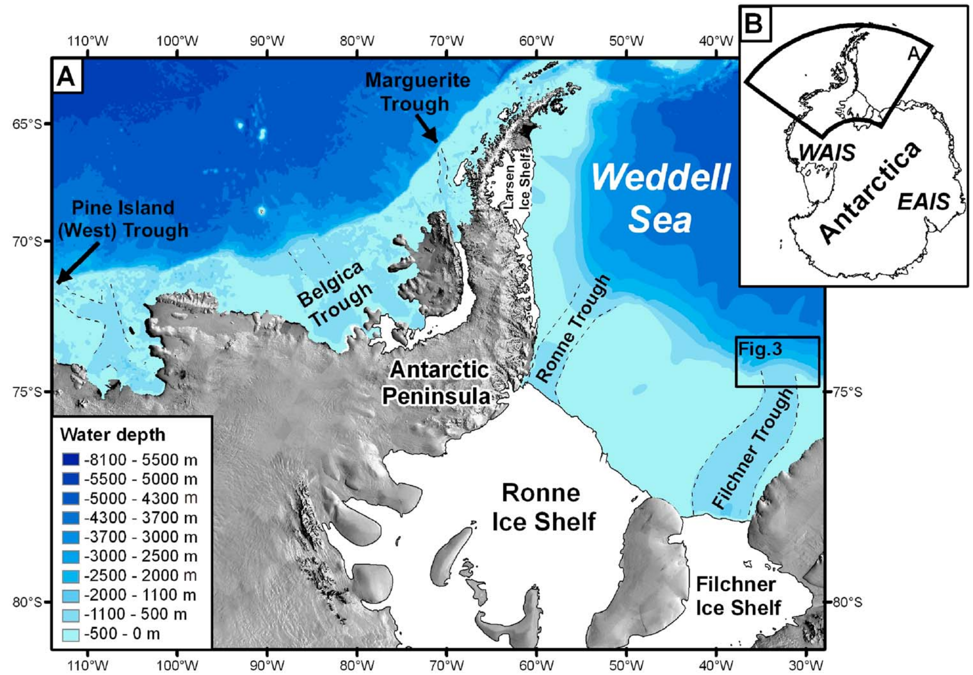

Figure 2. (a) Location map of the study area on the Antarctic continental margin, showing locations of major cross-shelf troughs mentioned in text, including Pine Island (West) Trough, Belgica Trough, Marguerite Trough, Ronne Trough, and Filchner Trough. (b) Inset shows the spatial extent of Figure 2a. Regional bathymetry from GEBCO data set [*Intergovernmental Oceanographic Commission*, 2003]. Antarctic continent is shaded Landsat Image Mosaic of Antarctica (LIMA) data [*U.S. Geological Survey*, 2007]. WAIS is West Antarctic Ice Sheet; EAIS is East Antarctic Ice Sheet.

present and discuss the potential for ISW to have eroded these features.

2. Study Area

[8] The Weddell Sea lies to the east of the Antarctic Peninsula (Figure 2). The Filchner and Ronne Ice Shelves form floating extensions of the East and West Antarctic Ice Sheet, respectively, covering 450,000 km^2 [*Nicholls et al.*, 2009]. The continental shelf edge lies mostly between 500 and 600 m water depth, increasing to around 630 m within the Filchner Trough [*Intergovernmental Oceanographic Commission*, 2003]. Filchner Trough is a major bathymetric cross-shelf feature, extending seaward of the Filchner Ice Shelf and reaching a width of 125 km at the shelf edge. The continental slope seaward of the Filchner Trough mouth is characterized by outward bulging contours, marking the presence of a Trough Mouth Fan (Crary Fan) [*Kuvaas and Kristoffersen*, 1991].

[9] The Weddell Sea is a major region of bottom water formation, contributing ~50–70% of the 10 Sv (1 Sv = 10^6 m^3 s^{-1}) of Antarctic Bottom Water (AABW) which is exported from the Southern Ocean [*Naveira Garabato et al.*, 2002; *Nicholls et al.*, 2009]. AABW forms the southern component of the global thermohaline circulation and is responsible for cooling and ventilating the abyssal world ocean [*Foldvik et al.*, 2004]. High Salinity Shelf Water (HSSW) is produced during sea ice production through brine rejection. HSSW is subsequently supercooled and slightly freshened by circulation beneath the ice shelves, producing cold and dense ISW [*Nicholls et al.*, 2009].

[10] Although past volume fluxes of ISW are difficult to estimate, this must have been closely related to circulation changes in the clockwise flowing Weddell Gyre. These, in turn, were closely related to circulation changes within the west-wind driven Antarctic Circumpolar Current. Studies of marine and terrestrial paleoclimate archives [e.g., *Bianchi and Gersonde*, 2004; *McGlone et al.*, 2010] did not reveal any significant changes in circulation of the Weddell Gyre or the westerly wind system for the time after ~8 ka before present, implying that any major changes in ISW production during the middle and late Holocene are unlikely. During the Last Glacial Maximum (LGM), when the ice sheet is thought to have advanced across the Weddell Sea shelf [*Hillenbrand et al.*, 2012], ISW production likely ceased as ice shelf cavities, needed to supercool HSSW, would not have existed if the ice sheet grounding line had reached the shelf edge. The maximum extent of grounded ice during the LGM is under debate but a recent review concluded that ice streams had reached the outer shelf of the Weddell Sea and grounded within the deepest parts of the Filchner and Ronne Troughs [*Hillenbrand et al.*, 2012]. *Hillenbrand et al.* [2012] interpreted sediments recovered in cores from the southern Weddell Sea shelf to be of subglacial origin and likely to be of LGM age. The latter conclusion is based on (1) radiocarbon ages of glaciomarine sediments overlying the subglacial sediments giving predominantly ages younger than the LGM; (2) current velocity measurements of bottom

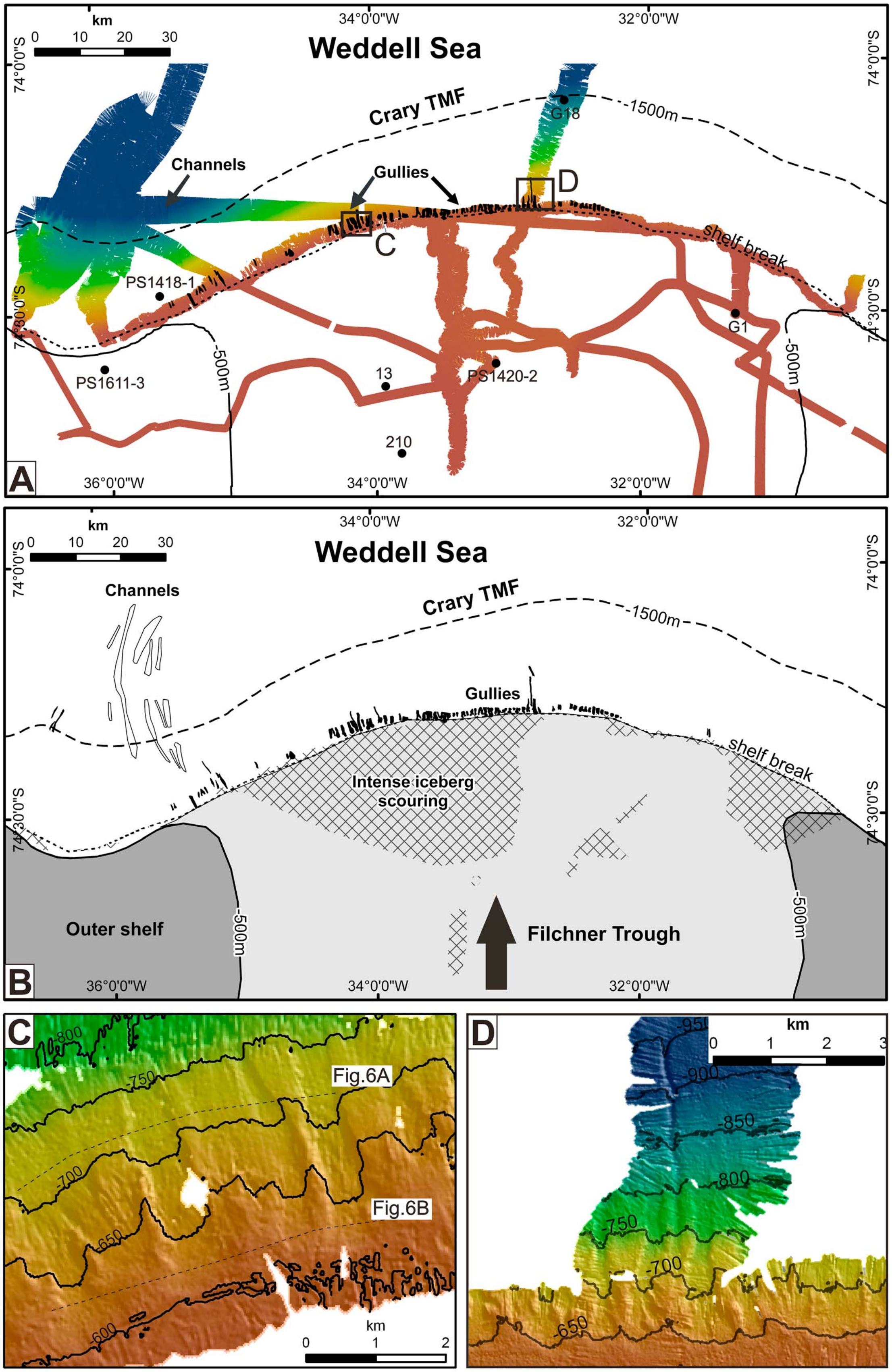
A
Weddell Sea
km
0 10 20 30
34°0'0"W
32°0'0"W
36°0'0"W
74°0'0"S
74°30'0"S
Crary TMF
-1500m
Channels
Gullies
shelf break
C
D
G18
G1
PS1418-1
PS1611-3
PS1420-2
13
210
-500m
B
Intense iceberg scouring
Outer shelf
Filchner Trough
Fig.6A
Fig.6B
-800
-750
-700
-650
-600
km
0 1 2
-950
-900
-850
0 1 2 3

Figure 3

Table 1. Data Sets Used in Figure 1[a]

	Data Set		
Figure	Cruise/ID	Year	Reference/PI (Principal Investigator)
1a	JR84	2003	*Evans et al.* [2006]; *Dowdeswell et al.* [2006]
	JR141	2006	*Larter et al.* [2007]; *Graham et al.* [2010]
	NBP0001	2000	*Nitsche et al.* [2007]
	NBP0702	2007	*Nitsche et al.* [2007]
	ANT-XXIII/4	2006	*Gohl* [2006]; *Nitsche et al.* [2007]
1b	JR97	2005	K. Nicholls (PI)
	JR244	2011	R. Larter (PI)
1c	JR104	2004	*Ó Cofaigh et al.* [2005b]; *Dowdeswell et al.* [2008]
	JR141	2006	*Noormets et al.* [2009]
1d	NBP0103	2008	*Bolmer* [2008]
	NBP0202	2008	*Bolmer* [2008]
1e	JR59	2001	*Ó Cofaigh et al.* [2002]
	JR71	2002	*Ó Cofaigh et al.* [2005a]; *Dowdeswell et al.* [2004]
	JR157	2007	*Noormets et al.* [2009]
	JR179	2008	R. Larter and P. Enderlein (PIs)
	NBP0103	2001	P. Wiebe (PI); *Bolmer* [2008]
	NBP0104	2001	P. Wiebe (PI); *Bolmer* [2008]
	NBP0202	2002	P. Wiebe (PI); *Bolmer* [2008]

[a]Cruise IDs beginning JR indicate RRS *James Clark Ross*, those beginning NBP indicate RVIB *Nathanial B. Palmer* and ANT-XXIII/4 was on RV *Polarstern.*

currents on the shelf, which are deemed unlikely to have eroded a widespread unconformity separating subglacial deposits from the overlying Holocene glaciomarine deposits; and (3) radiocarbon dates of post-LGM age obtained from glaciomarine sediments overlying terrigenous deposits on the continental slope, which indicate that glaciogenic detritus was supplied directly to the Weddell Sea shelf edge during the LGM [*Hillenbrand et al.*, 2012].

[11] ISW flows toward the shelf edge through the Filchner Trough, where it cascades downslope. Volume transport increases downslope from an estimated 1.6 Sv to 4.3 Sv due to mixing with surrounding Weddell Deep Water (WDW) [*Foldvik et al.*, 2004; *Wilchinsky and Feltham*, 2009]. Mean flow velocities of 0.38 m s^{-1} have been measured on the upper slope (10 m above seabed) with maximum current velocities of 0.8 m s^{-1} recorded, increasing to 1 m/s downslope [*Foldvik et al.*, 2004]. Calculating the bed shear stress (τ_0) from the mean flow velocity according to:

$$\tau_0 = C_d \rho |u|^2 \qquad (1)$$

where C_d is a friction factor, found typically to be 0.0025 (dimensionless), ρ is water density (kg m^{-3}), and $|u|$ is depth-averaged flow speed (m s^{-1}), the resulting τ_0 value (0.37 Pa) is within the general threshold for erosion of marine muds (0.05–2 Pa), although at the lower end of the erosion threshold for sandy muds (0.1–1.5 Pa) from experiments reviewed by *McCave* [1984] and *Jacobs et al.* [2011]. According to flume experiments by *Singer and Anderson* [1984], the mean current velocities measured on the shelf may be sufficiently high to winnow clay and silt particles resuspended by bioturbation from the seabed. Calculations are however based on mean flow velocities and high flow speeds associated with documented bursts within the flow [*Foldvik et al.*, 2004] will increases shear stress and may cause short-term erosion of the seabed.

[12] Surface seafloor sediments on the outer shelf consist largely of sand and gravelly sand due to winnowing of finer grained particles by ISW [*Melles et al.*, 1994]. Cores from the outermost shelf (Figure 3a) recovered glaciomarine and subglacial sediments, including overconsolidated deposits and diamictons [e.g., *Elverhøi*, 1984; *Melles and Kuhn*, 1993; *Hillenbrand et al.*, 2012].

3. Methods

[13] During cruise JR244 with RRS *James Clark Ross* in early 2011, a 177 km stretch of the Weddell Sea continental shelf edge and upper slope was imaged using a Kongsberg EM120 multibeam swath bathymetry system, with a frequency range of 11.75–12.75 kHz and swath width of up to 150° (Figure 3a). A TOPAS PS 018 subbottom acoustic profiling system was used to image the subsurface. The TOPAS system transmits two primary frequencies at around 18 kHz, from which 10- to 15-ms-long secondary chirp pulses containing frequencies ranging from 1300 to 5000 Hz were generated. In this configuration the system can image acoustic layering in unconsolidated, fine grained sediments to a depth of more than 50 m below the seafloor with a resolution better than 1 m. Data were digitally recorded at a sampling rate of 20 kHz. Traces were cross-correlated with the secondary transmission pulse signature and instantaneous amplitude records derived from the correlated output were displayed as variable density traces. Navigation data were acquired using a Seatex Global Positioning System receiver.

[14] Multibeam data were processed and gridded to 20 m cell size using public access MB-System software [*Caress and Chayes*, 1996]. These data were analyzed and compared with existing swath bathymetry and TOPAS data from previous cruises (Table 1) from other Antarctic continental margin areas, including the western Antarctic Peninsula, and the Bellingshausen and Amundsen seas. The slope morphology was quantitatively analyzed using standard geographic information system (GIS) tools, by extracting cross-sectional profiles parallel to the continental shelf edge, along which gully parameters were measured. Measured parameters include gully depth, width, length, gully density at 50 m below the shelf edge (gullies/km), gully cross-sectional area

Figure 3. The major morphological features of the outer shelf and slope offshore from Filchner Trough, Weddell Sea. (a) Shaded relief swath bathymetry image of the study area. Boxes indicate locations of Figures 3c and 3d. Black circles mark sediment core locations: cores PS1418–1, PS1420–2, PS1611–3 [*Melles*, 1991; *Melles and Kuhn*, 1993]; G1, G18 [*Anderson et al.*, 1980]; 13, 210 [*Elverhøi and Maisey*, 1983]. (b) Schematic diagram of Crary Trough Mouth Fan (TMF). Black arrow represents direction of paleo-ice stream flow. (c) Slope morphology offshore from Filchner Trough. Dashed lines in Figure 6a and Figure 6b indicate location of TOPAS profiles in Figure 6a and 6b. (d) Slope morphology offshore from Filchner Trough.

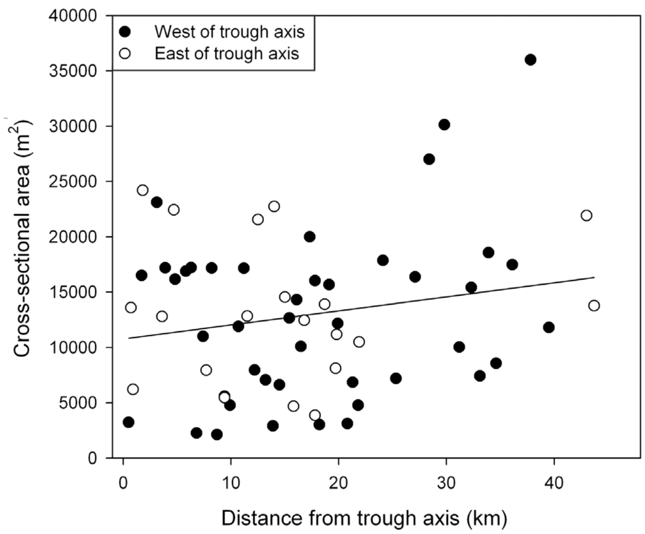

Figure 4. Gully distribution and cross-sectional area at Filchner trough mouth, Weddell Sea. Solid circles are gullies west of the trough axis; white circles are gullies east of the trough axis. Solid line is the least squares regression fit to both data sets (r^2 is 0.039).

(gully width times gully depth on the uppermost slope), and the general gradient of the continental slope. The cross-sectional shape of the gullies was analyzed using the General Power Law ($^{G}P_{L}$) program [*Pattyn and Van Huele*, 1998], which approximates gully cross-sectional shape according to the general power law equation:

$$y - y_0 = a|x - x_0|^{b} \quad (2)$$

where x and y are horizontal and vertical coordinates along a cross-sectional profile, x_0 and y_0 are the coordinates of the minimum of the fitted profile (automatically determined), and a and b are constants. The program carries out a least squares analysis for a range of b values and identifies the value giving the minimum RMS misfit between the observed profile and the idealized shape defined by the above equation. The resulting b value provides a measure of cross-sectional shape (U/V index), with 1 being "perfect V-shape" and 2 being parabolic shape, commonly referred to as "U-shape" by geomorphologists. Values <1 express a gully with convex-upward sides, and values >2 express a more box-shaped gully, where steepness increases away from the axis more rapidly than a parabolic curve.

4. Results

[15] Our new data show that 76 gullies incise the mouth of the Filchner Trough within the extent of the multibeam bathymetry data. We observe two separate gully types: (1) 72 small-scale U-shaped gullies with rounded gully heads (e.g., Figure 3c) and (2) four small-scale V-shaped gullies. The gully distribution is not uniform with the highest density found at the center of the trough, corresponding to the deepest section of the trough. This is the opposite of the pattern of gully distribution observed on the western Antarctic Peninsula, Amundsen and Bellingshausen Sea margins, where gully density increases toward the trough margins [*Noormets et al.*, 2009]. Gully cross-sectional area does not change significantly with distance from the trough axis (Figure 4). Measurements taken along a profile that is parallel to and 50 m below the shelf edge show that gullies are on average 630 m wide, 12.5 m deep, and 2.7 km long. Gully length measurements are, however, constrained in places by the limited downslope data extent. The gullies cut back on average 220 m into the shelf edge and are found on slope gradients of 2–3°. The frequency distribution of gully depths shows that most gullies (60%) at the shelf edge are between 5 and 15 m deep (Figure 5b).

[16] The V-shaped gullies are characterized by greater lengths and lower widths (average 283 m) and depths (9.5 m) (e.g., Figure 3d). Large, deeply incised V-shaped gullies as found on the western margin of the Antarctic Peninsula (Figure 1e), Bellingshausen (Figure 1c) and Amundsen seas (Figure 1a) are not observed in the study area. Regional data from the southeastern Weddell Sea do, however, show large channel systems further downslope, which do not initiate at the shelf edge [*Michels et al.*, 2002].

[17] Quantitative analysis we have carried out on gullied slopes offshore from the mouths of other paleo-ice stream troughs, such as Marguerite (western Antarctic Peninsula), Belgica (Bellingshausen Sea), and western Pine Island (Amundsen Sea) Troughs (Table 2), shows that they are geomorphically different from the U-shaped gullies offshore from Filchner Trough (Figure 5). The latter gullies measure close to 2 (U-shape) according to the general power law equation, display no branching or sinuosity, and have low depth:width and length:width ratios (Figures 5a, 5c, and 5d).

[18] TOPAS data show that the gullies are formed in poorly stratified or acoustically impenetrable layers (Figures 6a and 6b) indicating their erosion into the seabed, contrasting good TOPAS penetration into gully interfluves which would be expected if they were formed by interfluve aggradation. Headwall scars are not observed, but in some instances the TOPAS data show an acoustically transparent layer of variable thickness that covers the underlying topography and may subdue the expression of any headwall scars present along the Filchner Trough mouth (Figure 6b).

5. Discussion

[19] Along the Filchner Trough shelf edge, the predominant morphological signature is small-scale U-shaped gullies. Morphologically, the gullies resemble small-scale slide scars, displaying relatively flat-floored cross-sections and steep walls [*Kenyon*, 1987]. TOPAS data show an acoustically transparent layer of variable thickness overlying an acoustically impenetrable layer which the gully morphologies are formed in. The acoustically transparent layer was not resolved by earlier 3.5 kHz acoustic surveys, but may correspond to postglacial, bioturbated sands that overlie diamictons interpreted as gravitational slide deposits in cores (PS1494, PS1612) recovered from the upper slope in the southern Weddell Sea to the west of our study area [*Melles and Kuhn*, 1993]. The presence of an acoustically transparent layer that drapes over the gully morphologies and interfluves suggests that the seafloor topography is a relict with gullies likely formed under full glacial conditions/early stages of deglaciation rather than during the postglacial interval in which there have

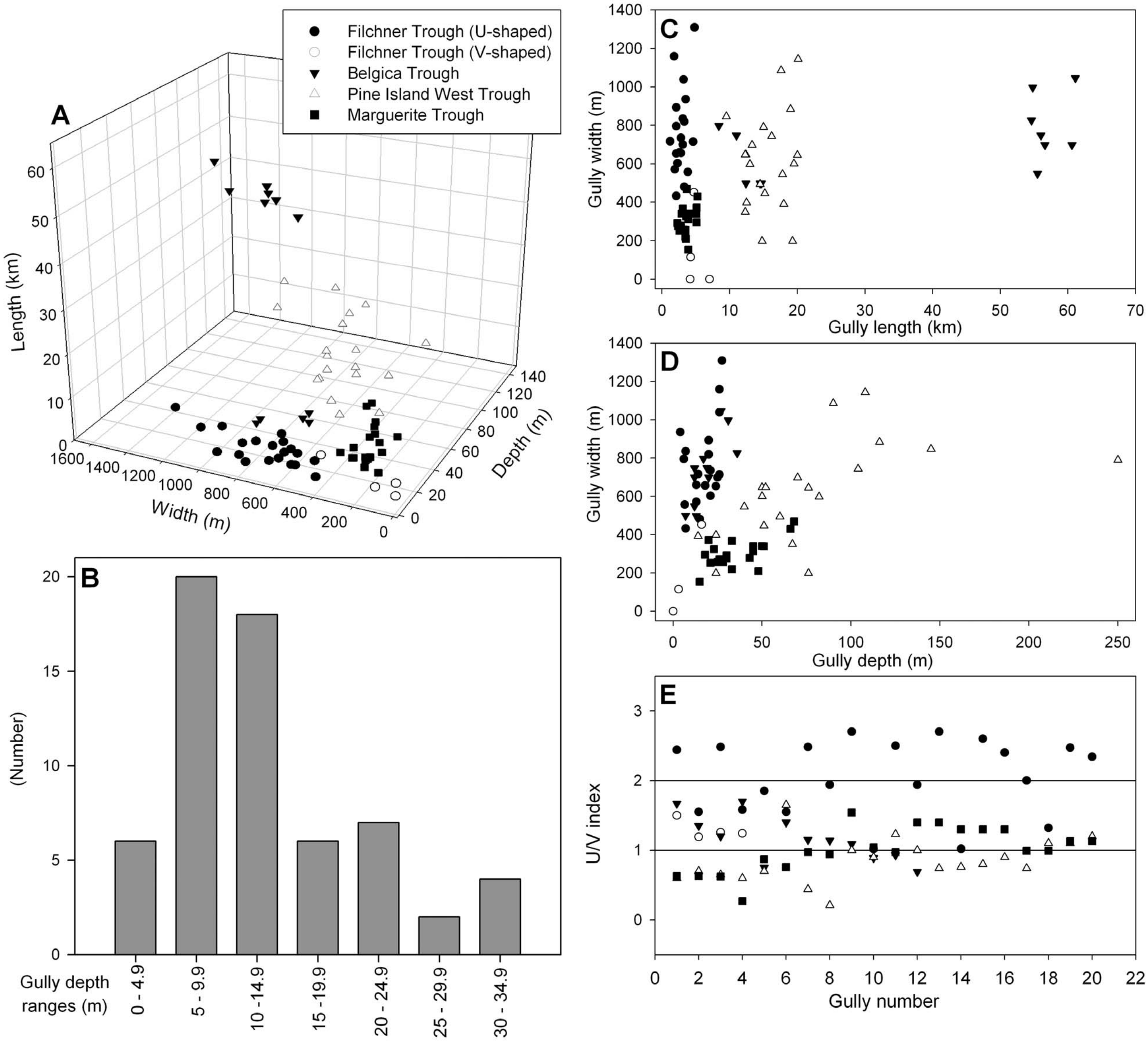

Figure 5. (a) Gully morphological parameters (length, width, and depth) offshore from four paleo-ice stream troughs around Antarctica: Filchner Trough (circles), Marguerite Trough (black squares), Belgica Trough (black triangles), and Pine Island Trough (West) (white triangles). For additional data on gully locations, see Table 2. (b) Frequency analysis of gully incision depth ranges across the shelf edge offshore from Filchner Trough. (c) Gully width versus gully length; (d) gully width versus gully depth; (e) gully cross-sectional shape (U/V index) from general power law analysis. U/V index values near "1" are distinctly V-shaped; values near "2" are distinctly U-shaped.

been seasonally open water conditions. Under full glacial conditions during the Last Glacial Maximum, the West Antarctic Ice Sheet extended to, or close to, the shelf edge on the western margin of the Antarctic Peninsula [*Vanneste and Larter*, 1995; *Heroy and Anderson*, 2005] and in the Bellingshausen [*Hillenbrand et al.*, 2010] and Amundsen seas [*Lowe and Anderson*, 2002; *Graham et al.* 2010], while the East Antarctic Ice Sheet is also considered to have extended across the Weddell Sea shelf during this period [*Hillenbrand et al.*, 2012]. If the ice sheet grounding line reached the shelf edge under full glacial conditions, ISW production would have been limited. No ice-shelf cavities would have existed to supercool HSSW, a precursor to dense bottom water formation. Under full glacial conditions it is also likely that thicker and more permanent sea ice was present, restricting the potential for the production of new sea ice and therefore the amount of HSSW produced.

[20] The slide scars are likely the result of small-scale slope failure. Sixty percent of the U-shaped gullies incise the seabed to a depth of 5–15 m (Figure 5b), suggesting that the sediment slides may be retrogressive, with sediment failure occurring along a plane of weakness in the sedimentary structure [*Laberg and Vorren*, 1995; *Canals et al.*, 2004]. This plane of weakness may result from the change from

Table 2. Average Gully Parameters Observed at the Mouths of Cross-Shelf Troughs Around Antarctica and in the Presence/Absence of Trough Mouth Fans

Location	Gully Density[a] (gully/km)	Mean Gully Cross-Sectional Area[a] (m^2)	Slope Gradient (deg)	Within Trough	Trough Mouth Fans Present?
Filchner Trough (U-shape), Weddell Sea (e.g., Figure 1b) (35°40′W–31°00′W)	0.6	14720	2.5	yes	yes
Filchner Trough (V-shape), Weddell Sea (e.g., Figure 3d) (35°40′W–31°00′W)	<0.1	3787	2.5	yes	yes
Belgica Trough, Bellingshausen Sea (88°W–84°30′W)	0.55	11518	1.7	yes	yes
Marguerite Trough, Western Antarctic Peninsula (e.g., Figure 1e) (72°W–70°48′W)	0.76	18184	9	yes	no
Pine Island (West) Trough, Amundsen Sea (e.g., Figure 1a) (114°30′W–113°2′W)	1.4	32442	4.5	yes	no

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

glacial to interglacial sedimentation, as hemipelagic sediments, which are common during deglacial and interglacial periods, have higher porosity than sediments deposited during glacial periods. This change may create a weakened layer which is more susceptible to failure [*Long et al.*, 2003]. Alternatively, planes of weakness may form during periods of stronger current flow when winnowing of finer grained sediment creates instabilities. Acoustic and seismic evidence from further down the continental slope also suggest that extensive mass wasting occurred on the Weddell Sea continental slope in the past [e.g., *Melles and Kuhn*, 1993; *Bart et al.*, 1999].

[21] Marine slope instability is influenced by factors including oversteepening, seismic activity, rapid sediment accumulation, gas charging, gas hydrate dissociation, glacial loading, slope angle, and mass movement history [*Locat and Lee*, 2002]. The Weddell Sea is a passive margin with no evidence for the presence of gas hydrates [*Bart et al.*, 1999] and with a relatively low slope gradient (2–3°) compared to most other Antarctic margins (Table 2). Small-scale slope failure along the Filchner Trough margin is likely the result of rapid accumulation of sediment due to glacial transport [cf. *Larter and Cunningham*, 1993; *Melles and Kuhn*, 1993]. Bottom currents may also have enhanced sediment transport toward the shelf edge during interglacials as the present ISW flow velocities are capable of eroding medium-sand particles and transporting gravel grains [*Melles et al.*, 1994]. Current winnowing of fine-grained particles from the shelf edge and

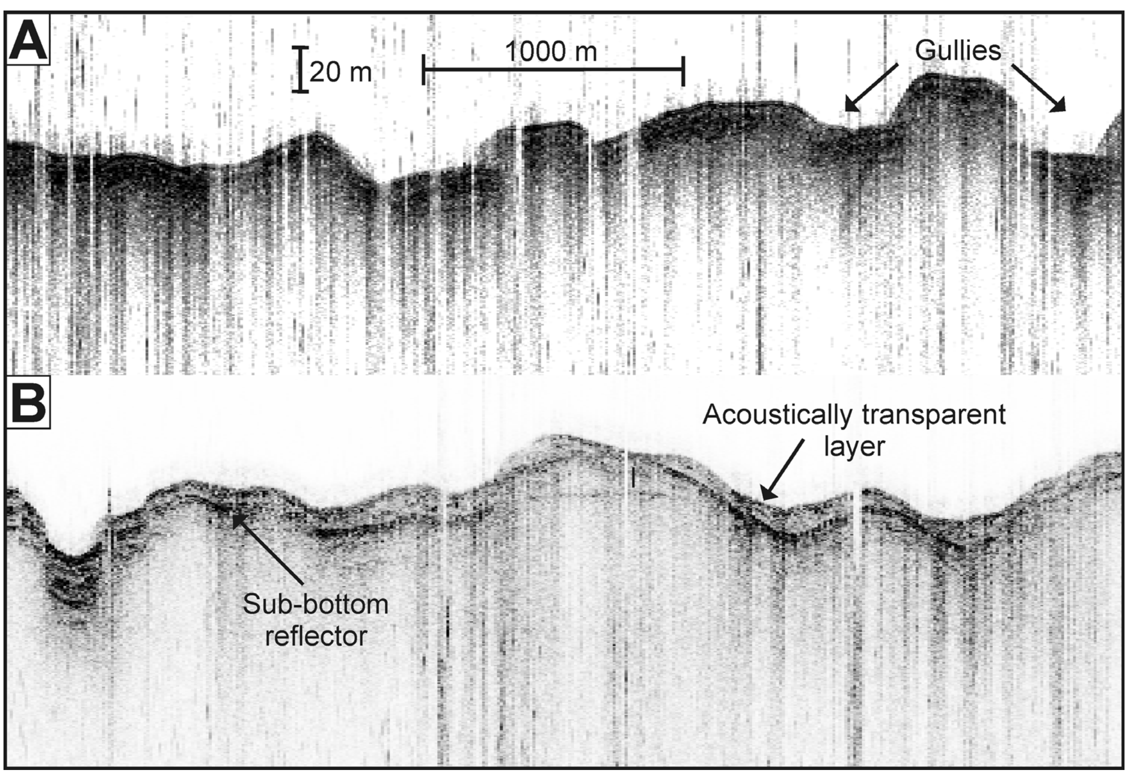

Figure 6. (a) TOPAS profile through lower section of continental slope along profile “Figure 6a” in Figure 3c (dashed black line). (b) TOPAS profile through upper section of continental slope along profile “Figure 6b” in Figure 3c (dashed black line).

redeposition on the slope may influence slope stability by interleaving fine-grained, high water content sediment layers with denser, coarse-grained layers [cf. *Melles and Kuhn*, 1993]. This process may also explain the local occurrence of winnowed, coarse-grained surface sediments on the slope [*Melles et al.*, 1994], while formation of a similar winnowed lag at the shelf edge might have inhibited further erosion and explain the lack of large erosional features at the shelf edge when compared to some other Antarctic continental margins.

[22] Along the southern Weddell Sea margin, highly erosional and V-shaped gullies like those observed on other parts of the Antarctic continental slope are not present. Assuming that fluid flow produces V-shaped incisions, as seen in the terrestrial environment [*Simons and Sentürk*, 1992], their absence in the southern Weddell Sea indicates that there is no fluid erosional process occurring here. The underlying geology of these areas (Table 2) shows a limited range of characteristics as the slopes are constructed largely of prograded sequences [*Cooper et al.*, 2008] with sediment cores giving evidence that these consist of glaciogenic debris flows with similar lithology, physical properties, grain-size composition, and mineralogical composition [e.g., *Anderson and Andrews*, 1999; *Michels et al.*, 2002; *Dowdeswell et al.*, 2004, 2006, 2008; *Hillenbrand et al.*, 2005, 2009]. The differences in the observed shelf edge morphologies are therefore unlikely to be controlled by the underlying substrate and instead are more likely due to differences in slope processes. ISW overflow may be exerting an influence further downslope, as current velocities have been shown to increase downslope [*Foldvik et al.*, 2004] with large channel-levee systems also present toward the Weddell Sea continental rise [*Michels et al.*, 2002]. However, even on the lower continental slope of the southern Weddell Sea, erosional features are attributed to erosion by gravitational downslope transport and contour currents during glacials, but not modern ISW overflow [*Melles and Kuhn*, 1993]. This is fully consistent with our observation that there is no significant geomorphic signature of cold, high-salinity water overflow at the shelf edge and upper slope.

[23] *Noormets et al.* [2009] observed a clear pattern of gully size and density increasing toward the trough margins at the mouths of the Marguerite, Belgica, and western Pine Island cross-shelf troughs. However, at the Filchner Trough mouth, highest gully densities are found at the center of the trough and gully cross-sectional area does not change significantly. This difference suggests that the processes operating on other Antarctic continental slopes had a lesser effect on the Filchner Trough margin. The flow velocity of ice streams within cross-shelf troughs may explain the observed pattern of gullying, where in a horizontal sense, the velocity of an ice stream would be at a maximum at the trough axis and lower at the trough margins [*Bindschadler and Scambos*, 1991; *Whillans and Van der Veen*, 1997]. Sediment delivery would therefore be higher at the trough axis, leading to increased slope instability and increased gully density.

[24] A potential process forming the deeply incised and V-shaped gullies observed on other Antarctic continental margins is sediment laden subglacial meltwater [*Noormets et al.*, 2009]. For subglacial meltwater to overcome the buoyancy of freshwater in normal seawater, 33 g l^{-1} of detritus must be entrained in order for it to remain at the seafloor [*Syvitski*, 1989]. A possible mechanism for sufficient sediment to become entrained is high fluxes of meltwater associated with episodic discharge. Our observations suggest that if this was indeed the main process for eroding large V-shaped gullies, less episodic meltwater would have been discharged from the Filchner Trough mouth during glacial periods compared to troughs along the Pacific margin. A smaller amount of basal melt from this region is consistent with colder surface temperatures in the Weddell Sea embayment compared to the Antarctic coast in the Pacific sector [*Dixon*, 2008], a difference which probably persisted through glacial periods and would have resulted in colder ice. Basal ice temperatures are also affected by geothermal heat flux and strain heating, but as the southern Weddell Sea has been tectonically inactive since at least mid-Cretaceous times [*DiVerere et al.*, 1996], geothermal heat flux is expected to be relatively low. Antarctic heat fluxes inferred from a global seismic model support this suggestion [*Shapiro and Ritzwoller*, 2004]. Strain heating is an important factor affecting basal temperatures, but it is a feedback effect and not a primary cause of basal melting and ice flow [*Hindmarsh*, 2009].

[25] Our results suggest that cold, high-salinity water overflow is an unlikely formation mechanism for the deeply incised and V-shaped gullies observed at the shelf break along other parts of the Antarctic continental margin. Other possible explanations for such features include sediment laden subglacial meltwater discharge from the base of an ice sheet grounded at the shelf edge during glacial maxima through either episodic release, possibly by subglacial lake water outbursts, or more continuous release.

6. Conclusions

[26] We have presented geomorphological analyses of new bathymetric data from an area of active cold, dense water overflow along the Weddell Sea continental margin. The analyses show that U-shaped gullies offshore from Filchner Trough are geomorphologically distinct from gullies observed elsewhere on the Antarctic continental margins. These gullies are likely produced by small-scale slides, probably resulting from the rapid accumulation and subsequent failure of proglacial sediment during glacial maxima. The features are quantitatively different from the highly incisional and V-shaped gullies which dominate some other Antarctic continental margins. The distinctly different geometry of the gullies in the southern Weddell Sea will have a significant impact on the calculation of dense water outflow and will enhance the ability of models to predict the flow and entrainment of dense water as it passes over the shelf break [*Muench et al.*, 2009].

[27] Our findings indicate that past overflow of cold, high salinity water was unlikely to be the dominant mechanism for the extensive gully erosion observed in other areas of the Antarctic, confirming the speculation of earlier workers. We hypothesize that other processes, such as mass flows or subglacial meltwater discharge, likely played a greater role in gully formation elsewhere along Antarctic continental margins.

[28] **Acknowledgments.** This study is part of the British Antarctic Survey Polar Science for Planet Earth Program. It was funded by the Natural Environmental Research Council (NERC) with logistical support provided by the American Association of Petroleum Geologists Grant-in-Aid award and by the British Antarctic Survey under the NERC Antarctic Funding Initiative (CGS-64). The first author was funded by NERC studentship NE/G523539/1. We thank the scientific party, in particular Alastair G. C. Graham, and the officers and crew of the RRS *James Clark Ross* for their assistance during cruise JR244. Finally, we thank Martin Truffer, Eugene Domack, Julia Wellner, and Julian Dowdeswell for their insightful comments, which have helped to improve this manuscript.

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