Marine Geology 252 (2008) 129–140

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

A major trough-mouth fan on the continental margin of the Bellingshausen Sea, West Antarctica: The Belgica Fan

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ARTICLE INFO

Article history:
Received 17 July 2007
Received in revised form 5 March 2008
Accepted 27 March 2008

Keywords:
submarine fan
West Antarctic Ice Sheet
Bellingshausen Sea
fast-flowing ice streams
iceberg scouring
submarine channels
gullies

ABSTRACT

A 330-km length of the little known continental shelf edge and slope of the Bellingshausen Sea, West Antarctica, is investigated using multibeam swath-bathymetric and sub-bottom profiler evidence. The shelf break is at 650–700 m across the 150-km wide Belgica Trough, and to either side is about 500 m. When full-glacial ice advanced across the shelf to reach the shelf break, it was partitioned into fast- and slow-flowing elements, with an ice stream filling the trough. This had important consequences for the nature and rate of sediment delivery to the adjacent continental slope. Off Belgica Trough, the upper continental slope has convex-outward contours indicating a major sedimentary depocentre of gradient 1–2°. Acoustic profiles and cores from the depocentre show a series of diamictic glacigenic debris flows. The depocentre is interpreted as a trough-mouth fan, built largely by debris delivered from the ice stream. The slope is steeper beyond the trough margins at up to 6°. The main morphological features on the Bellingshausen Sea slope are gully systems and channels. Major canyons and Late Quaternary slides are absent. Most gullies and channels are found on the fan. Gullies are about 15–25 m deep, a few hundred metres wide and some are >25 km long. The largest channel is over 60 km long, about a kilometre wide and 10 to 15 m deep. The channels provide pathways for sediment by-passing of the upper slope and transfer to the continental rise and beyond by turbidity currents. Gullies on the Bellingshausen Sea margin cut through debris flows on the slope. Assuming the debris flows are linked mainly to downslope transport of diamictic debris when ice was at the shelf edge under full-glacial conditions, then those gullies cut into them formed during deglaciation. Belgica Fan is >22,000 km^2 in area and about 60,000 km^3 in volume. It is the largest depocentre identified to date on the continental margin of the West Antarctic Ice Sheet, fed by an interior ice-sheet basin of approximately 200,000 km^2.

1. Introduction

The growth and decay of ice sheets results in highly variable rates of sediment delivery to high-latitude continental margins. During full-glacial periods, when ice advances across continental shelves to the shelf edge, the upper continental slope becomes the focus of sediment delivery from the ice-sheet margin (e.g. Anderson, 1999; Dowdeswell et al., 2002). Conversely, when ice retreats often several hundreds of kilometres across the shelf in interglacial and interstadial periods, sedimentation is instead focused on inner shelves and fjords. Even when ice is at the shelf edge, variability in ice dynamics superimposes additional spatial variability on the pattern and rate of ice flow and, hence, on sediment delivery. Fast-flowing ice streams, often located in cross-shelf troughs, deliver a high flux of ice and sediment to the ice-sheet margin, whereas the remainder of the ice-sheet is slow-flowing and sediment transport is more limited even under full-glacial conditions (e.g. Dowdeswell and Siegert, 1999; Dowdeswell and Elverhøi, 2002; Mosola and Anderson, 2006). On many polar margins, large sedimentary depocentres or submarine fans have built up offshore of these troughs over successive glacial–interglacial cycles during the Late Cenozoic (e.g. Kuvaas and Kristoffersen, 1991; O'Brien, 1994; Dowdeswell et al., 1996; Vorren et al., 1998; Canals et al., 2002; Ó Cofaigh et al., 2003).

The continental margin of the Bellingshausen Sea, West Antarctica (Fig. 1), presents an opportunity to investigate the sedimentary consequences of variations in sediment delivery from the Antarctic Ice Sheet during past glacial maxima. Marine-geophysical and geological

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doi:10.1016/j.margeo.2008.03.017

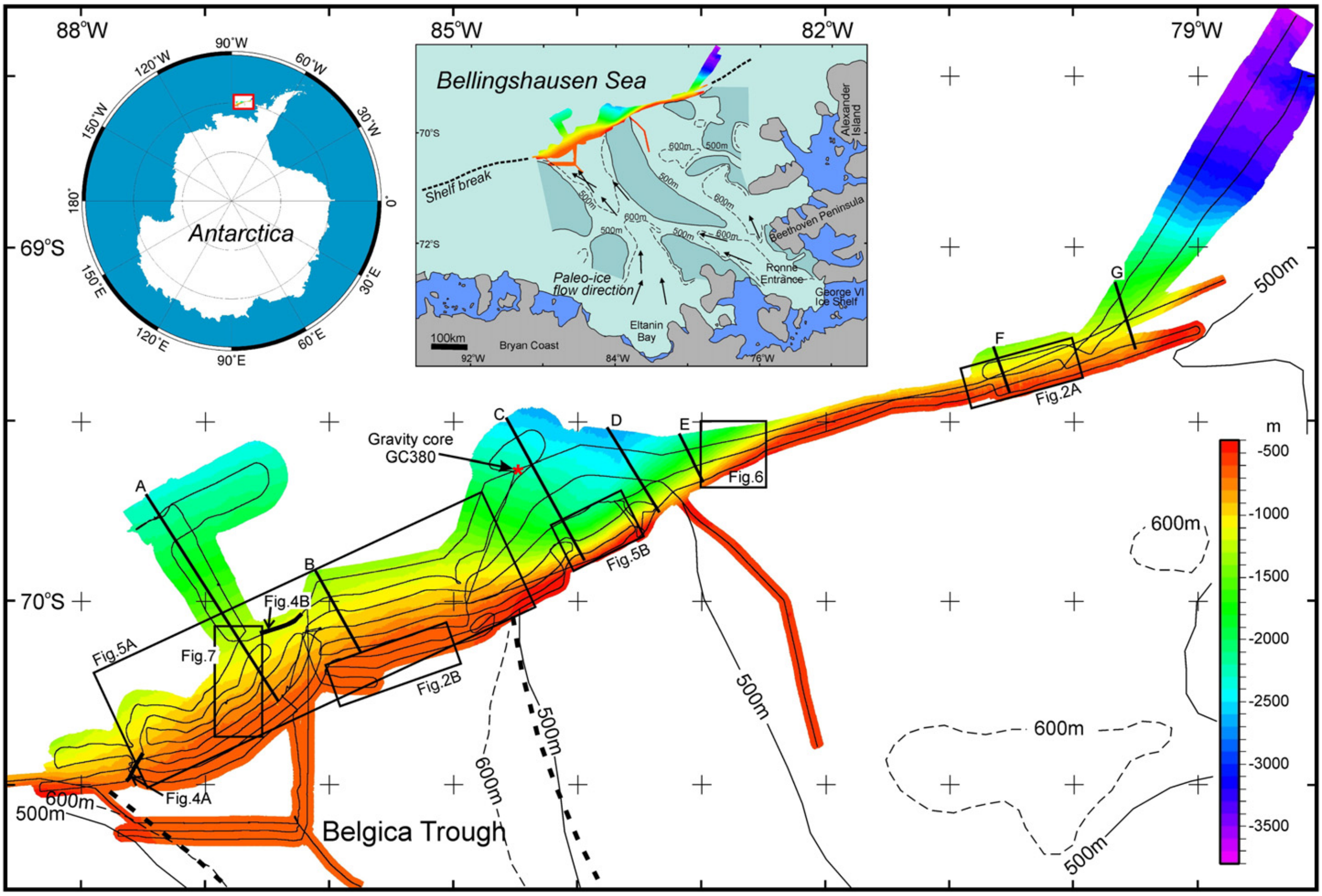

Fig. 1. Location map of the study area on the Bellingshausen Sea slope, West Antarctica. Boxes mark the locations of subsequent figures and insets show the position of the study area within Antarctica. Dark blue shading in the inset map of the Bellingshausen Sea represents ice shelves and grey shading is grounded ice. Arrows on this inset map indicate the former ice-flow directions inferred from the orientation of mega-scale glacial lineations on the shelf (Ó Cofaigh et al., 2005). The area of swath-bathymetric data is shown with depths identified by colour. Depth contours on the shelf are from Ó Cofaigh et al. (2005). Ship tracks along which marine-geophysical data were acquired are shown. Lines marked A to G are shown in Fig. 2C.

evidence has shown that, when full-glacial ice advanced across the Bellingshausen Sea continental shelf to reach the shelf break, it was partitioned into fast- and slow-flowing elements at the Last Glacial Maximum (LGM) about 15–20,000 yr ago (Ó Cofaigh et al., 2005) with important consequences for the nature and rate of sediment delivery to the adjacent continental slope. The area is also of interest because ice draining into the Bellingshausen Sea is derived from the little known Pacific margin of the West Antarctic Ice Sheet (WAIS), which, because much of it is grounded well below sea level, is regarded as being potentially less stable than the much larger East Antarctic Ice Sheet (e.g. Bindschadler, 1998).

In this paper, the morphology and the sedimentary processes that have acted on the continental margin of the Bellingshausen Sea during the Late Quaternary are described and interpreted (Fig. 1). The form of a 330-km length of the little known continental slope and shelf edge is investigated using multibeam swath-bathymetric and sub-bottom profiler methods. These geophysical data are then interpreted and discussed in the context of ice-sheet dynamics, and the processes of sediment delivery to, and transfer down, the continental slope, leading to the deposition of a major submarine fan.

2. Study area and background

The Bellingshausen Sea is located offshore of West Antarctica between about 69° to 73°S and 75° to 95°W (Fig. 1). The continental shelf is a maximum of approximately 500 km wide from the margin of the ice sheet in the Ronne Entrance to the shelf break. The shelf break occurs in water depths of 500–700 m and is centred around 70° to 70°30′S. Ice from the WAIS drains into the Bellingshausen Sea along a marine margin of approximately 500 km, along flowlines up to 150 km long from the ice divide to the modern ice-sheet terminus (Vaughan et al., 2001). Tectonically, the Bellingshausen Sea and western Antarctic Peninsula have been dominated by subduction, which ceased progressively from southwest to northeast since the Late Cretaceous (Larter and Barker, 1991; Larter et al., 2002). Specifically, subduction ceased at the eastern part of the Bellingshausen margin about 40 to 50 million years ago as segments of the Antarctic–Phoenix Ridge migrated into the trench.

Swath-bathymetric studies of the morphology of the Bellingshausen Sea continental shelf have been used to map the locations and orientations of streamlined submarine bedforms produced at the base of the ice sheet that flowed across the shelf at the LGM (Fig. 1) (Ó Cofaigh et al., 2005). These bedforms record the flow of a grounded fast-flowing ice stream across the shelf in Belgica Trough, fed by ice draining from the WAIS through Eltanin Bay, and also from the southern part of the Antarctic Peninsula Ice Sheet draining through the Ronne Entrance (Fig. 1). The drainage basin feeding this ice stream exceeded 200,000 km^2 and included parts of southern Alexander Island, south-western Palmer Land and the Bryan Coast of Ellsworth Land (Ó Cofaigh et al., 2005). Grounded ice reached at least as far north as 70°37′S on the outermost shelf, and probably to the shelf break in the Bellingshausen Sea.

This ice-sheet reconstruction is similar to those further to the west in the Amundsen Sea (Lowe and Anderson, 2002; Dowdeswell et al., 2006; Evans et al., 2006) and northeastward around the Antarctic Peninsula (Pudsey et al., 1994; Larter and Vanneste, 1995; Ó Cofaigh et al., 2002, 2005; Canals et al., 2003; Evans et al., 2005; Heroy and Anderson, 2005; Amblas et al., 2006). Collectively, they imply an extensive ice-sheet configuration during the LGM along the western Antarctic Peninsula, Bellingshausen Sea and Amundsen Sea margins, characterised by fast-flowing ice streams which drained very large interior basins through cross-shelf bathymetric troughs, reaching the shelf edge and delivering glacier-derived sediments directly to the upper continental slope during full-glacial periods (Larter and Barker, 1989; Canals et al., 2000; Anderson et al., 2002; Ó Cofaigh et al., 2002; Heroy and Anderson, 2005).

Progradation of the continental margin in front of Belgica Trough is also evident on seismic profiles from the outermost shelf and upper slope (Cunningham et al., 1994; Nitsche et al., 1997). Nitsche et al. (2000) described two multi-channel seismic-reflection profiles which trended NW–SE and crossed the continental shelf edge at about 87°30'W at the mouth of the trough. These two profiles are less than 25 km apart and showed depositional sequences with evidence for progradation of the continental margin. In addition, Scheuer et al. (2006) identified three sedimentary depocentres from a single along-slope seismic profile collected about 100 to 150 km off the Bellingshausen Sea shelf edge. It is the shelf break and continental slope seaward of Belgica Trough, together with that to the east beyond the trough margin, which we will describe and discuss in detail here.

3. Methods

Geophysical data were obtained from a 330 km stretch of the continental slope and outermost shelf of the Bellingshausen Sea

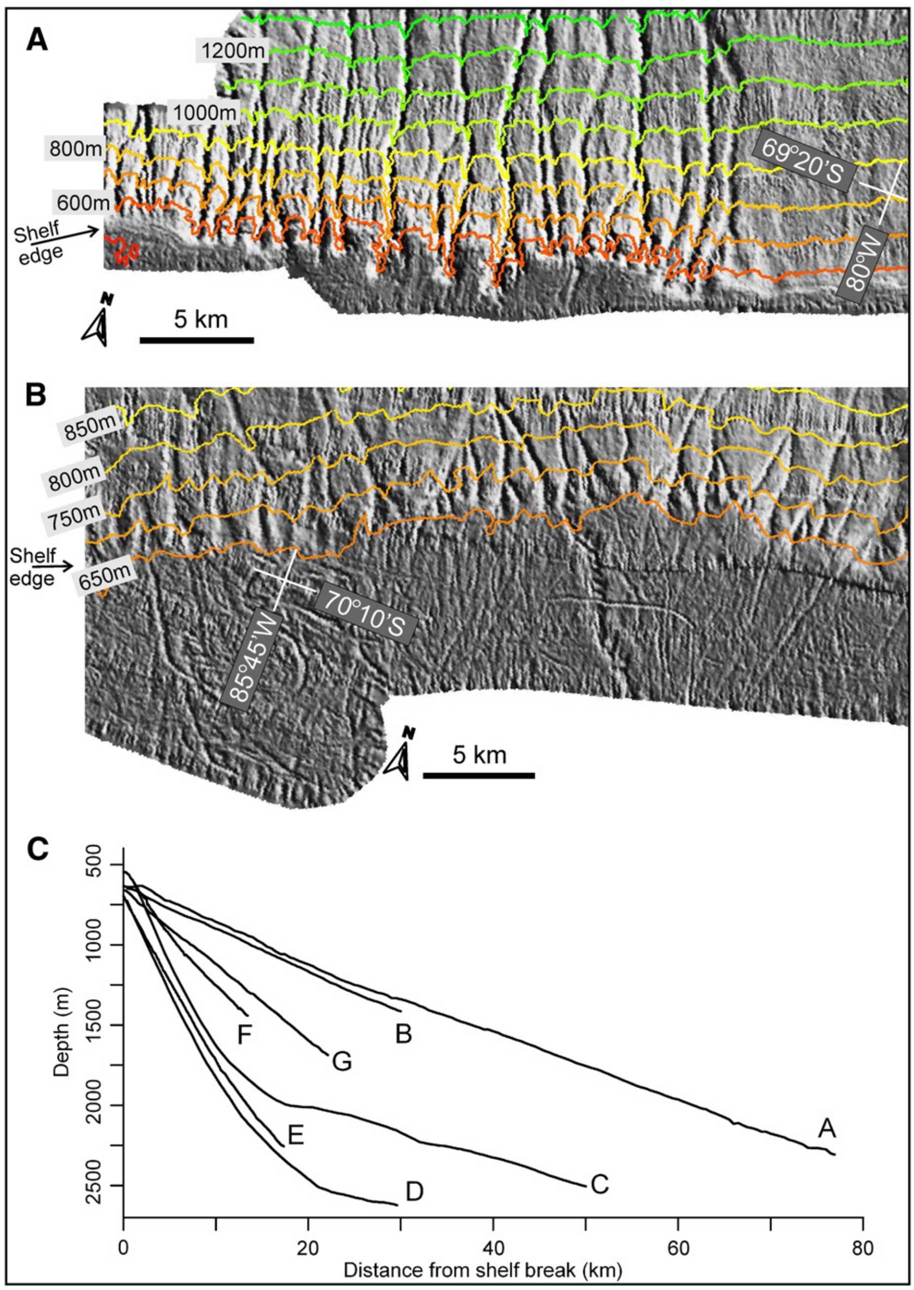

Fig. 2. (A) Closely-spaced gullies eastward of the margin of Belgica Trough. Note the three gullies cutting back into the shelf. Depth is shown with colour-coded contours. (B) Swath bathymetry of the shelf edge offshore of Belgica Trough, showing extensive iceberg ploughmarks on the outermost shelf and gullies on the upper slope. Narrow bands of small-scale ribbing in the shaded bathymetry result from dynamic motion residuals in the data. Locations of swath imagery are given in Fig. 1. (C) Slope angles on the Bellingshausen Sea continental margin (profiles A–G are located in Fig. 1).

during cruises JR104 and JR141 of the RRS *James Clark Ross* in 2004 and 2006. The data were acquired using hull-mounted Kongsberg–Simrad multibeam swath-bathymetry and Topographic Parametric Sonar (TOPAS) sub-bottom profiler systems. Swath-bathymetric data cover an area of approximately 14,000 km^2, and about 3400 km of TOPAS track were acquired. The ship tracks and area of geophysical data acquisition on the Bellingshausen Sea continental slope and outermost shelf are shown in Fig. 1.

The swath-bathymetry system was a hull-mounted deep-water EM120 with 191 beams, a 1° by 1° beam configuration, and frequencies in the range of 11.75–12.75 kHz. The swath data allowed detailed mapping of the morphology of the sea floor. Data processing was carried out using Kongsberg–Simrad Neptune software and public-access MB-system software, and involved removal of anomalous data points and application of corrected sound-velocity profiles. Narrow bands of small-scale ribbing remain in some swath imagery despite processing, due to dynamic motion residuals in the outermost parts of individual swaths. These effects are noted, where present, in subsequent figures. Swath data were gridded at a cell size of 100 m on the continental slope and 50 m on the outer shelf. Depth measurements have vertical and

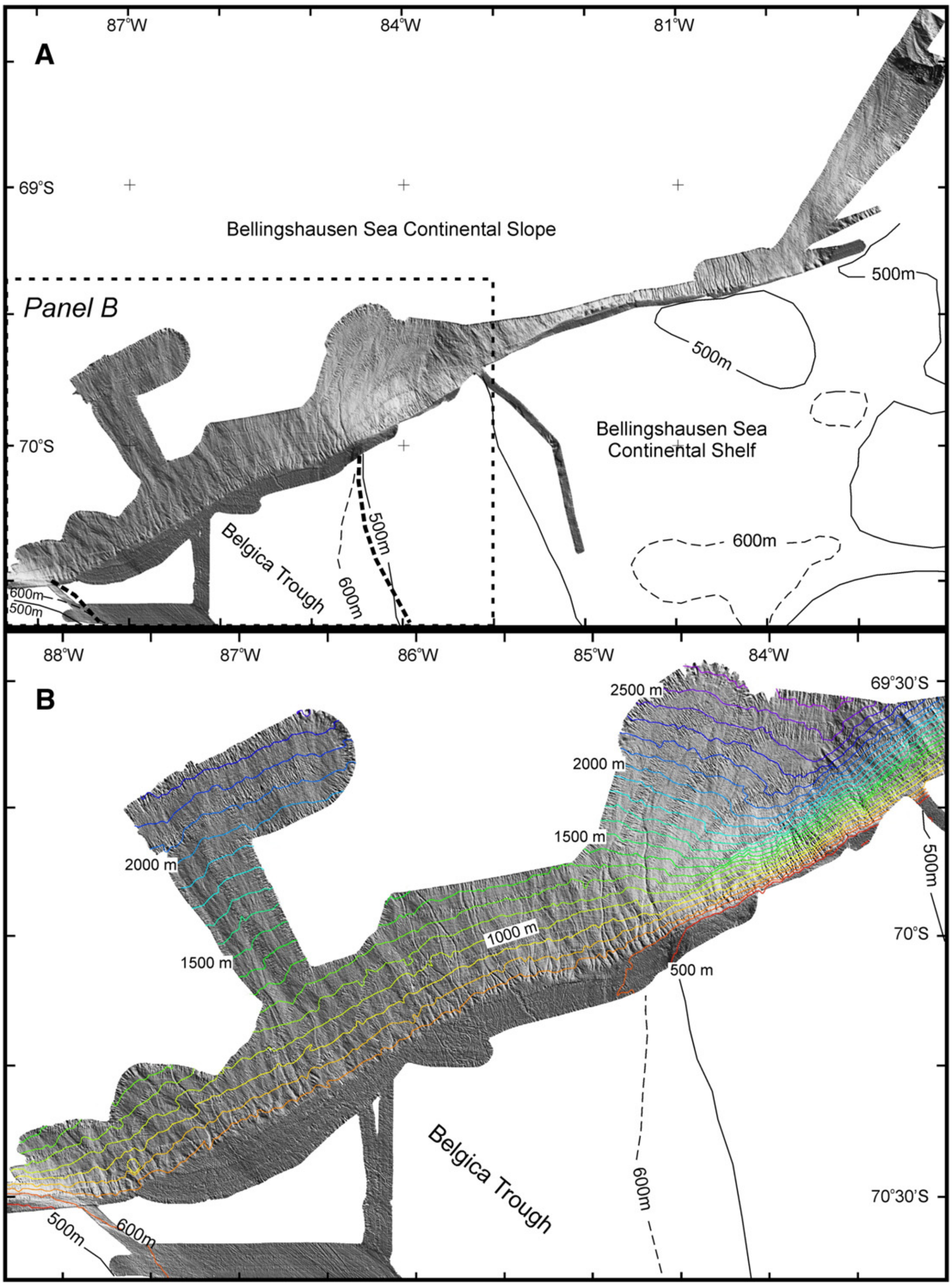

Fig. 3. Sun-illuminated swath-bathymetric images of: (A) the continental slope of the Bellingshausen Sea between 78° and 89°W; and (B) depocentre and trough-mouth off Belgica Trough, with depth contours at 100 m intervals. Narrow bands of small-scale ribbing in the shaded bathymetry result from dynamic motion residuals in the data. Depth contours on the shelf are from Ó Cofaigh et al. (2005).

horizontal uncertainties of about 1 m and 5 m, respectively. The TOPAS parametric acoustic profiler has a narrow (5°) beam with secondary frequencies between 0.5 and 5 kHz. Vertical resolution is better than 1 m for TOPAS. Navigation data were acquired using differential GPS.

4. Results: geophysical observations on the Bellingshausen Sea margin

4.1. Shelf-edge morphology

The continental shelf break along the 330 km-long section of the Bellingshausen Sea that we have investigated is at 650–700 m water depth across the 150-km wide Belgica Trough, and to either side of the trough it is at about 500 m (Fig. 1). The cross-shelf trough itself is defined by pronounced lateral margins, averaging about 2°, and locally up to 11° in gradient. The trough is a major bathymetric feature on the Bellingshausen Sea continental shelf, stretching over 250 km inshore from the shelf edge (Fig. 1). Its detailed morphology is described in Ó Cofaigh et al. (2005). The shelf edge is very apparent on swath-bathymetric imagery because the irregular pattern of sea-floor furrows, produced by iceberg-keel ploughing of the shelf sediments (e.g. Barnes and Lien, 1988; Pudsey et al., 1994; O'Brien et al., 1997; Heroy and Anderson, 2005), ceases abruptly in the deeper water beyond this point (Fig. 2A–B). The maximum depth of iceberg-keel ploughing we observe on the outermost shelf of the Bellingshausen Sea is about 650 m.

Most of the shelf edge is relatively smooth in plan view and, although the gullies running down the continental slope appear to originate mainly on the uppermost part of the slope, they rarely cut back deeply into the shelf itself (Figs. 2A–B, 3). An exception is the area at about 80°30'W, where three gullies extend downslope from small concavities about 80 to 100 m deep that bite back about 1 km into the outermost shelf (Fig. 2A). There are also some small features that may be slide scars at the shelf edge about 82°W. Apart from these relatively restricted features, no major canyons are cut into the outermost continental shelf or upper slope of the Bellingshausen Sea in the area of our data coverage (Figs. 2A–B, 3). Neither is there evidence of widespread large-scale Late Quaternary slope failure affecting the shelf edge and upper slope, although we do not have comprehensive reflection-seismic data to comment on the presence or otherwise of older slide deposits.

4.2. Continental-slope gradient

The gradient of the Bellingshausen Sea continental slope varies considerably, as demonstrated by several bathymetric profiles (Fig. 2). Between about 84° and 88°W, slope angles are generally low at between 1° and 2°. By contrast, the continental slope is steeper at up to 5° from about 81° to 83°W. Further east, between 79° and 81°W, intermediate slope angles of about 3 to 3.5° are observed. These three areas represent: (i) a low-gradient submarine depocentre formed seaward of Belgica Trough (Fig. 2C, profiles A, B), (ii) a steeper continental slope to the east of the trough margin, and (iii) possibly a smaller depocentre in the easternmost part of the study area. There is a transition zone around 84°W, where both steep and more gentle slope elements are present, and the gradient here is therefore a composite of the two main areas (Fig. 2C, profile C). Profiles on the steeper slope are generally concave downslope (Fig. 2C), indicating that the angle of the slope decreases with water depth and distance from the shelf edge to the lower gradient of the continental rise (profiles D, E). The profiles on the depocentres show a more uniform slope angle with increasing depth (Fig. 2C, profiles A, B, F, G).

4.3. Trough-mouth morphology

Swath-bathymetric investigations of the Bellingshausen Sea margin show that the upper continental slope has convex-outward contours for a length of about 150 km between 84° and 88°S (Fig. 3). A low-gradient fan-shaped slope in the continental margin is also inferred from a satellite-derived free-air gravity anomaly map of the margin in this area (McAdoo and Laxon, 1997), and from the interpretation of regional seismic-reflection and sub-bottom acoustic profiler data (Nitsche et al., 2000; Scheuer et al., 2006). This bathymetry, together with the seismic profiles, provides evidence of a major depocentre offshore of Belgica cross-shelf trough. In addition, mega-scale glacial lineations on the sea floor indicative of fast-flowing

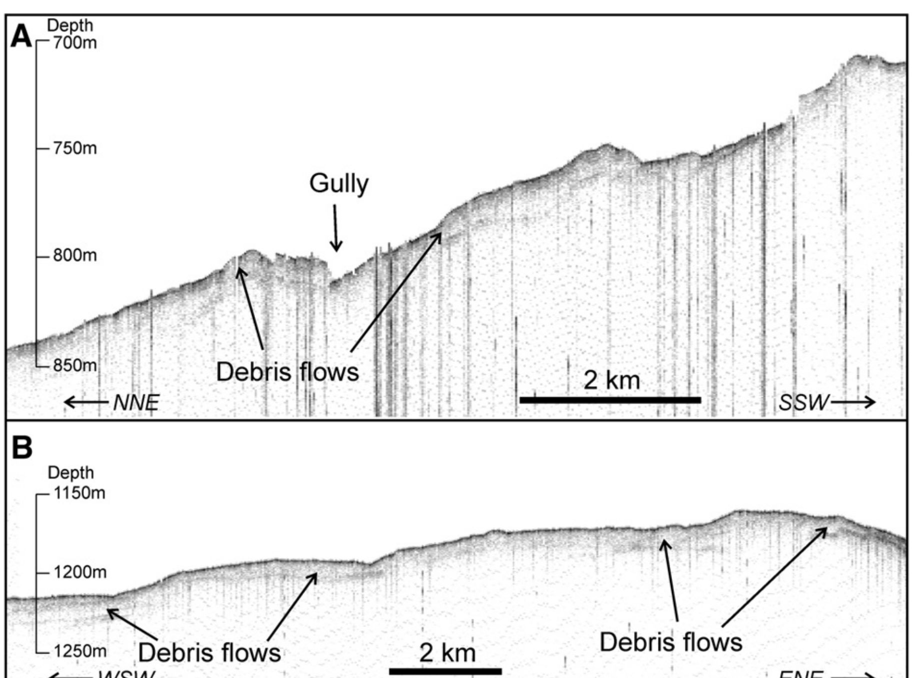

Fig. 4. TOPAS acoustic records of debris flows on the depocentre offshore of Belgica Trough (located in Fig. 1). (A) Down-slope profile (vertical exaggeration c. 24×). (B) Along-slope profile (vertical exaggeration c. 28×).

ice and enhanced sediment delivery to the shelf edge in this area are found in the adjacent trough (Fig. 1) (Ó Cofaigh et al., 2005).

The TOPAS sub-bottom profiles across and down the slope on the depocentre show the presence of a series of sediment lenses (Ó Cofaigh et al., 2005). Individual lenses for which we have acoustic data, and which appear transparent on TOPAS profiles, are up to a number of kilometres in length and about 10 m thick (Fig. 4A, B). These lenses extend downslope from the shelf break, and are indicators of a pattern of sediment delivery that has built out the bulging contours of the depocentre to at least 65 km from the shelf edge in water depths of up to 2500 m at the outer limit of our swath-bathymetric data coverage (Fig. 3). Core material shows that the uppermost few metres of the depocentre is composed mainly of massive grey diamict that is generally overlain by a layer less than 60 cm-thick consisting of muddy sand passing upwards into olive grey hemiplegic, bioturbated foraminifera-bearing mud with dropstones. The latter is inferred to be postglacial, deposited since ice retreated across the Bellingshausen Sea shelf.

A seismic-reflection profile along the continental rise of the Bellingshausen Sea has been interpreted to suggest that there may be another, smaller depocentre on the part of the margin centred at

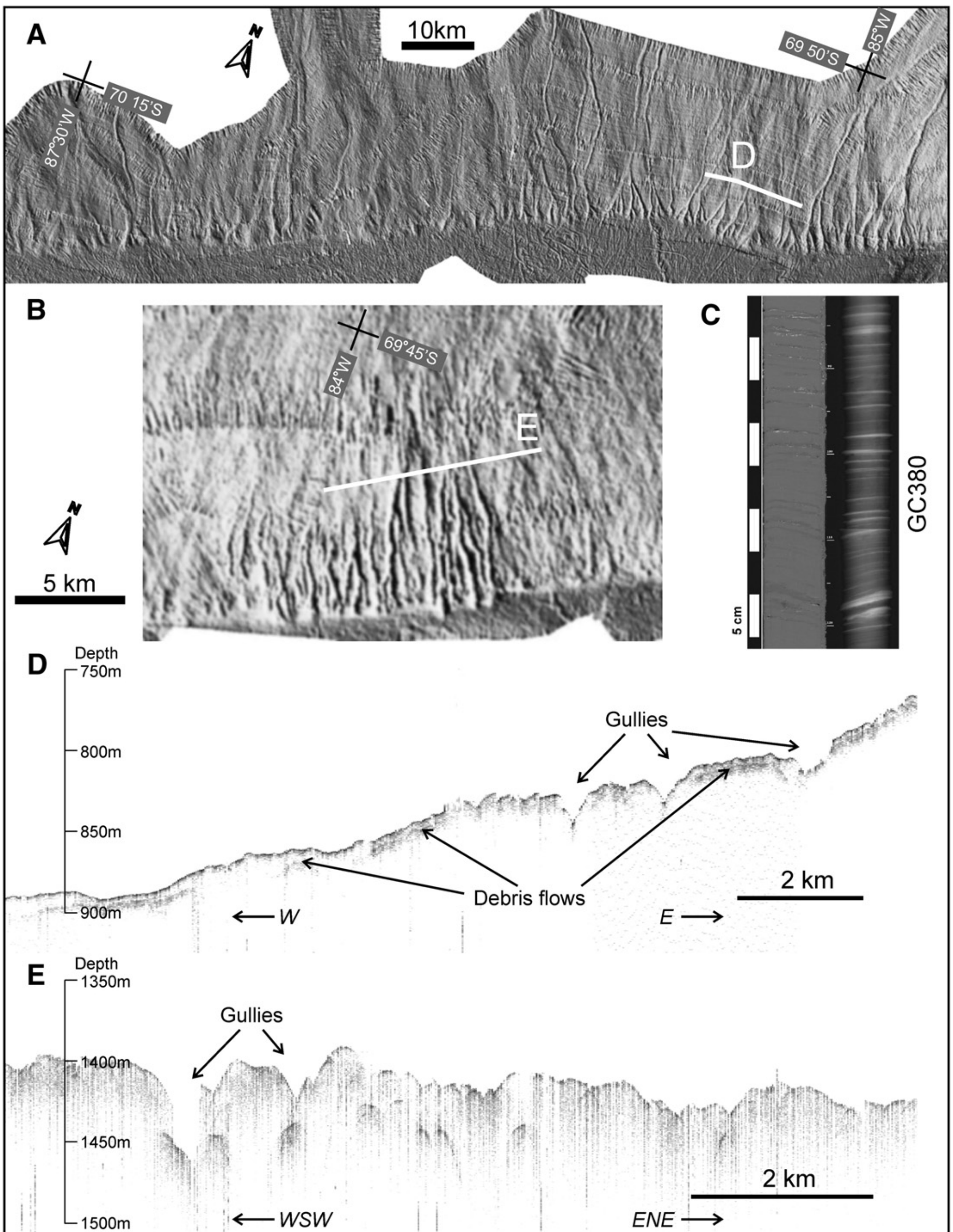

Fig. 5. Detailed morphology of gullies on the Bellingshausen Sea continental slope (locations given in Fig. 1). (A) Swath bathymetry of gully systems on the major depocentre off Belgica Trough (centred on 69°56'S, 85°W). (B) Swath bathymetry of gully systems beyond the eastward margin of Belgica Trough (centred on 69°50'S, 83°45'W). Note the small concavities biting back into shelf at gully heads. Narrow bands of small-scale ribbing in the shaded bathymetry result from dynamic motion residuals in the data. (C) A 40 cm section of core JR104-GC-380 (69°38.5'S, 84°30.7'W), located in Fig. 1, showing sandy silt and clay laminae interpreted as turbidity-current deposits. (D) TOPAS record of debris flows on the depocentre, located in A (vertical exaggeration c. 26×). (E) TOPAS record of gullies on the slope east of the depocentre, located in B (vertical exaggeration c. 17×).

about 81° to 82°W (Scheuer et al., 2006). The limited swath-bathymetric coverage we have from this part of the Bellingshausen Sea margin is compatible with this suggestion, although a cross-shelf trough in this area is only hinted at in our existing geophysical data. Streamlined sedimentary lineations on the shelf indicate two ice-flow directions out of the Ronne Entrance (Fig. 1) (Ó Cofaigh et al., 2005): the first set of submarine landforms, at 72°20'S 78°W, is orientated WNW and feeds into the head of Belgica Trough; the second and more easterly set, at 71°45'S 76°W, flows NNW. The latter set of mega-scale glacial lineations implies that an ice stream could have flowed across the continental shelf about 100 km east of Belgica Trough to provide a full-glacial sediment source for this smaller depocentre.

4.4. Gully and channel morphology

The main morphological features on our swath-bathymetric imagery of the Bellingshausen Sea slope are a number of gully systems and channels (Figs. 3, 5). Gullies are generally relatively deep compared with their width, whereas channels are wider and shallower. Average axial and cross-sectional gradients of gullies are 1.5–3° (locally up to 5–6°) and 3–5° (locally up to 15°), respectively. The axial gradients of channels are usually 1–1.5° and rarely exceed 3°, whereas their cross-sectional gradients are typically between 1 and 2°, locally reaching up to 5°.

Most of the major gully systems are located on the surface of the depocentre offshore of Belgica Trough, and are distributed fairly evenly across its width (Figs. 3, 5A). Their mean density is approximately one gully every 2 km along the shelf edge. A number of the gully systems are about 15 to 25 m deep, several hundred metres wide and over 25 km long, extending beyond the limits of swath-bathymetric data at water depths of between 1200 and 2000 m (Fig. 3). TOPAS acoustic profiles show that many of the gully systems are cut into transparent lenses of sediment that are interpreted as debris flows (Fig. 5D). The gully systems almost all have their origins at or very close to the shelf edge (Fig. 5). They often form an aborescent pattern whose confluences downslope produce stream networks of up to order four (Fig. 5A; Shreve, 1966), a value similar to that observed for gully systems on the Amundsen Sea slope about 1000 km to the west (Dowdeswell et al., 2006).

Some gullies are also present on the steeper part of the slope, eastward of the margin of Belgica Trough at 84°30'W (Figs. 2C, 3, 5B). These gullies tend to be straighter, of lower stream order, and less wide, but are spaced closer together than those on the major depocentre (Fig. 5). Their density is approximately one gully per kilometre along the shelf edge, giving a density about twice that of gullies off Belgica Trough. However, they are not ubiquitous, with most developed in a 50-km wide zone between 80°15' and 81°40'W. A number of these gullies are about 40 to 50 m deep and several hundred metres wide. There are few gullies on the 90 km-long stretch of the upper slope between 81°40'W and the eastern side of Belgica Trough (Figs. 3, 6).

Several channels occur on the surface of the major depocentre offshore of Belgica Trough (Figs. 3, 7). They are of low sinuosity and show few indications of meandering. The largest channel system imaged on the continental slope of the Bellingshausen Sea is over 60 km long, about a kilometre wide and 10 to 15 m deep (Fig. 7A). It continues beyond the edge of our imagery at 69°45'S. Some channels appear to originate on the uppermost slope close to the shelf break, whereas others form from the coalescence of gully systems on the mid-slope. TOPAS acoustic records show little penetration, indicating that the channel floors are made up of relatively coarse sediment (Fig. 7B). This observation was confirmed by acoustic backscatter imagery extracted from the EM120 data, which systematically yielded back-scatter values 10–15% higher in the bottoms of the channels as compared to the adjacent continental-slope areas. No major channels are observed on the steeper slopes in the eastern part of the study area.

5. Interpretation and discussion

5.1. Patterns and processes of sedimentation on the continental slope

Acoustically transparent or semi-transparent lenses of sediment are relatively common on TOPAS records from the depocentre offshore of Belgica Trough (Fig. 4). Such lenses are seldom observed on areas of the slope to either side of the trough mouth. Their acoustic character and their elongate shape with consistent thinning downslope suggests that they are debris flows derived from failures on the upper slope (e.g. King et al., 1996; Taylor et al., 2002). The debris flows are composed of diamictic sediments, and are interpreted as glacigenic debris flows (Hillenbrand et al., 2005). Diamicts are the typical product of erosion and transport at the base of glaciers and ice sheets (Benn and Evans, 1998), implying that the material was delivered to the shelf edge and upper slope by the fast-flowing ice stream present in Belgica Trough during the last glacial period (Ó Cofaigh et al., 2005; Hillenbrand et al., 2005). Mega-scale glacial lineations on the trough floor demonstrate that a grounded WAIS reached at least to 70°37'S, and most likely to the shelf edge, under full-glacial conditions (Ó Cofaigh et al., 2005).

Debris-flow processes are interpreted to have been important in transporting glacier-derived sediment down the upper continental slope and were probably associated with building out the depocentre beyond

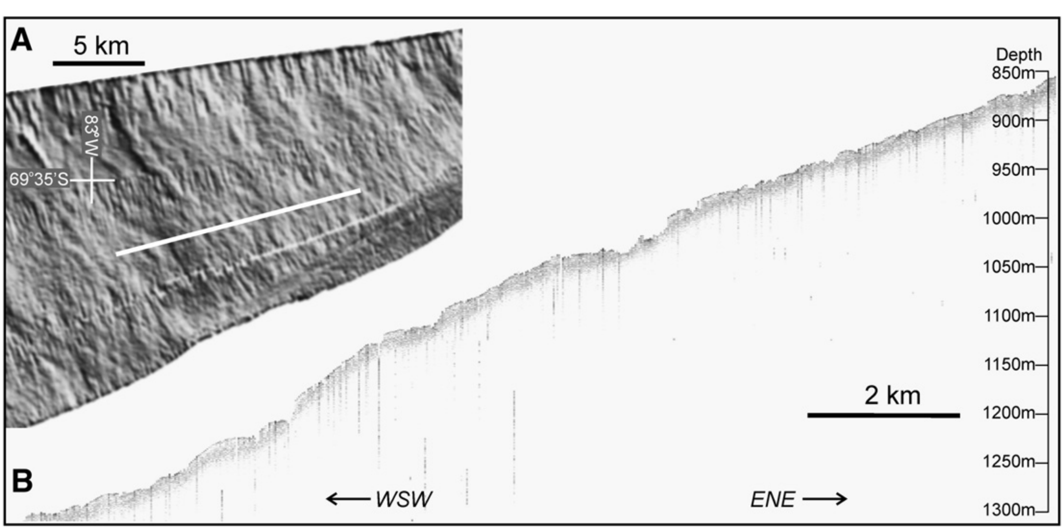

Fig. 6. Morphology of the Bellingshausen Sea continental slope beyond the margin of Belgica Trough. (A) Swath bathymetry of the slope (centred at 69°35'S, 82°50'W, located in Fig. 1). Narrow bands of small-scale ribbing in the shaded bathymetry result from dynamic motion residuals in the data. (B) TOPAS record, located in part (A) (vertical exaggeration c. 13×).

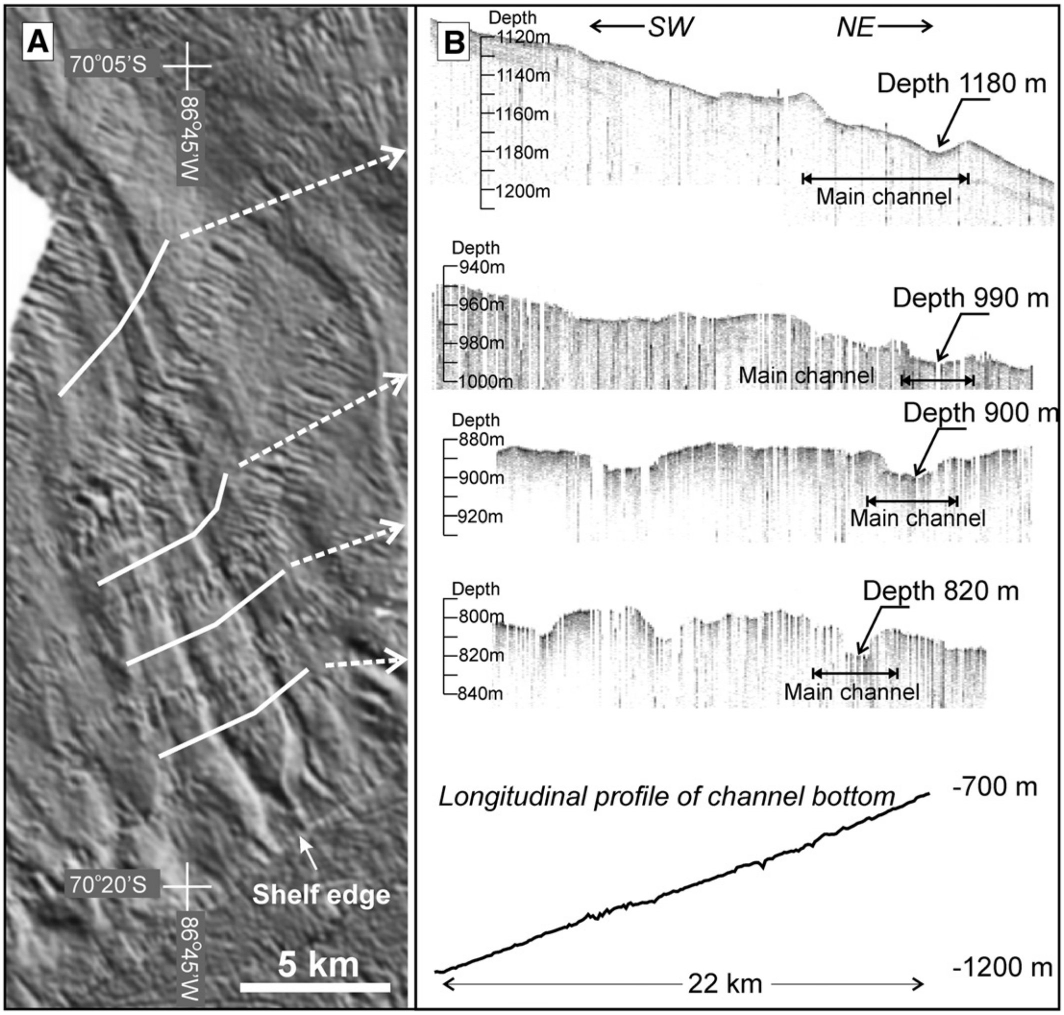

Fig. 7. Channel system on the major depocentre off Belgica Trough (located in Fig. 1). (A) Swath bathymetry of the channel system. Narrow bands of small-scale ribbing in the shaded bathymetry result from dynamic motion residuals in the data. (B) Four TOPAS cross profiles and one long profile from the channel system in (A).

the shelf edge. Similar sedimentary processes, resulting in the development of major depocentres beyond cross-shelf troughs, have been observed on other Antarctic and Arctic continental margins (e.g. Anderson et al., 1986; Laberg and Vorren, 1995; Dowdeswell et al., 1996, 1997; Vorren et al., 1998; Taylor et al., 2002). Debris flows on the Bear Island Fan, Norwegian margin, are dated to full-glacial conditions, linked to enhanced sediment supply from ice streams reaching the shelf edge (Laberg and Vorren, 1995; Vorren et al., 1998).

The well-developed networks of gullies and channels on the Bellingshausen Sea slope are interpreted to be related to the downslope transfer of sediments from the upper slope to the continental rise (Figs. 5, 7). The lack of acoustic penetration through the beds of the gullies and channels, and the higher acoustic backscatter returns from the beds of the channels, suggest a hard, eroded surface and/or a relatively coarse-grained component to the downslope flows that cut them. Unlike the debris flows on the upper slope, which provide sediment to build out the depocentre, channel systems on the Bellingshausen Sea margin and elsewhere around Antarctica and the Arctic provide a pathway for sediment by-passing of the upper slope and the transfer of debris to the continental rise and beyond (e.g. Tomlinson et al., 1992; Rebesco et al., 1997, 2002; Pudsey and Camerlenghi, 1998; Vorren et al., 1998; Shipp et al., 1999; Nitsche et al., 2000; Dowdeswell et al., 2002, 2004, 2006; Michels et al., 2002; Ó Cofaigh et al., 2004, 2006; Mosola and Anderson, 2006). This is achieved through the intermittent occurrence of turbidity currents flowing down the channels (Anderson, 1999). Gullies, in particular where they connect to channels downslope, are also pathways for sediment transfer beyond the upper slope. Where they do not connect directly to channels, gully-mouth lobes of sediment may form as the gullies lose their definition downslope and contribute to the development of the depocentre (Anderson, 1999).

There is some evidence for turbidity-current activity adjacent to channel banks on the slope offshore of Belgica Trough, in the form of acoustically laminated sediments and X-radiographs indicating alternating coarse and fine units of sandy silt and clay laminae (Fig. 5C). The terrigenous material for turbidity currents on high-latitude margins can be supplied by resuspension of sediments at the shelf break by iceberg disturbance or strong currents. Turbidity currents can also form by a downslope transition from slumps and debris flows (Wright and Anderson, 1982; Vanneste and Larter, 1995). Down-slope transport of suspended particles can also be caused by the delivery of highly turbid meltwater from the subglacial drainage system of ice sheets and by dense-water formation through salt rejection during sea-ice freezing on continental shelves (e.g. Anderson, 1999; Lowe and Anderson, 2002; Dowdeswell et al., 2006). Production of turbid meltwater flows and transitions from other types of mass flow are predominantly full-glacial processes, when ice-sheet margins are at the shelf edge, whereas saline-water formation can also take place in interglacials when ice sheets have retreated across the shelf and are replaced by annual sea-ice formation and accompanying brine rejection. All of these processes can generate the dense water necessary to produce downslope flow, debris entrainment and turbidity-current formation.

Gullies on the Bellingshausen Sea margin are also observed on acoustic records to cut through debris flows on the slope (Fig. 5D). In addition, some cores from the eastern part of the depocentre show that diamictic debris flows are overlain by gravelly sands, interpreted as grain flows, or by turbidity-current derived sandy silt and clay laminae (Fig. 5C). An implication of this is that processes taking place in association with the gullies occurred following the most recent phase of debris-flow activity on the depocentre and thus were probably active during late glacial and deglacial phases and perhaps subsequent to this.

Gullies and channels of similar morphology to those on the upper continental slope of the Bellingshausen Sea have been reported from immediately below the shelf break in the eastern Amundsen Sea, the central and eastern Ross Sea (Shipp et al., 1999; Anderson et al., 2002; Dowdeswell et al., 2006), on the western Antarctic Peninsula slope (Vanneste and Larter, 1995; Heroy and Anderson, 2005; Amblas et al., 2006) and in the southern Weddell Sea (Michels et al., 2002). However, large sedimentary depocentres on the continental slope have seldom been identified in these other areas (Kuvaas and Kristoffersen, 1991). Offshore from Marguerite Bay, Antarctic Peninsula, gullies are also present along the uppermost continental slope, but occur more frequently and are deeper beyond the shallower banks defining the edges of the Marguerite Trough than in the trough itself (Dowdeswell et al., 2004). A similar distribution of gullies is observed around the mouth of the cross-shelf trough that reaches the Antarctic Peninsula margin off Anvers Island (Vanneste and Larter, 1995). This is the opposite of the situation in the eastern Amundsen Sea, where gullies occur seaward of the major cross-shelf trough (Dowdeswell et al., 2006). Gullies seem, therefore, to occur in front of some Antarctic ice streams but not others. However, many appear to post-date the full-glacial delivery of debris to the slope, implying that they are either deglacial (formed by meltwater) and/or postglacial (formed by brine rejection during sea-ice formation or perhaps fluid seepage at gully heads).

Marine-geophysical investigations of the continental slope of the Bellingshausen Sea appear to record no evidence of major slides or other major mass-wasting failures during the Quaternary (Nitsche et al., 2000; Cunningham et al., 2002) (Fig. 3). The major upper-slope slide scars and lower-slope deposition of huge blocks of failed material, that are characteristic of large-scale slope failures on the ice-sheet influenced

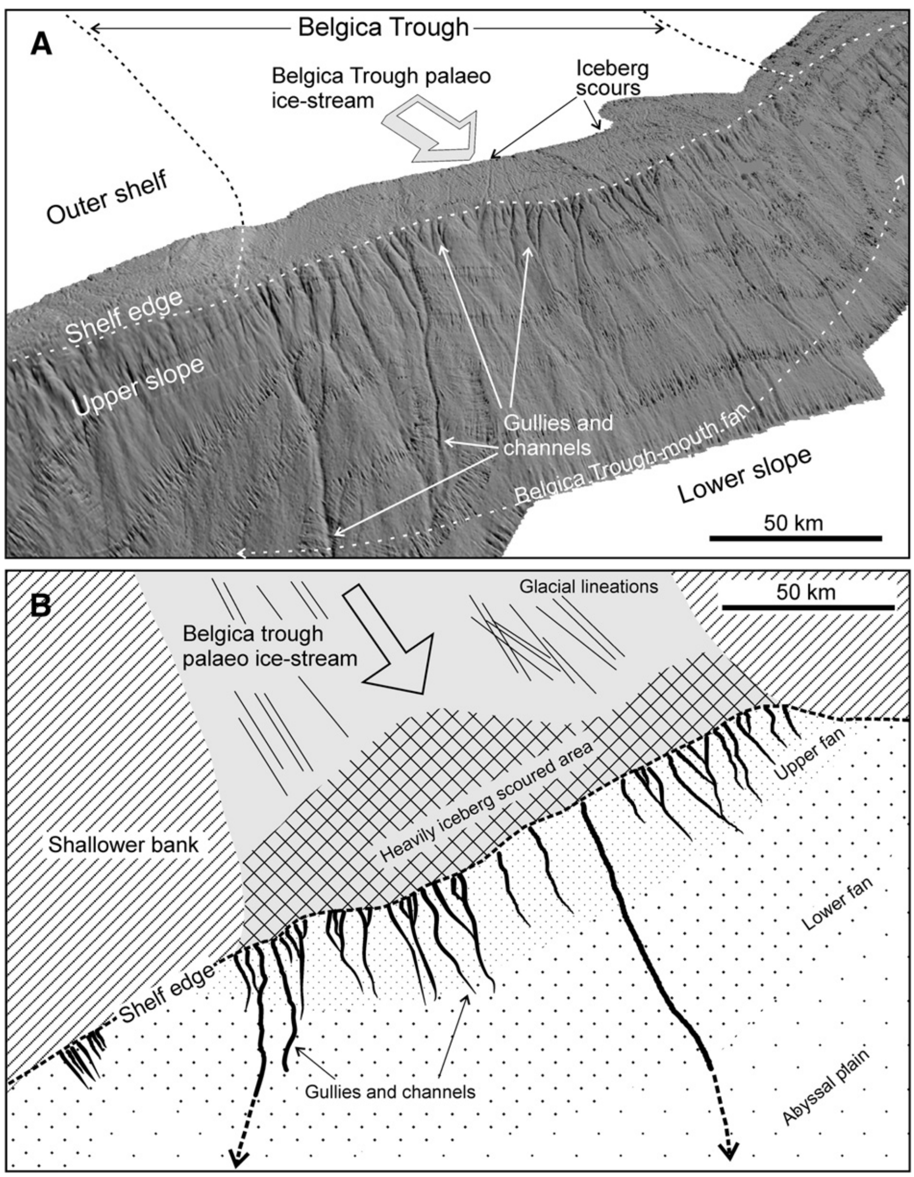

Fig. 8. The major morphological features on the Belgica trough-fan sedimentary system, Bellingshausen Sea continental margin. (A) Oblique view (from the north) of sun-illuminated swath bathymetry of the fan and major sedimentary features. Narrow bands of small-scale ribbing in the shaded bathymetry result from dynamic motion residuals in the data. (B) Schematic diagram of the Belgica Fan.

margins of Northwest Europe (e.g. Vorren et al., 1998; Dowdeswell et al., 2002; Haflidason et al., 2004; Vanneste et al., 2006), have not been observed to date. The situation in the Bellingshausen Sea is similar to the Pacific margins of the eastern Amundsen Sea and the Antarctic Peninsula, where canyons and major slides and slide scars associated with mass-wasting on the continental slope are also uncommon (e.g. Tomlinson et al., 1992; Larter and Cunningham, 1993; Rebesco et al., 1998; Nitsche et al., 2000; Dowdeswell et al., 2004, 2006). However, recent studies of seismic-reflection data have revealed older buried slide deposits of Pliocene age on the continental rise west of the Antarctic Peninsula (Diviacco et al., 2006; Hernández-Molina et al., 2006).

5.2. Belgica trough-mouth fan

Trough-mouth fans are formed where ice sheets reach the continental shelf edge as fast-flowing ice streams, delivering large volumes of glacier-derived sediment directly to the upper slope (Vorren and Laberg, 1997; Dowdeswell et al., 2002; Ó Cofaigh et al., 2003). The presence of a palaeo-ice stream in Belgica Trough is indicated by mega-scale glacial lineations formed in diamicton interpreted as soft till (Fig. 1) (Ó Cofaigh et al., 2005). The outward-bulging bathymetric contours in front of Belgica Trough (Figs. 1, 3), the acoustically-transparent lenses imaged by TOPAS on the slope (Fig. 4), and the poorly-sorted nature of sediment making up the lenses interpreted as glacigenic debris flows (Hillenbrand et al., 2005), combined with seismic-reflection studies (Nitsche et al., 1997; Scheuer et al., 2006), lead to the interpretation of the depocentre seaward of Belgica Trough as a trough-mouth fan. Glacigenic debris flows are likely to have contributed large volumes of sediment to the fan's progradation. We refer to this major depositional feature of the Bellingshausen Sea margin as the 'Belgica Fan', after the first ship to explore this part of Antarctica.

Belgica Fan is the only major trough-mouth fan so far identified along the entire Antarctic margin stretching across the eastern Amundsen Sea, the Bellingshausen Sea and the western Antarctic Peninsula. The slope of Belgica Fan is between about 1° and 2° (Fig. 2C), and seismic-reflection profiles indicate it has developed as a prograding sedimentary wedge (Nitsche et al., 2000). Elsewhere on the Bellingshausen Sea margin, slope angles vary from about 1° to 6°. Off the Antarctic Peninsula margin, slopes often exceed 10° (e.g. Larter and Cunningham, 1993; Rebesco et al., 1998, 2002; Canals et al., 2002; Ó Cofaigh et al., 2003; Dowdeswell et al., 2004; Amblas et al., 2006). However, Scheuer et al. (2006) found indications of two further depocentres in an across-slope seismic line further out from the shelf edge, beyond our area of swath-bathymetric data coverage. Conclusions on the origin of these depocentres await further geophysical work (Scheuer et al., 2006). Other major trough-mouth fans around Antarctica, including the Crary Fan in the Weddell Sea (Kuvaas and Kristoffersen, 1991; Moons et al., 1992; Bart et al., 1999), the Northern Basin Fan in the Ross Sea (Bart et al., 2000) and the Amery or Prydz Bay Fan (Kuvaas and Leitchenkov, 1992; O'Brien, 1994), also have relatively low gradients.

The Belgica Fan has an area of at least 22,000 km^2 (approximately 180 km wide by 120 km long). This is likely to represent a minimum size, remembering that the most distal part of the fan is difficult to define and extends beyond our swath-bathymetric data coverage (Figs. 1, 3). The WAIS drainage basin that fed the ice stream that flowed through Belgica Trough under full-glacial conditions has been estimated at about 200,000 km^2 in area (Ó Cofaigh et al., 2005). By contrast, the sandy mid-portion of the Weddell Fan alone is almost 300,000 km^2 (Anderson et al., 1986), and the combined area of the Weddell and adjacent Crary fans in Antarctica's Weddell Sea make them one of the largest fan systems in the World (Anderson, 1999). The ice-sheet drainage basins flowing into the Weddell Sea from both West and East Antarctica are, in turn, an order of magnitude larger than that supplying ice to Belgica Trough, at several million square kilometres (Drewry, 1983). In the Arctic, fan dimensions include, for example, the 15,000 km^2 Scoresby Sund Fan off East Greenland (Dowdeswell et al., 1997), and the huge 215,000 and 140,000 km^2 areas of the Bear Island and North Sea fans. The latter are among the largest glacier-influenced fans in the Northern Hemisphere (King et al., 1996; Vorren et al., 1998).

In terms of fan volume, two reflection-seismic profiles presented by Nitsche et al. (2000) showed that the Belgica Fan is up to 4 km thick. Average fan thickness is estimated at roughly 3 km, with the glacial sediments overlying a body of material that Cunningham et al. (2002) interpreted as a relict accretionary prism. Combining this mean thickness value with an area of 22,000 km^2 yields an approximate volume of about 60,000 km^3 for the Belgica Fan. This volume is again likely to be a minimum estimate, since our calculations may not include the most distal parts of the fan system. Scheuer et al. (2006) suggest, by correlation with seismic profiles and ODP and DSDP cores offshore of the Antarctic Peninsula (Rebesco et al., 1997, 2002; Iwai et al., 2002), that the glacier-derived debris making up the fan may have accumulated over the past 5.3 Ma through a series of ice-sheet advances to the shelf break. The Belgica Fan, in terms of area and volume, is the largest depocentre recognised to date on the continental margin surrounding the WAIS.

6. Conclusions

The form of a 330-km length of the little known continental slope and shelf edge of the Bellingshausen Sea has been investigated using multibeam swath-bathymetric and sub-bottom profiler observations (Figs. 1, 3). The continental shelf break is at 650–700 m water depth across the 150-km wide Belgica Trough, and to either side of the trough is at about 500 m.

The upper continental slope has convex-outward contours for a length of about 150 km between 84° and 88°W (Fig. 3), forming a low-gradient (1° to 2°) submarine depocentre seaward of Belgica Trough (Fig. 2C, profiles A, B). Seismic-reflection profiles indicate it has developed as a prograding sedimentary wedge (Nitsche et al., 2000). To the east, the continental slope is steeper (up to about 5°), and there may be a smaller depocentre in the easternmost part of the study area between 79° and 81°W (Scheuer et al., 2006).

No major canyons are cut into the outermost continental shelf or upper slope of the Bellingshausen Sea (Fig. 3). Neither is there evidence of widespread large-scale Late Quaternary slope failure. The main morphological features are a number of gully systems and channels (Figs. 2, 3). Most major gully systems are located on the surface of the depocentre offshore of Belgica Trough. Their mean density is approximately one gully every 2 km. Gully systems have axial gradients of 1.5–3°, are often about 15 to 25 m deep, several hundred metres wide and over 25 km long, with their origins at or very close to the shelf edge (Figs. 3, 5).

Several channels of low sinuosity occur on the surface of the major depocentre offshore of Belgica Trough (Figs. 3, 7). The largest channel system imaged is over 60 km long, about a kilometre wide, has an axial gradient of 1 to 1.5° and is 10 to 15 m deep (Fig. 7A). TOPAS acoustic records show little penetration, suggesting that the channel floors are made up of relatively coarse sediment (Fig. 7B). The channel systems provide pathways for sediment by-passing of the upper slope and the intermittent transfer of debris to the continental rise and beyond by turbidity currents.

On the depocentre, TOPAS acoustic profiles show that many of the gully systems are cut into acoustically-transparent lenses of diamictic sediment that are interpreted as debris flows (Fig. 5D). The acoustic character, elongate shape and consistent downslope orientation and thinning of the lenses suggests that they are glacigenic debris flows, probably derived from failures on the upper slope. Debris-flow processes are interpreted to have been important in transporting glacier-derived sediment down the upper continental slope and were probably associated with building out the depocentre on the continental margin.

The outward-bulging bathymetric contours in front of Belgica Trough, and the diamictic lenses imaged by TOPAS on the slope, combined with seismic-reflection studies (Nitsche et al., 1997; Scheuer et al., 2006), lead to the interpretation of the depocentre seaward of Belgica Trough as a trough-mouth fan. The sediment source for the depocentre was a palaeo-ice stream in Belgica Trough, fed from a full-glacial WAIS drainage basin in excess of 200,000 km^2, whose presence is indicated by mega-scale glacial lineations formed in diamict interpreted as soft till.

This sedimentary depocentre, Belgica Fan (Fig. 8), has an area of at least 22,000 km^2 (approximately 180 km wide by 120 km long). Average fan thickness is estimated at 3 km, with an approximate volume of 60,000 km^3. This is probably a minimum estimate, since our calculations may not include the most distal parts of the fan system. The Belgica Fan is the largest depocentre so far recognised on the continental margin of West Antarctica.

Acknowledgements

This research was funded by UK Natural Environment Research Council (NERC) grants GR3/JIF/02, NER/G/S/2002/0192 (University of Cambridge), NER/G/S/2002/00009 and the GRADES-QWAD project (British Antarctic Survey). Logistical support was provided by the British Antarctic Survey under the NERC Antarctic Funding Initiative (project AFI4/17). We thank the officers and crew of the RRS *James Clark Ross* for their expert assistance during cruises JR104 and JR141.

References

Amblas, D., Urgeles, R., Canals, M., Calafat, A.M., Rebesco, M., Camerlenghi, A., Estrada, F., De Batist, M., Hughes-Clarke, J.E., 2006. Relationship between continental rise development and palaeo-ice sheet dynamics, northern Antarctic Peninsula Pacific margin. Quat. Sci. Rev. 25, 933–944.

Anderson, J.B., 1999. Antarctic Marine Geology. Cambridge University Press, Cambridge.

Anderson, J.B., Wright, R., Andrews, B., 1986. The Weddell fan and associated abyssal plain, Antarctica: morphology, sediment processes, and factors influencing sediment supply. Geo-Mar. Lett. 6, 121–129.

Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., Mosola, A.B., 2002. The Antarctic ice sheet during the last glacial maximum and its subsequent retreat history: a review. Quat. Sci. Rev. 21, 49–70.

Barnes, P.W., Lien, R., 1988. Icebergs rework shelf sediments to 500 m off Antarctica. Geology, 16, 1130–1133.

Bart, P.J., De Batist, M., Jokat, W., 1999. Interglacial collapse of Crary Trough Mouth Fan, Weddell Sea Antarctica: implications for Antarctic glacial history analysis. J. Sed. Res. 69, 1276–1289.

Bart, P.J., Anderson, J.B., Trincardi, F., Shipp, S.S., 2000. Seismic data from the Northern basin, Ross Sea, record extreme expansions of the East Antarctic Ice Sheet during the late Neogene. Mar. Geol. 166, 31–50.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London.

Bindschadler, R.A., 1998. Future of the West Antarctic Ice Sheet. Science 282, 428–429.

Canals, M., Urgeles, R., Calafat, A., 2000. Deep sea-floor evidence of past ice streams off the Antarctic Peninsula. Geology 28, 31–34.

Canals, M., Casamor, J.L., Urgeles, R., Calafat, A.M., Domack, E.W., Baraza, J., Farran, M., De Batist, M., 2002. Seafloor evidence of a subglacial sedimentary system off the northern Antarctic Peninsula. Geology 30, 603–606.

Canals, M., Calafat, A., Camerlenghi, A., De Batist, M., Urgeles, R., Farran, M., Geletti, R., Versteeg, W., Amblas, D., Rebesco, M., Casamor, J.L., Sanchez, A., Willmott, V., Lastras, G., Imbo, Y., 2003. Uncovering the footprint of former ice streams off Antarctica. EOS, Trans. Am. Geophys. Union 84, 97, 103.

Cunningham, A.P., Larter, R.D., Barker, P.F., 1994. Glacially prograded sequences on the Bellingshausen Sea continental margin near 90°W. Terra Antarctica 1, 267–268.

Cunningham, A.P., Larter, R.D., Barker, P.F., Gohl, K., Nitsche, F.O., 2002. Tectonic evolution of the Pacific margin of Antarctica 2. Structure of Late Cretaceous–early Tertiary plate boundaries in the Bellingshausen Sea from seismic reflection and gravity data. J. Geophys. Res. 107, 2346. doi:10.1029/2002JB001897.

Diviacco, P., Rebesco, M., Camerlenghi, A., 2006. Late Pliocene mega debris flow deposit and related fluid escapes identified on the Antarctic Peninsula continental margin by seismic reflection data analysis. Mar. Geophysic. Res. 27, 109–127.

Dowdeswell, J.A., Elverhøi, A., 2002. The timing of initiation of fast-flowing ice streams during a glacial cycle inferred from glacimarine sedimentation. Mar. Geol. 188, 3–14.

Dowdeswell, J.A., Siegert, M.J., 1999. Ice-sheet numerical modeling and marine geophysical measurements of glacier-derived sedimentation on the Eurasian Arctic continental margins. Geol. Soc. Am. Bull. 111, 1080–1097.

Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.-J., Mienert, J., Siegert, M.J., 1996. Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: long-range side-scan sonar evidence. Geophys. Res. Lett. 23, 3535–3538.

Dowdeswell, J.A., Kenyon, N.H., Laberg, J.S., 1997. The glacier-influenced Scoresby Sund Fan, East Greenland continental margin: evidence from GLORIA and 3.5 kHz records. Mar. Geol. 143, 207–221.

Dowdeswell, J.A., Ó Cofaigh, C., Taylor, J., Kenyon, N.H., Mienert, J., Wilken, M., 2002. On the architecture of high-latitude continental margins: the influence of ice-sheet and sea-ice processes in the Polar North Atlantic. In: Dowdeswell, J.A., Ó Cofaigh, C. (Eds.), Glacier-Influenced Sedimentation on High-Latitude Continental Margins. Geological Society, London, Special Publication, 203, pp. 33–54.

Dowdeswell, J.A., Ó Cofaigh, C., Pudsey, C.J., 2004. Continental slope morphology and sedimentary processes at the mouth of an Antarctic palaeo-ice stream. Mar. Geol. 204, 203–214.

Dowdeswell, J.A., Evans, J., Ó Cofaigh, C., Anderson, J.B., 2006. Morphology and sedimentary processes on the continental slope off Pine Island Bay, Amundsen Sea, West Antarctica. Geol. Soc. Am. Bull. 118, 606–619.

Drewry, D.J., 1983. Antarctica: Glaciological and Geophysical Folio. Scott Polar Research Institute, Cambridge.

Evans, J., Pudsey, C.J., Ó Cofaigh, C., Morris, P.W., Domack, E.W., 2005. Late Quaternary glacial history, dynamics and sedimentation of the eastern margin of the Antarctic Peninsula Ice Sheet. Quat. Sci. Rev. 24, 741–774.

Evans, J., Dowdeswell, J.A., Ó Cofaigh, C., Benham, T.J., Anderson, J.B., 2006. Extent and dynamics of the West Antarctic Ice Sheet on the outer continental shelf of Pine Island Bay, Amundsen Sea, during the last deglaciation. Mar. Geol. 230, 53–72.

Haflidason, H.P., Sejrup, H.P., Nygard, A., Mienert, J., Bryn, P., Lien, R., Forsberg, C.F., Berg, K., Mason, D., 2004. The Storegga Slide: architecture, geometry and slide development. Mar. Geol. 213, 201–234.

Hernández-Molina, F.J., Larter, R.D., Maldonado, A., Rodríguez-Fernández, J., 2006. Evolution of the Antarctic Peninsula Pacific margin offshore from Adelaide Island since the Late Miocene: an example of a glacial passive margin. Terra Antartica Reports 12, 81–90.

Heroy, D.C., Anderson, J.B., 2005. Ice-sheet extent of the Antarctic Peninsula region during the Last Glacial Maximum (LGM) — insights from glacial geomorphology. Geol. Soc. Am. Bull. 117, 1497–1512.

Hillenbrand, C.-D., Baesler, A., Grobe, H., 2005. The sedimentary record of the last glaciation in the western Bellingshausen Sea (West Antarctica): implications for the interpretation of diamictons in a polar-marine setting. Mar. Geol. 216, 191–204.

Iwai, M., Acton, G.D., Lazarus, D., Osterman, L.E., Williams, T., 2002. Magnetobiochronologic synthesis of ODP Leg 178 rise sediments from the Pacific sector of the Southern Ocean: Sites 1095, 1096 and 1101. In: Barker, P.F., Camerlenghi, A., Acton, G.D., Ramsay, A.T.S. (Eds.), Proceedings of the Ocean Drilling Program. Scientific Results, vol. 78, pp. 1–40.

King, E.L., Sejrup, H.P., Haflidason, H., Elverhøi, A., Aarseth, I., 1996. Quaternary seismic stratigraphy of the North Sea Fan: glacially-fed gravity flow aprons, hemipelagic sedimentation, and submarine sliding. Mar. Geol. 130, 293–315.

Kuvaas, B., Kristoffersen, Y., 1991. The Crary Fan: a trough-mouth fan on the Weddell Sea continental margin, Antarctica. Mar. Geol. 97, 345–362.

Kuvaas, B., Leitchenkov, G., 1992. Glaciomarine turbidite and current controlled deposits, Prydz Bay, Antarctica. Mar. Geol. 108, 365–381.

Laberg, J.S., Vorren, T.O., 1995. Late Weichselian submarine debris flow deposits on the Bear Island Trough Mouth Fan. Mar. Geol. 127, 45–72.

Larter, R.D., Barker, P.F., 1989. Seismic stratigraphy of the Antarctic Peninsula Pacific margin: a record of Pliocene–Pleistocene ice volume and paleoclimate. Geology 17, 731–734.

Larter, R.D., Barker, P.F., 1991. Effects of ridge crest–trench interaction on Antarctic–Phoenix spreading: forces on a young subducting plate. J. Geophys. Res. 96, 19,583–19,607.

Larter, R.D., Cunningham, A.P., 1993. The depositional pattern and distribution of glacial–interglacial sequences on the Antarctic Peninsula Pacific margin. Mar. Geol. 109, 203–219.

Larter, R.D., Vanneste, L.E., 1995. Relict subglacial deltas on the Antarctic Peninsula outer shelf. Geology 23, 33–36.

Larter, R.D., Cunningham, A.P., Barker, P.F., Gohl, K., Nitsche, F.O., 2002. Tectonic evolution of the Pacific margin of Antarctica 1. Late Cretaceous tectonic reconstructions. J. Geophys. Res. 107, 2345. doi:10.1029/2000JB000052.

Lowe, A.L., Anderson, J.B., 2002. Reconstruction of the West Antarctic ice sheet in Pine Island Bay during the Last Glacial Maximum and its subsequent retreat history. Quat. Sci. Rev. 21, 1879–1897.

McAdoo, D., Laxon, S., 1997. Antarctic tectonics: constraints from an ERS-1 satellite marine gravity field. Science 276, 556–560.

Michels, K.H., Kuhn, G., Hillenbrand, C.-D., Diekmann, B., Fütterer, D.K., Grobe, H., Uenzelmann-Neben, G., 2002. The southern Weddell Sea: combined contourite–turbidite sedimentation at the southeastern margin of the Weddell Gyre. In: Stow, D.A.V., Pudsey, C.J., Howe, J., Faugeres, J.-C., Viana, A.R. (Eds.), Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics. Memoirs. Geological Society of London, vol. 22, pp. 305–323.

Moons, A., De Batist, M., Henriet, J.P., Miller, H., 1992. Sequence stratigraphy of Crary Fan, southeastern Weddell Sea. In: Yoshida, Y., Kaminuma, K., Shiraishi, K. (Eds.), Recent Progress in Antarctic Earth Science, pp. 613–618.

Mosola, A.B., Anderson, J.B., 2006. Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: possible consequence of over-extended ice streams? Quat. Sci. Rev. 25, 2177–2196.

Nitsche, F.O., Gohl, K., Vanneste, K.A., Miller, H., 1997. Seismic expression of glacially deposited sequences in the Bellingshausen and Amundsen Seas, West Antarctica. In: Barker, P.F., Cooper, A.K. (Eds.), Geology and Seismic Stratigraphy of the Antarctic Margin: 2. Antarctic Research Series, vol. 71, pp. 95–108.

Nitsche, F.O., Cunningham, A.P., Larter, R.D., Gohl, K., 2000. Geometry and development of glacial continental margin depositional systems in the Bellingshausen Sea. Mar. Geol. 162, 277–302.

O'Brien, P.E., 1994. Morphology and late glacial history of Prydz Bay, Antarctica, based on echo sounder data. Terra Antarctica 1, 403–405.

O'Brien, P.E., Leitchenkov, G., Harris, P.T., 1997. Iceberg plough marks, subglacial bedforms and grounding zone moraines in Prydz Bay, Antarctica. In: Davies, T.A., Bell, T., Cooper, A.K., Josenhans, H., Polyak, L., Solheim, A., Stoker, M.S., Stravers, J.A. (Eds.), Glaciated Continental Margins: an Atlas of Acoustic Images, pp. 228–231.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., Morris, P., 2002. Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf. Geophys. Res. Lett. 29. doi:10.1029/2001GL014488.

Ó Cofaigh, C., Taylor, J., Dowdeswell, J.A., Pudsey, C.J., 2003. Palaeo-ice streams, trough mouth fans and high-latitude continental slope sedimentation. Boreas 32, 37–55.

Ó Cofaigh, C., Dowdeswell, J.A., Kenyon, N.H., Evans, J., Taylor, J., Mienert, J., Wilken, M., 2004. Timing and significance of glacially-influenced mass wasting in the submarine channels of the Greenland Basin. Mar. Geol. 207, 39–54.

Ó Cofaigh, C., Larter, R.D., Dowdeswell, J.A., Hillenbrand, C.D., Pudsey, C.J., Evans, J., Morris, P., 2005. Flow of the West Antarctic Ice Sheet on the continental margin of the Bellingshausen Sea at the Last Glacial Maximum. J. Geophys. Res. 110, B11103. doi:10.1029/2005JB003619.

Ó Cofaigh, C., Dowdeswell, J.A., Kenyon, N.H., 2006. Geophysical investigations of a high-latitude submarine channel system and associated channel-mouth lobe in the Lofoten Basin, Polar North Atlantic. Mar. Geol. 226, 41–50.

Pudsey, C.J., Camerlenghi, A., 1998. Glacial–interglacial deposition on a sediment drift on the Pacific Margin of the Antarctic Peninsula. Antarc. Sci. 10, 286–308.

Pudsey, C.J., Barker, P.F., Larter, R.D., 1994. Ice sheet retreat from the Antarctic Peninsula shelf. Cont. Shelf Res. 14, 1647–1675.

Rebesco, M., Larter, R.D., Barker, P.F., Camerlenghi, A., Vanneste, L.E., 1997. History of sedimentation on the continental rise west of the Antarctic Peninsula. In: Cooper, A.K., Barker, P.F. (Eds.), Geology and Seismic Stratigraphy on the Antarctic Margin: 2. American Geophysical Unions. Antarctic Researc Series, vol. 71, pp. 29–49.

Rebesco, M., Camerlenghi, A., Zanolla, C., 1998. Bathymetry and morphogenesis of the continental margin west of the Antarctic Peninsula. Terra Antarc. 5, 715–725.

Rebesco, M., Pudsey, C.J., Canals, M., Camerlenghi, A., Barker, P.F., Estrada, F., Giorgetti, A.R., 2002. Case study 27: sediment drifts and deep-sea channel systems, Antarctic Peninsula Pacific margin, mid-Miocene to present. In: Stow, D.A.V., Pudsey, C.J., Howe, J., Faugeres, J.-C., Viana, A. (Eds.), Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics. Memoirs. Geological Society of London, Vol. 22, pp. 353–371.

Scheuer, C., Gohl, K., Larter, R.D., Rebesco, M., Udintsev, G., 2006. Variability in Cenozoic sedimentation along the continental rise of the Bellingshausen Sea, West Antarctica. Mar. Geol. 227, 279–298.

Shipp, S.S., Anderson, J.B., Domack, E.W., 1999. Late Pleistocene–Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: part 1 — geophysical results. Geol. Soc. Am. Bull. 111, 1486–1516.

Shreve, R.L., 1966. Statistical law of stream numbers. J. Geol. 74, 17–37.

Taylor, J., Dowdeswell, J.A., Kenyon, N.H., Ó Cofaigh, C., 2002. Late Quaternary architecture of trough-mouth fans: debris flows and suspended sediments on the Norwegian margin. In: Dowdeswell, J.A., Ó Cofaigh, C. (Eds.), Glacier-Influenced Sedimentation on High-Latitude Continental Margins. Geological Society, London, Special Publication, vol. 203, pp. 55–71.

Tomlinson, J.S., Pudsey, C.J., Livermore, R.A., Larter, R.D., Barker, P.F., 1992. Long-range sidescan sonar (GLORIA) survey of the Antarctic Peninsula Pacific margin. In: Yoshida, Y., et al. (Ed.), Recent Progress in Antarctic Earth Science. Terra, Tokyo, pp. 423–429.

Vanneste, L.E., Larter, R.D., 1995. Deep-tow boomer survey on the Antarctic Peninsula Pacific margin: an investigation of the morphology and acoustic characteristics of late Quaternary sedimentary deposits on the outer continental shelf and upper slope. In: Cooper, A.K., Barker, P.F., Brancolini, G. (Eds.), Geology and Seismic Stratigraphy of the Antarctic Margin. American Geophysical Union. Antarctic Research Series, Vol. 68, pp. 97–121.

Vanneste, M., Mienert, J., Bünz, S., 2006. The Hinlopen Slide: a giant, submarine slope failure on the northern Svalbard margin, Arctic Ocean. Earth Planet. Sci. Lett. 245, 373–388.

Vaughan, D.G., Smith, A.M., Corr, H.F.J., Jenkins, A., Bentley, C.R., Stenoien, M.D., Jacobs, S.S., Kellogg, T.B., Rignot, E., Lucchitta, B., 2001. A review of Pine Island Glacier, West Antarctica: hypotheses of instability vs. observations of change. In: Alley, R.B., Bindschadler, R.A. (Eds.), The West Antarctic Ice Sheet: Behavior and Dynamics. Antarctic Research Series, vol. 77, pp. 237–256.

Vorren, T.O., Laberg, J.S., 1997. Trough mouth fans — palaeoclimate and ice-sheet monitors. Quat. Sci. Rev. 16, 865–881.

Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J., Werner, F., 1998. The Norwegian–Greenland Sea continental margins: morphology and Late Quaternary sedimentary processes and environment. Quat. Sci. Rev. 17, 273–302.

Wright, R., Anderson, J.B., 1982. The importance of sediment gravity flow to sediment transport and sorting in a glacial-marine environment — eastern Weddell Sea, Antarctica. Geol. Soc. Am. Bull. 93, 951–963.