

Morphology and sedimentary processes on the continental slope off Pine Island Bay, Amundsen Sea, West Antarctica

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ABSTRACT

Morphology and sedimentation on the Pine Island Bay continental margin, eastern Amundsen Sea, is investigated using swath bathymetry, parametric subbottom profiler (TOPAS) records, and sediment cores. A major cross-shelf trough extends to the continental shelf edge at 114°W, through which fast-flowing ice drained the West Antarctic Ice Sheet under full-glacial conditions. The slope adjacent to the trough mouth is 4°, whereas to the east and west it is steeper. A bulge in bathymetric contours beyond and east of the trough mouth indicates some slope progradation. Elsewhere, seismic-reflection profiles indicate major shelf aggradation and minor slope progradation. Networks of gullies and channels dominate the slope adjacent to Pine Island Bay. In front of the trough mouth, gullies at the shelf edge and uppermost slope connect directly with channels that continue to the continental rise. Other gullies connect indirectly with channels further downslope. TOPAS records indicate that gully-channel systems acted as conduits for coarse-grained sediment transfer. Cores comprise turbidites representing channel deposits and diamicton facies deposited by debris flows. Sandy turbidites interbedded with hemipelagic muds occur on the rise and abyssal plain. The West Antarctic Ice Sheet extended to the shelf edge during full glacials, delivering water-saturated till and turbid water directly to the continental slope along a line source. Gully-channel systems are probably a product of sediment gravity flows derived

from the release of water-saturated till and turbid water along the ice-sheet margin, perhaps augmented subsequently by downslope flow of dense cold and saline water associated with sea-ice production during the Holocene. The gully-channel systems enable sediment to bypass the continental slope. Spatial variations in gully-channel system morphology along the Amundsen Sea continental slope are probably linked to differences in sediment gravity flow processes and the rate and composition of sediment delivered to the shelf edge from the ice sheet. Cored sediments on the slope and abyssal plain record the widespread presence of turbidite sands, indicating that downslope transfer of glacier-derived sediments has taken place. This supports our interpretation that submarine channels are derived from, and are conduits for, mass wasting. Submarine channels on the upper slope continue into the abyssal plain as far north as ~67°S. They are separated by sediment drifts and sediment waves resulting from the interaction between downslope turbidity current processes and along-slope bottom currents. Similar deep-sea sedimentary processes operate along much of West Antarctica and the western side of the Antarctic Peninsula.

Keywords: Amundsen Sea, continental slope, gullies, turbidites, submarine channels, ice streams, Pine Island Bay, West Antarctic Ice Sheet.

INTRODUCTION

The development and morphology of high-latitude continental margins during the Cenozoic has been influenced strongly by intermittent

sediment delivery from ice sheets. In Antarctica, a major ice sheet first built up ca. 30–40 Ma ago, and large Northern Hemisphere ice sheets have grown and decayed a number of times in the past few million years (e.g., Anderson, 1999; Dowdeswell et al., 2002). In response to climatic changes, these ice sheets have advanced and retreated repeatedly across polar continental shelves, shifting the focus of sediment delivery from inner-shelf and fjord settings to the continental shelf edge and upper slope. In addition, ice sheets are often divided into fast-flowing ice streams, fed from major interior drainage basins, set within slower-moving ice that may be frozen to the bed. The rate of glacier-derived sediment delivery to the continental slope is, therefore, variable both through time and space (e.g., Rebesco et al., 1998; Dowdeswell and Siegert, 1999; Dowdeswell and Elverhøi, 2002; Pollard and DeConto, 2003).

In this paper, we report on the nature of the continental slope and shelf break in the isolated Amundsen Sea sector of the Antarctic margin, south of the Pacific Ocean (Fig. 1). We use marine-geophysical methods to examine a 750-km-long section of this margin between 100° and 115°W, beyond the wide continental shelf forming Pine Island Bay (Fig. 1). About 300,000 km² of the modern West Antarctic Ice Sheet drain into Pine Island Bay, mainly through two major ice streams (Vaughan et al., 2001). Morphological evidence, in the form of large-scale streamlined sedimentary bedforms, suggests that fast-flowing ice streams extended to the shelf edge under full-glacial conditions (Lowe and Anderson, 2002, 2003; J. Evans, 2005, personal commun.), making the continental slope here of particular interest. In addition, we use our morphological data, combined with information on slope sediments

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from cores, to infer the processes of sediment delivery and downslope transfer on this glacier-influenced Antarctic margin.

STUDY AREA AND SCIENTIFIC BACKGROUND

The Amundsen Sea is located between $\sim 100^\circ$ and 140° W, offshore of the Marie Byrd Land area of West Antarctica (Fig. 1). The 1500-km-long continental shelf break, occurring at ~ 500 – 600 m in water depth, generally lies between $\sim 71^\circ$ and 72° S. The Amundsen Sea shelf is between 300 km and 450 km wide from the edge of the West Antarctic Ice Sheet to the shelf edge, and tends to deepen inshore in response to isostatic

loading and long-term glacial erosion by the ice sheet (e.g., Anderson, 1999; Lowe and Anderson, 2002). Pine Island Bay is the longest embayment in this part of the Antarctic coastline, with a distance from the ice-sheet terminus to the shelf break of almost 500 km (Fig. 1). The ocean circulation, known as the East Wind Drift or Antarctic Coastal Current, is generally westward along the Amundsen Sea margin (Gordon, 1971).

In contrast with the Bellingshausen and Antarctic Peninsula margins to the east, the Amundsen Sea was a divergent plate margin that formed as New Zealand was rifted away from Antarctica ca. 90 Ma (Lawver et al., 1992). The margin has been passive since ca. 85 Ma, whereas much of the Bellingshausen Sea and western

Antarctic Peninsula were dominated by subduction, with plate collisions between ca. 55 and 4 Ma that took place successively from southwest to northeast (Larter and Barker, 1991). Thus, tectonic processes are likely to have had a much less significant influence on sedimentation on the Amundsen Sea margin than on the more easterly Bellingshausen and, especially, the Peninsula margin (Nitsche et al., 1997).

Limited existing seismic-reflection studies show that the eastern Amundsen Sea margin, at ~ 104 – 105° W, has undergone a phase of progradation, followed by a more recent phase of combined progradation and aggradation; the two seismic units together account for almost 25 km of seaward migration of the shelf edge and are interpreted to be of mainly glacial origin. They were probably deposited since the late Miocene (Nitsche et al., 1997).

Glaciologically, the part of the West Antarctic Ice Sheet flowing into Pine Island Bay is of particular interest for two reasons. First, ice flows into the bay in two fast-flowing ice streams; Pine Island Glacier and Thwaites Glacier (Fig. 1), which each drain ice-sheet basins of $\sim 165,000$ km² (Bamber and Bindschadler, 1997; Rignot, 2001; Vaughan et al., 2001). Combined with estimates of precipitation over these basins, the balance flux, or the amount of ice that must leave the basin for a balance between input and loss to be maintained, is ~ 70 – 80 km³ yr⁻¹ in each case (Vaughan et al., 1999, 2001). Pine Island Glacier alone contributes $\sim 4\%$ of the outflow from the whole Antarctic Ice Sheet (Vaughan et al., 2001). Secondly, ice in both the Pine Island and Thwaites Glacier drainage basins is grounded mainly below present sea level by up to 2500 m (Vaughan et al., 2001), making both basins potentially susceptible to collapse (e.g., Hughes, 1981; Kellogg and Kellogg, 1987). The present and past behavior of this sector of the Antarctic Ice Sheet is thus of wider environmental significance.

DATA ACQUISITION AND METHODS

The geophysical and geological data sets used in this study were acquired during several cruises. Geophysical data were obtained from the RRS *James Clark Ross* in March 2003 using hull-mounted Kongsberg Simrad multibeam swath bathymetry and topographic parametric sonar (TOPAS) subbottom profiler systems. The swath system was a deep-water 12 kHz EM120 with 191 beams and a $1^\circ \times 1^\circ$ beam configuration. 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 horizontal uncertainties of ~ 1 m and 5 m, respectively. The TOPAS parametric acoustic

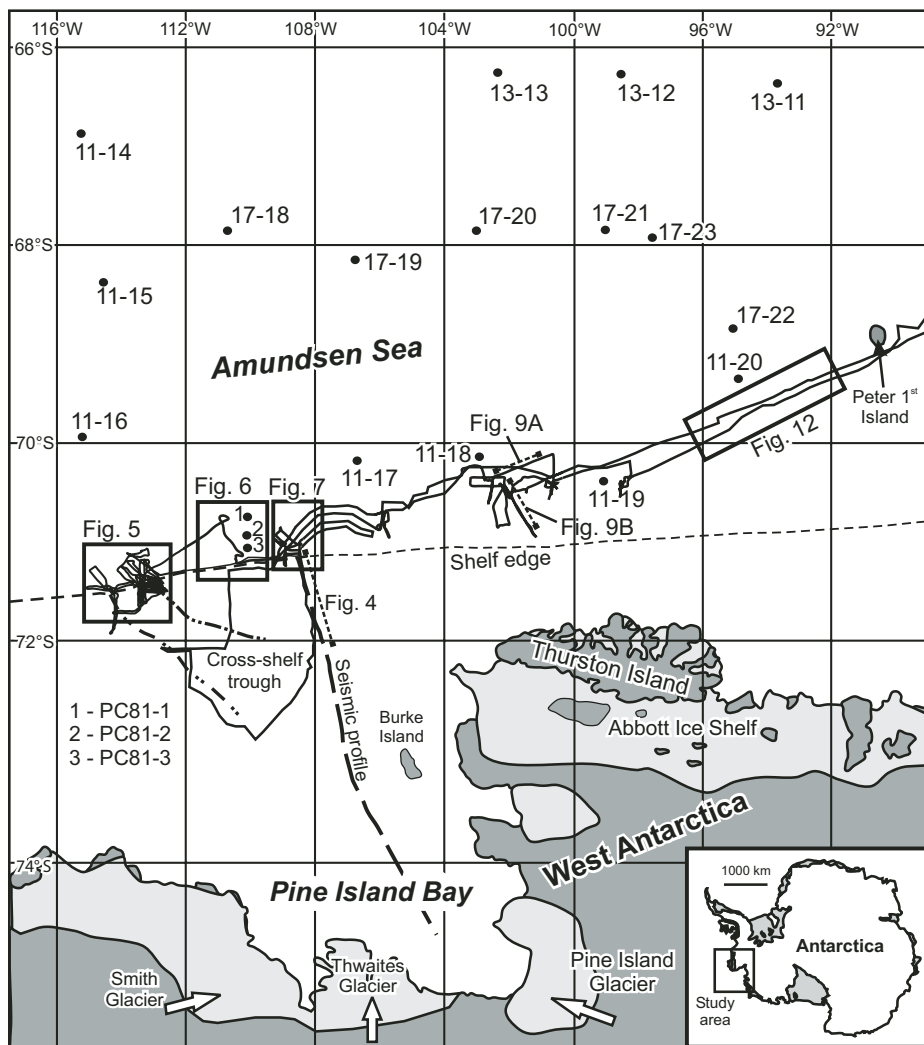


Figure 1. Location map of Pine Island Bay and the adjacent continental margin, West Antarctica, showing track lines of the RRS *James Clark Ross* during cruise JR84. The locations of Figures 4–7, 9, and 12 are shown. Grounded and floating parts of the Antarctic Ice Sheet are shaded dark and light, respectively.

profiler has a secondary frequency of 0.5–5 kHz. The area of geophysical data acquisition on the Amundsen Sea continental slope and outermost shelf is shown in Figure 1.

A SSE- to NNW-trending single-channel seismic-reflection profile was collected along the axis of the main trough in Pine Island Bay to the upper slope between $\sim 107^\circ\text{W}$ to $108^\circ 30'\text{W}$ (Fig. 1) using a 210 cubic inch GI air gun (cf. Lowe and Anderson, 2002). The data were recorded digitally with an Elics seismic acquisition system and were band-pass filtered. The quality of the data collected on the outer shelf and upper slope is poor due to severe sea-ice cover in that area.

Piston cores were collected along a shelf-edge to base-of-slope transect during *Deep Freeze 81* cruise and on the Amundsen Sea continental rise and abyssal floor during *Eltanin* cruises 11 and 17 (Fig. 1). Detailed sedimentological and petrographic analyses of turbidite sands within these cores were performed by Baegi (1985).

GEOPHYSICAL AND GEOLOGICAL OBSERVATIONS OF THE AMUNDSEN SEA MARGIN

Continental Slope Gradient and Morphology

The morphology of the continental slope off Pine Island Bay is illustrated in Figures 2 and 3. The analysis of several bathymetric profiles down the continental slope between 108° and 115°W shows that slope angles vary between $\sim 4^\circ$ and 7° . In addition, a seismic-reflection line oriented down the slope at $\sim 104^\circ\text{W}$, just east of our study area, has an angle of 3° – 4° (Nitsche et al., 1997, 2000). Seismic-reflection data from 104°W show that the slope has undergone both progradation and aggradation since the middle Miocene (Nitsche et al., 1997, 2000), with the most recent stage of strata formation dominated by aggradation. Similarly, seismic-reflection data from the outer shelf and upper slope at $\sim 108^\circ\text{W}$ show mainly aggradation of the shelf and very minor progradation of the shelf edge and slope (Fig. 4).

The continental slope of the eastern Amundsen Sea is, for the most part, concave upward in long profile, with the steepest gradients on the upper slope above 1200 m in water depth (Fig. 2). However, slope gradient sometimes remains fairly constant, such as in front of a cross-shelf trough located around 114°W (Figs. 2A–B and 3). The five slope profiles presented in Figure 2 show that the continental slope is less steep west of $\sim 113^\circ\text{W}$. The lowest slope gradients are found in front of the cross-shelf trough at $\sim 114^\circ\text{W}$ (Fig. 2A–B), extending westward at least 10 km beyond the trough edge (Fig. 2C). A steeper region of the

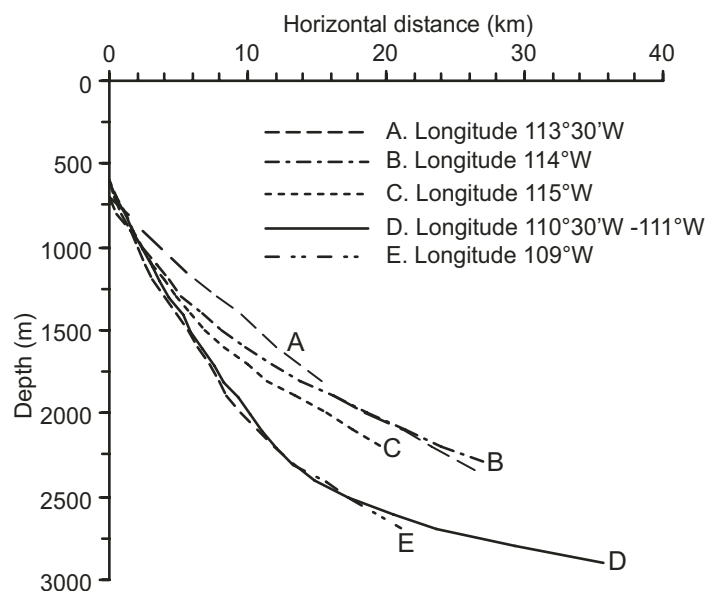


Figure 2. Bathymetric profiles from the shelf edge down the continental slope offshore of Pine Island Bay, including slope profiles: (A) in front of the eastern side of the cross-shelf trough; (B) in front of the western side of the cross-shelf trough; (C) the trough margin to the west of the cross-shelf trough; (D) between western and eastern gully-channel systems; and (E) eastern gully-channel system. The profiles are located in Figure 3.

slope (6° – 7°) extends from east of $\sim 113^\circ\text{W}$ to the area at the edge of our swath coverage corresponding to an eastern gully-channel system ($108^\circ 30'\text{W}$) (Fig. 3).

In addition, a bulge in the bathymetric contours of the Pine Island Bay continental slope is present in front and immediately east of the cross-shelf trough centered on $\sim 114^\circ\text{W}$ (Fig. 3A). Our swath bathymetric coverage of the upper slope is less complete between 109° and 113°W . However, there is some suggestion that a less clearly defined bulge may also be present at $\sim 110^\circ 30'\text{W}$ (Fig. 3A).

The continental slope in the eastern Amundsen Sea has two major morphological features (Fig. 3). First, there are a number of submarine channels that occur along the whole of our study area; they are present on the upper slope and continue onto the continental rise beyond our swath bathymetric coverage (Figs. 5–7). The channels are up to 40 m deep, <1 km wide, and are spaced at intervals of between <0.5 km and 5 km. They are moderately sinuous, but do not form clearly identifiable meanders. The channels are widely developed on the slope in front of the eastern side of the cross-shelf trough, but are more sparsely distributed and smaller in scale further to the west (Fig. 5). The channels in front of the cross-shelf trough differ from those further to the east between 108° and 111°W , where they are much wider, less sinuous, and have more prominent elevated banks (Figs. 5–7). Secondly,

there are several series of gullies on the uppermost slope, forming a number of branching systems that feed directly or indirectly into the larger channels further down the slope (Figs. 5–7). TOPAS subbottom profiler records from the gullied and channeled region of the continental slope reveal a prolonged or distinct seafloor reflector with little or no subseafloor acoustic structure (Fig. 8). This suggests that this region of the slope is characterized mainly by coarse-grained sediment transported through the gullies and channels.

Seaward of the areas of gullies and larger-scale channels, the remainder of the continental slope is relatively smooth and undifferentiated on swath bathymetric imagery with a horizontal resolution of 100 m. There is evidence on TOPAS subbottom profiler records from the slope below a water depth of 2500 m between 100° and 104°W (north to northwest of Thurston Island) of acoustically transparent sediments that form discrete lens-shaped bodies oriented in a downslope direction (Figs. 1 and 9). These features are interpreted as debris-flow deposits, but their extent and scale is difficult to ascertain with the few records available. Similar debris flows have been reported from the base of the continental slope further west at 105°W from both subbottom profiler and seismic-reflection records by Nitsche et al. (2000). It has been suggested that downslope sediment transfer of glacier-derived debris may be a result of

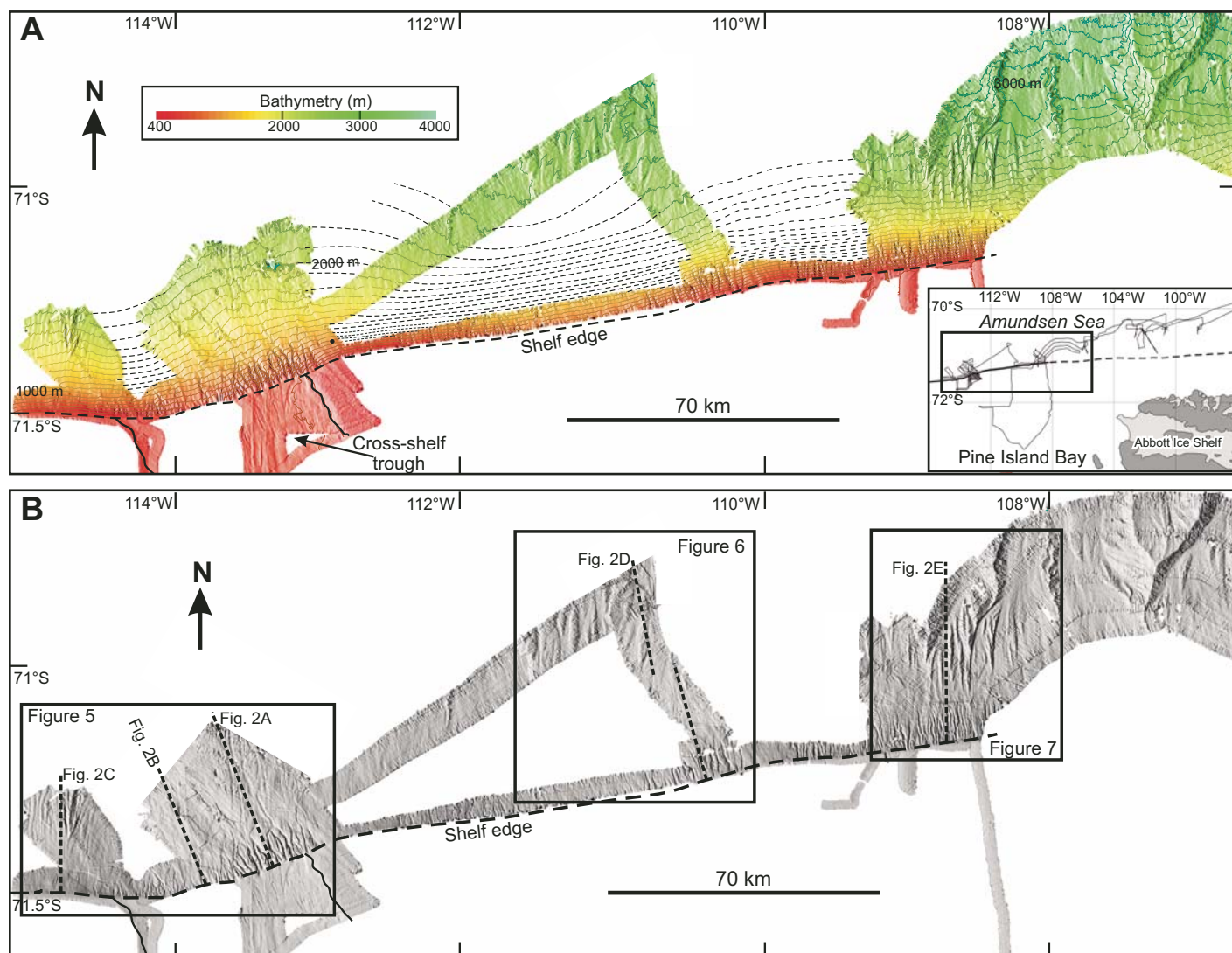


Figure 3. (A) EM120 color-contoured sun-illuminated swath bathymetry image of the outer shelf, shelf edge, and slope off Pine Island Bay (contoured at 100 m intervals), with its location in relation to West Antarctica shown in the inset map. (B) EM120 sun-illuminated swath bathymetry image of the same area showing the morphological features in the main continental margin study area. The locations of the five slope profiles shown in Figure 2A–E, together with Figures 5–7, are indicated.

large numbers of small-scale slides and slumps of ice-sheet-fed sediment on the upper slope, which were not resolved on our swath bathymetric records (Larter and Cunningham, 1993; Dowdeswell et al., 2004a).

Finally, there are no major canyons cut into the upper slope or outermost continental shelf of the eastern Amundsen Sea. Neither does there appear to be any evidence of widespread large-scale slope failure. This is similar to the Pacific margin of the Antarctic Peninsula, where canyons and major mass-failure scars and deposits are also uncommon (e.g., Tomlinson et al., 1992; Larter and Cunningham, 1993; Rebesco et al., 1998; Nitsche et al., 2000; Dowdeswell et al., 2004a).

Shelf-Edge Morphology

The detailed morphology of the shelf edge in the eastern Amundsen Sea shows the presence of several well-developed sets of gullies, some of which cut back into the outermost shelf (Fig. 5). The two main areas of gullies are present between 108°–110°W and 113°–114°30'W (Figs. 5–7), and we refer to them as the eastern and western gully systems, respectively. Gullies are present outside these areas, where they are much less well developed and sparsely distributed.

Swath imagery from along the shelf edge between 107° and 115°W shows the locations of all the gullies identified on swath bathymetric imagery, and also maps the seafloor char-

acter of the outermost part of the continental shelf; in particular, it shows whether megascale glacial lineations are present (Figs. 3 and 5). The swath data also show the variable depth of the shelf edge, and indicate that a clearly defined cross-shelf trough reaching ~680 m in depth and a width of ~50 km is present between ~113° and 114°W (J. Evans, 2005, personal commun.). J. Evans (2005, personal commun.) has mapped the extent of this trough, which contains megascale glacial lineations, indicating the former presence of fast-flowing ice over the outer shelf and reaching the shelf edge. The trough may merge with a large trough that was mapped on the inner shelf by Lowe and Anderson (2002). This

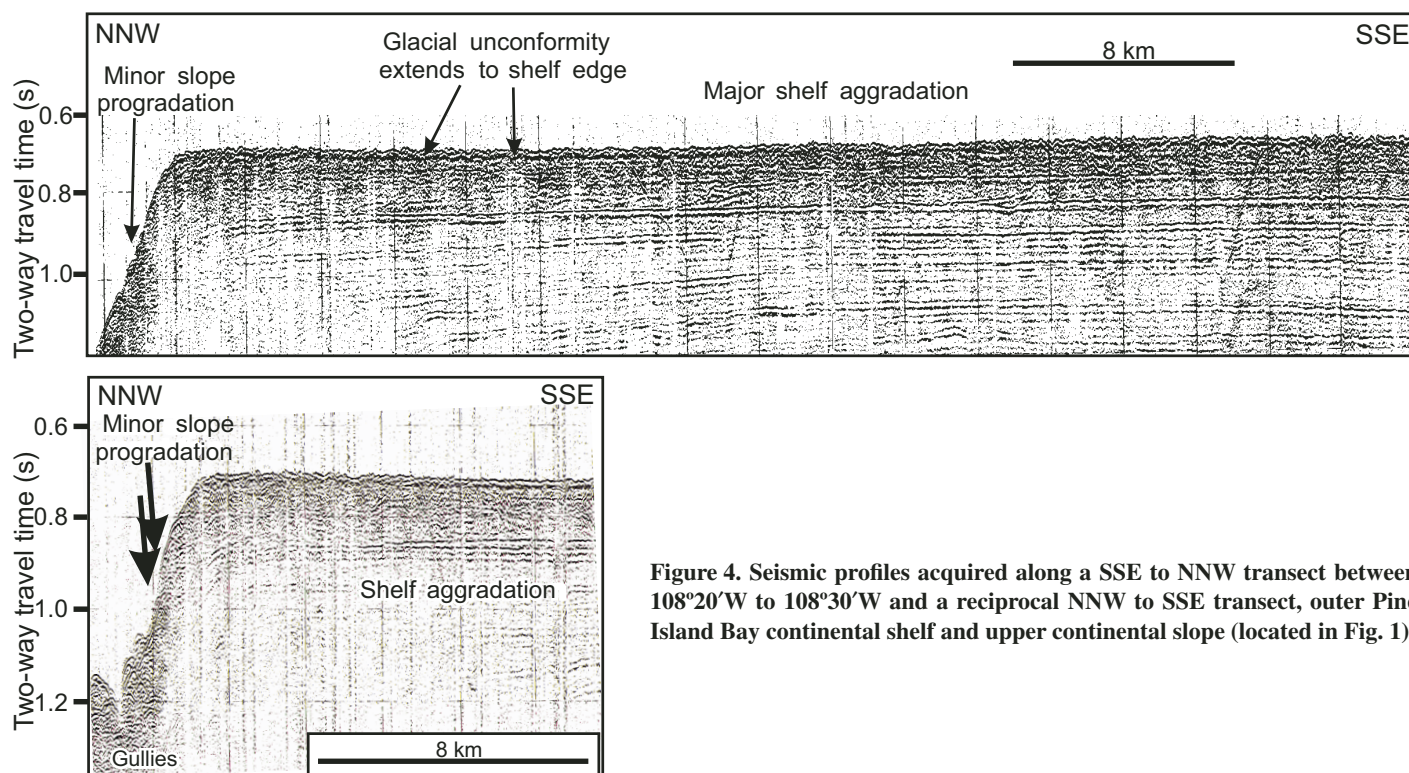


Figure 4. Seismic profiles acquired along a SSE to NNW transect between 108°20'W to 108°30'W and a reciprocal NNW to SSE transect, outer Pine Island Bay continental shelf and upper continental slope (located in Fig. 1).

inner-shelf trough contains a variety of subglacial features that range from subglacial meltwater features in the most landward portion of the trough to drumlins and megascale glacial lineations in the seaward portion (Lowe and Anderson, 2002, 2003).

The gullies are up to 120 m deep, although averaging ~60 m, and are up to 20 km in length (Figs. 5–7). However, the two systems of gullies take slightly different forms. The western system is the more complex, exhibiting a branching pattern, with a series of confluences downslope that produce a fourth-order network (Shreve, 1966) connecting directly with the channel system in this area of the slope (Fig. 5). The eastern system, by comparison, has gullies that are generally straighter and has a network order of only two. These gullies do not appear to connect directly with the larger-scale channels further down the slope (Figs. 6 and 7).

The western gully network is developed in front of and up to a short distance beyond the margins of the well-defined cross-shelf trough, through which a fast-flowing paleo-ice stream drained during the last glaciation. The gullies originate on the outer shelf rather than at or below the shelf edge (Fig. 5). Our swath bathymetric coverage of the outer shelf between 110° and 114°W (Fig. 1) allows this trough, and the megascale glacial lineations within it, to be defined clearly (J. Evans, 2005, personal commun.).

Inshore of the eastern network of gullies, there is no clear-cut evidence for a trough, although its presence cannot be positively ruled out given that our swath bathymetric and seismic data coverage is limited in this area (J. Evans, 2005, personal commun.) (Fig. 1). The outer shelf here is also heavily dissected by iceberg furrows (Lowe and Anderson, 2002; J. Evans, 2005, personal commun.). Thus, in the eastern area, reworking of the seafloor since ice retreated from the shelf edge means that even if megascale lineations produced by fast-flowing ice were once present, they would have been removed by the subsequent action of deep-keeled icebergs derived from the interglacial, fast-flowing Pine Island and Thwaites Glaciers (e.g., Lucchitta et al., 1995; Rignot, 2001). However, the presence of only minor slope progradation on seismic records, together with the probable lack of a clearly defined trough, implies that a fast-flowing ice-sheet outlet may not have been present in this region of the Pine Island Bay continental margin during at least the last glaciation (Figs. 2 and 3).

Gullies of similar morphology to those in the eastern Amundsen Sea have been reported from immediately below the shelf break in the central and eastern Ross Sea (Anderson et al., 2002). The Ross Sea gullies begin abruptly at the shelf break, where they connect to megascale glacial lineations inshore. The gullies converge downslope and then appear to bifurcate once

more into small channels, beyond which minor upper-slope sediment fans are present. Seafloor imagery in Anderson (1999) and Anderson et al. (2002) shows that these gully systems are ~5 km long. The similarity of the Ross Sea gullies to those observed on the upper slope of parts of the Weddell Sea and offshore of Wilkes Land in East Antarctica was also noted. In the Marguerite Bay area of the Antarctic Peninsula, gullies are also present along the uppermost continental slope, but occur more frequently and are deeper beyond the banks defining the edges of the Marguerite Trough than in the trough itself (Dowdeswell et al., 2004a). This is the opposite of the situation in the eastern Amundsen Sea and further north along the Antarctic Peninsula, where gullies occur seaward of all major troughs (Heroy and Anderson, 2005).

Sediments on the Amundsen Sea Margin

Piston cores were recovered along a transect parallel to 110°W from the shelf break to the continental rise (PC81-1 to PC81-3) within the region of the gully-channel system imaged in this study (Figs. 1 and 10). Cores (e.g., PC81-3) collected at water depths of less than ~1000 m were made up mainly of massive matrix-supported pebbly mud to muddy diamicton, and are interpreted to have been deposited by debris flows (Fig. 10). Cores collected between 1600 and 2498 m depths

sampled pebbly sand and ungraded sandy gravel, respectively (Fig. 10). These facies are interpreted to have been deposited by high-concentration turbidity current activity, and represent submarine channel deposits. Similar sediment-distribution patterns with depth occur on the Ross Sea and the Antarctic Peninsula continental margins (Anderson, 1999).

Cores recovered from the base of the continental slope and rise and across the abyssal plain of the Amundsen Sea adjacent to the study area indicate

that there are two zones of turbidity current deposition in this region. Cores collected at the base of the slope and on the continental rise (Fig. 1) sampled thin turbiditic sand layers (mostly 1–2 cm thick) within otherwise hemipelagic muds. These sediments are associated with sediment mounds and sediment waves on the rise (e.g., Lucchi et al., 2002). Seaward of these mounds and sediment waves, on the abyssal plain, several cores sampled turbiditic sand beds that are tens of centimeters thick within hemipelagic mud and

pelagic (diatomaceous) sediments. These sand beds display size grading and have mineralogical and clast compositions that indicate a source area from land on Thurston Island and around Pine Island Bay (Fig. 1) (Wright et al., 1983). Their mineralogy includes abundant K-feldspar and pink granite similar to rocks collected in grab samples from Pine Island Bay.

The presence of coarse-grained turbidites on the continental slope and continental rise, and on the abyssal plain of the eastern Amundsen

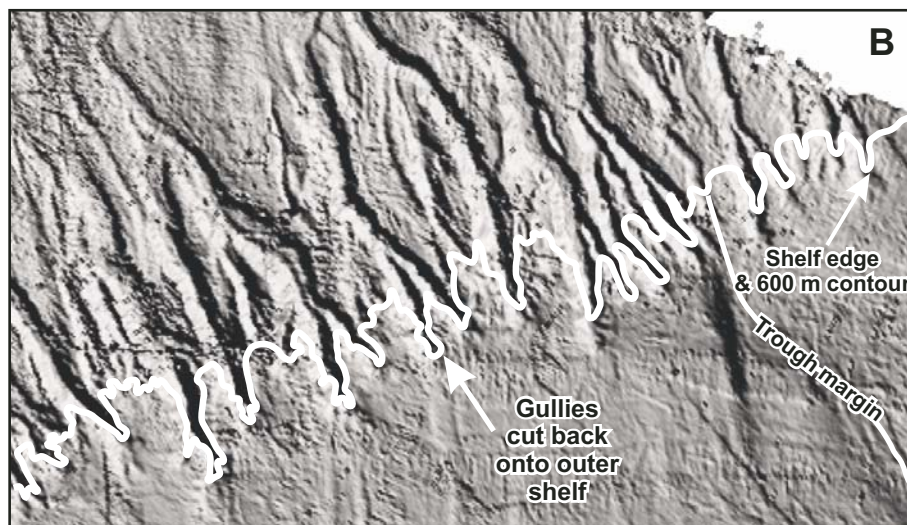
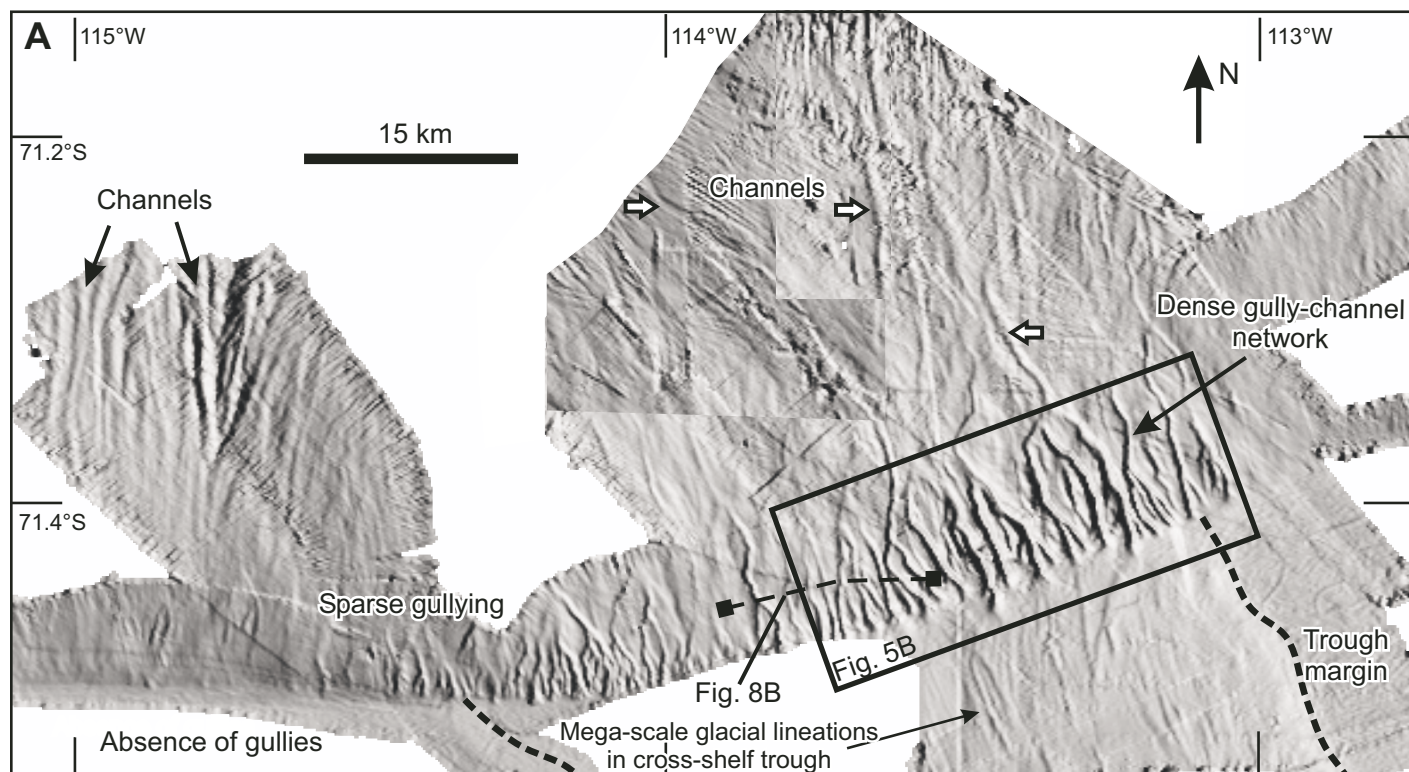


Figure 5. (A) EM120 swath bathymetric images of the outer shelf, shelf edge, and slope in front of and beyond the margins of the major cross-shelf trough ($\sim 113^{\circ}$ – 114° W), illustrating the gully-channel system on the slope and megascale glacial lineations within the trough. The location of the topographic parametric sonar (TOPAS) subbottom profile in Figure 8A is illustrated. The location of this Figure is shown in Figures 1 and 3. (B) Enlarged image of the shelf edge, showing gullies cut back into the continental shelf of Pine Island Bay. The 600 m contour is located.

Sea, indicates that sediment gravity flows (in particular turbidity currents) are a major sedimentary process in this region. The distribution and mineralogical and clast composition of these turbidite deposits indicate that sediment gravity flow processes transport sediment, brought to the shelf edge by the West Antarctic Ice Sheet during past glacial periods, downslope from the shelf edge to the abyssal plain via the gully-channel systems, resulting in sediment bypass of the upper continental slope.

DISCUSSION

Patterns and Processes of Sedimentation on the Continental Slope

The form of the upper continental slope in the eastern Amundsen Sea has been little investigated up until now. A diagram published by Nitsche et al. (2000) showed this area as largely void of data. We summarize the major morphological features observed in our swath bathymetric and subbottom profiler data sets for this region in Figure 11, and also include earlier observations from the adjacent deep-sea basin collated by Nitsche et al. (2000) (Fig. 11). It can be seen that the submarine channels we image from the upper slope continue into abyssal depths as far north as ~67°S (Fig. 11).

In both the Bellingshausen Sea and on the western margin of the Antarctic Peninsula, a combination of channels, intervening sediment drifts, and sediment waves has also been observed (Tucholke and Houtz, 1976; Nitsche et al., 2000). This has been interpreted to suggest that downslope turbidity current processes, as well as westward- to southwestward-flowing along-slope currents, are acting to produce the suite of observed morphological and sedimentary seafloor features (e.g., Rebesco et al., 1996; Nitsche et al., 2000; Pudsey, 2000; Lucchi et al., 2002; Rebesco et al., 2002; Dowdeswell et al., 2004a). Similar deep-sea sedimentary processes, therefore, appear to be operating along the whole of this margin of West Antarctica and the western side of the Antarctic Peninsula. The turbidity current mechanism of downslope sediment transport via gullies and channels that delivered sands far out on the abyssal floor of the Amundsen Sea is also believed to be similar to that which has been described in the Weddell Sea, where graded sands of more than a meter in thickness occur up to 800 km from the shelf break (Wright and Anderson, 1983; Anderson et al., 1986).

At depths of over 4000 m, beyond the Amundsen Sea continental slope between 66° and 69°S, Japanese multichannel seismic data show channels and sediment mounds (Yamaguchi et al., 1988; Nitsche et al., 2000). Typical mounds

have widths of ~60 km and rise ~300–400 m above the surrounding seafloor. The mounds have been interpreted as sediment drifts. In some areas, sediment waves are also present, similar to those we have imaged on the lower slope of the eastern Amundsen Sea between 107° and 108°W and in the western Bellingshausen Sea (Fig. 12).

The apparent lack of major slope failures on the glacier-influenced margin of the eastern Amundsen Sea is similar to the Pacific margin of Antarctica in general (e.g., Tomlinson et al., 1992; Bart and Anderson, 1995; Nitsche et al., 2000) and the eastern Ross Sea (Anderson and Bartek, 1992). In the Northern Hemisphere, the Northeast Greenland margin also shows little evidence of large-scale mass failure (Mienert et al., 1993; Dowdeswell et al., 2002; Evans et al., 2002; Ó Cofaigh et al., 2004). However, these areas contrast with the 2500-km-long Norwegian margin, which has been influenced strongly by sediment delivery from the Eurasian Ice Sheet at intervals over the past 2 m.y. or so. In this part of the Polar North Atlantic, a number of very large-scale slope failures, from 10³ to 10⁵ km², have taken place (e.g., Kenyon, 1987; Vorren et al., 1998; Dowdeswell et al., 2002).

Interestingly, the Norwegian continental slope has few prominent submarine channels, whereas off the Pacific margin of Antarctica and Northeast Greenland, a number of major channel systems are present (e.g., Mienert, 1993; Rebesco et al., 1998; Nitsche et al., 2000; Dowdeswell et al., 2002; Ó Cofaigh et al., 2004). It may be that sediment largely bypasses the continental slope where channels are present, but is more likely to build up and fail intermittently where channels and associated turbidity currents are a less significant conduit for the relatively rapid downslope transfer of sediment.

Origin of the Continental Slope Gully-Channel System

The gullies at the head of the gully-channel system that we observed along the Pine Island Bay continental margin are cut back into the continental shelf edge and were probably produced during periods when the ice sheet was situated at the shelf break, providing a higher-energy environment than today's interglacial setting. We know that active glacier ice was present close to the shelf break, probably at the last full glacial, because J. Evans (2005, personal commun.)

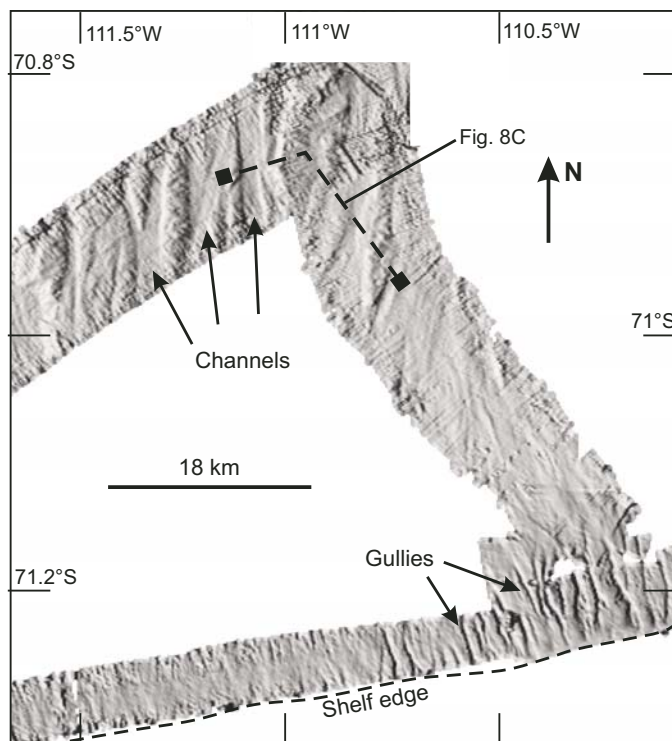


Figure 6. Enlarged EM120 swath bathymetry images of the shelf edge and slope between 110° and 111°W, illustrating the main gully and channel features on the slope. The location of the topographic parametric sonar (TOPAS) subbottom profile in Figure 8C is illustrated. The location of this Figure is shown in Figures 1 and 3.

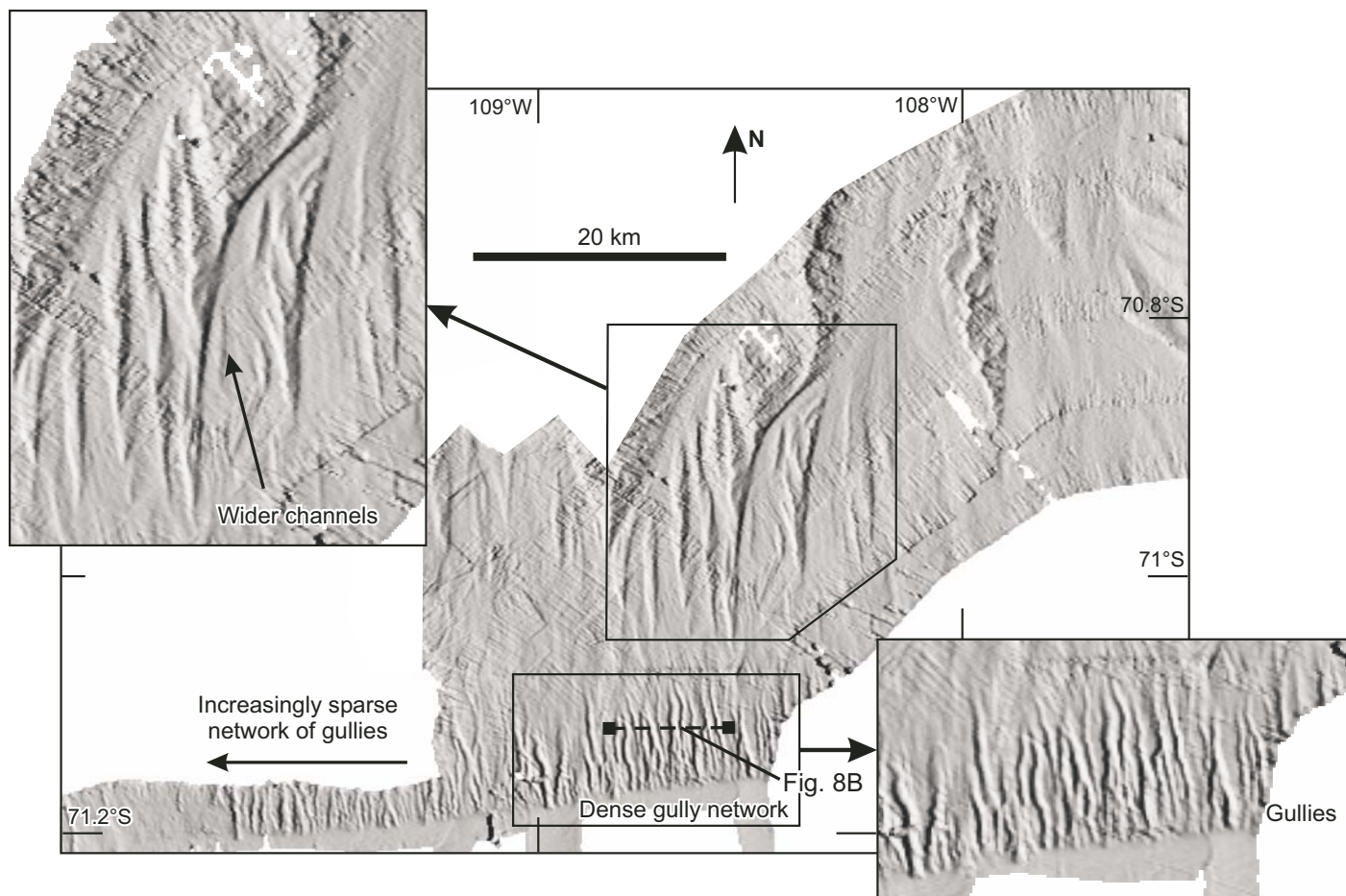


Figure 7. Enlarged EM120 swath bathymetry images of the shelf edge and slope between 108° and 110°W, illustrating the eastern gully-channel system. The location of the topographic parametric sonar (TOPAS) subbottom profile in Figure 8B is illustrated. The location of this Figure is shown in Figures 1 and 3.

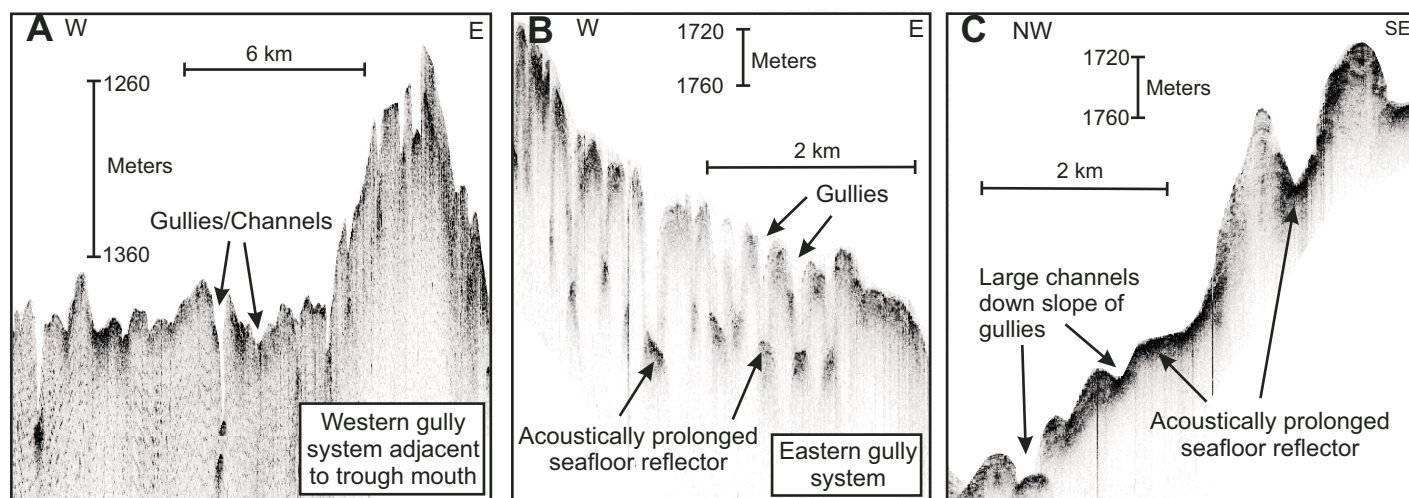


Figure 8. Topographic parametric sonar (TOPAS) profiles from the upper-middle slope showing subbottom record of: (A) the western gully-channel system adjacent to the cross-shelf trough (Fig. 5); (B) the eastern gully-channel system (Fig. 7); and (C) the large-scale channels downslope of the upper slope gullies at 111°W (Fig. 6).

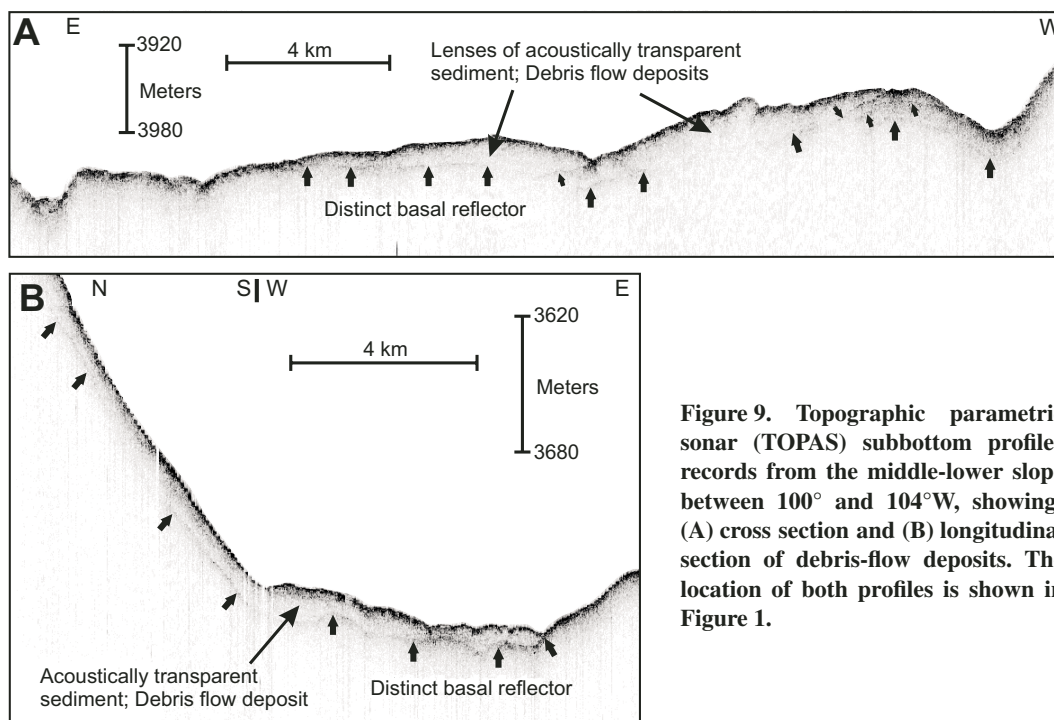


Figure 9. Topographic parametric sonar (TOPAS) subbottom profiler records from the middle-lower slope between 100° and 104°W, showing: (A) cross section and (B) longitudinal section of debris-flow deposits. The location of both profiles is shown in Figure 1.

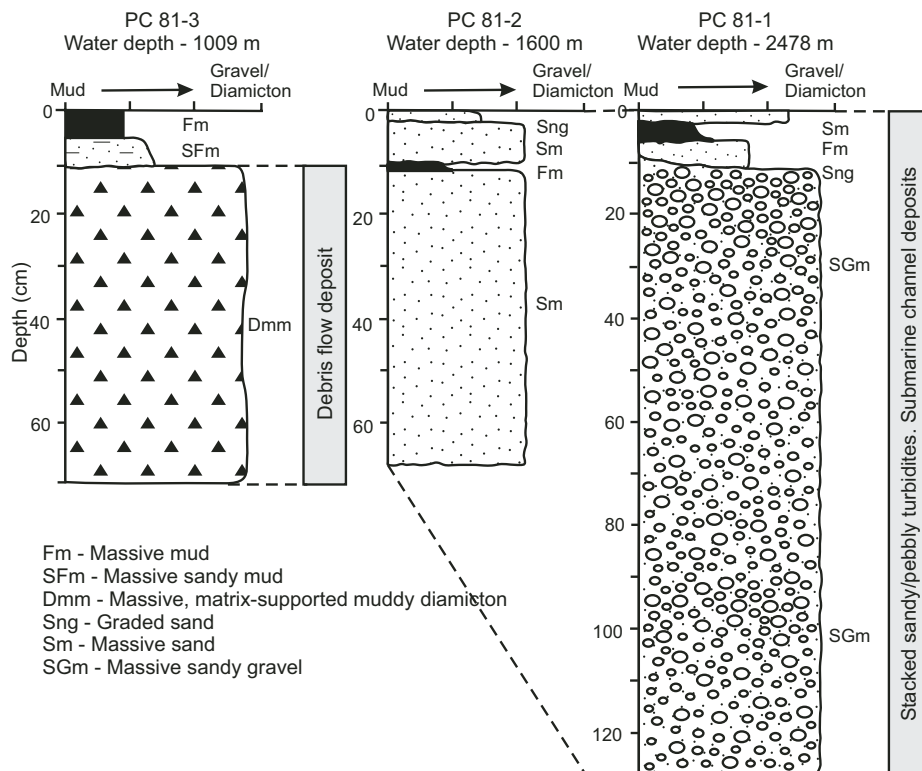


Figure 10. Sedimentological logs of cores recovered from a transect parallel to ~110°W from the uppermost slope to the base of the continental slope (PC81-3 to PC81-1) of the eastern Amundsen Sea continental margin. Cores are located in Figure 1.

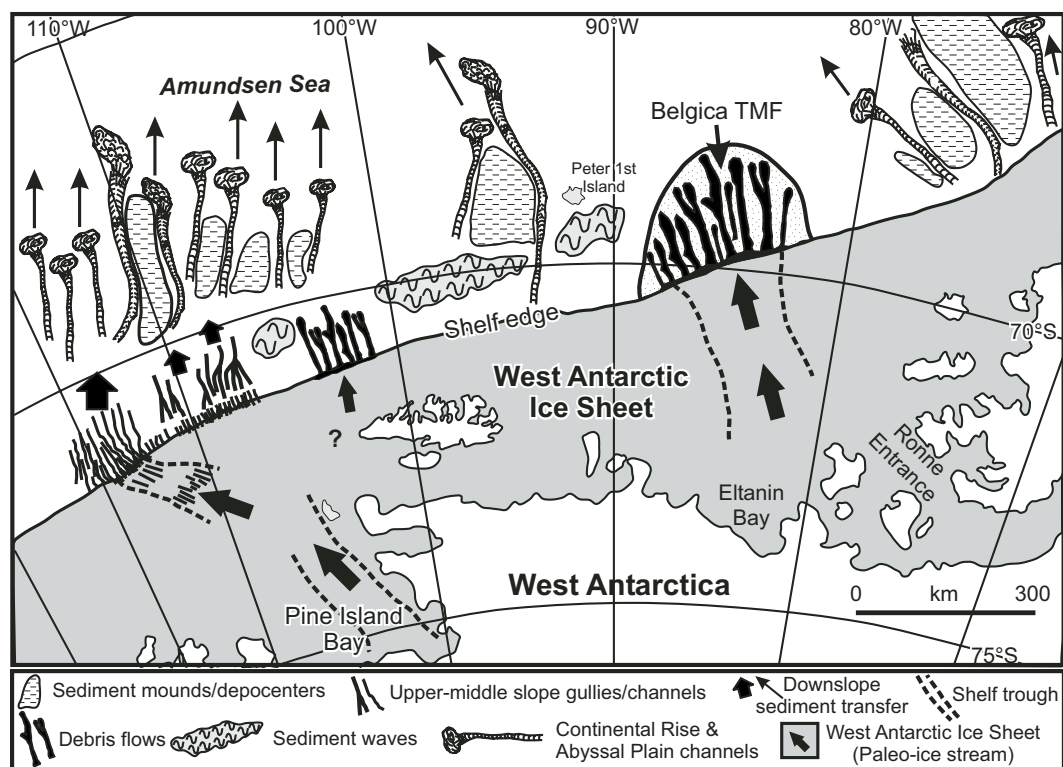


Figure 11. Summary line diagram of the main morphological features on the margins of the Amundsen and Bellingshausen Seas based on the data set outlined in this paper and those of Rebesco et al. (1996) and Nitsche et al. (2000). TMF—trough-mouth fan.

has observed megascale glacial lineations on the outermost shelf between 113° and 114°W. These streamlined glacial bedforms indicate the presence of fast-flowing, grounded ice (Clark, 1993), and have been observed in a number of cross-shelf troughs around Antarctica (e.g., Shipp et al., 1999; Canals et al., 2000, 2003; Wellner et al., 2001; Ó Cofaigh et al., 2002, 2003; Dowdeswell et al., 2004b). Earlier work by Lowe and Anderson (2002) had inferred the presence of grounded ice at the shelf break at the Last Glacial Maximum, based on the presence of a prominent glacial unconformity that extended to the shelf edge on seismic-reflection records (Fig. 4).

There are at least two possible explanations for the deep gully-channel systems on the shelf edge and across the upper slope. First, Lowe and Anderson (2003) suggested that similar gullies were formed through incision by sediment-laden meltwater and associated sediment gravity flows from the base of a full-glacial ice sheet grounded at the shelf edge. Requirements of this explanation are that significant quantities of water must flow from the base of the ice sheet at its margin, and that this water must be dense enough to overcome the buoyant effect of meltwater, which would normally rise to the surface (e.g., Powell, 1990). A suspended sediment content of 33 g l⁻¹ is needed to produce an underflow from glacial meltwater flowing into ocean water

of normal salinity (Syvitski, 1989). This form of turbidity current could be generated by the delivery of water-saturated till to the shelf break, linked to the process of fast glacier flow over a deforming sedimentary bed (e.g., Alley et al., 1986; Kamb, 2001; Dowdeswell et al., 2004b). However, the mechanism by which water-saturated sediment is released at the ice margin remains unobserved. The fact that distinct channels are not reported from swath bathymetric investigations of the outermost shelf where megascale lineations are present suggests that saturated-sediment delivery along a line source may be more likely than the channelized drainage of such sediment at the ice-sheet edge.

A second possibility is that the gully-channel systems are formed by downslope flow of dense water associated with sea-ice production on the shelf and upper slope. Coastal areas of open water, or polynyas, are common around the Antarctic today. They are generated by katabatic winds produced by descending air from the ice-sheet interior (e.g., Bromwich and Kurtz, 1984). In winter in particular, sea ice is constantly produced in these polynyas and evacuated by the offshore-flowing winds. The repetitive formation of sea ice results in the production of cold and saline water due to the rejection of brine associated with sea-ice freezing. When the full-glacial ice sheet expanded to fill the Pine Island shelf, polynyas

probably developed and sea-ice formation became focused at the shelf break. This particularly dense water would sink and flow down the continental slope, producing gullies as it did so. This scenario clearly assumes that there was no floating ice shelf extending beyond the shelf break into the Amundsen Sea.

Several observations suggest that incision by sediment-laden meltwater rather than that associated with sea-ice formation and brine rejection may be the more important process in gully formation. First, the gullies cut back into the shelf edge, thereby suggesting a source on the outermost shelf (Figs. 5–7). Secondly, the widespread presence of turbidite facies across the continental slope, rise, and abyssal plain (Fig. 10) also suggests that turbid-water production and associated downslope sediment gravity flows at former ice-sheet and ice-stream margins were probably the more significant processes in the formation and development of the gully-channel systems. In addition, the coarse sand grains and larger clasts associated with the turbidite facies cored on the continental slope are unlikely to have been derived and transported by dense water associated with sea-ice formation due to the predominantly fine-grained nature of sea-ice rafted sediments (e.g., Nürnberg et al., 1994).

Spatial variations in the form and morphology of the gully-channel systems exist between the

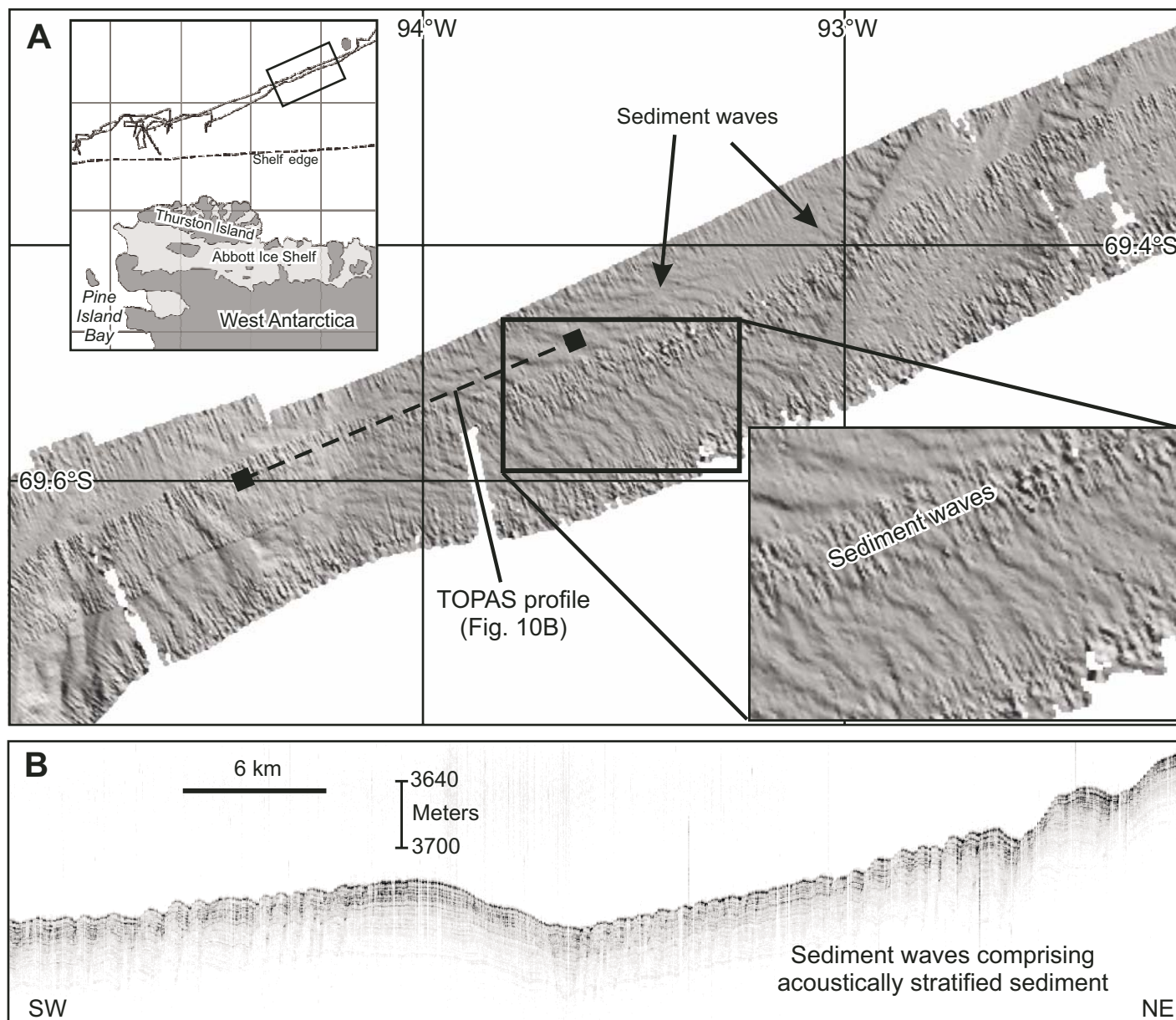


Figure 12. (A) Swath bathymetric and (B) topographic parametric sonar (TOPAS) records of sediment waves in the western Bellingshausen Sea, with acoustic lamination showing migration to the west and southwest. The location of the data is shown in the inset and in Figure 1.

slope in front of the paleo-ice stream draining through the Pine Island Bay cross-shelf trough, and the gully-channel systems away from the trough. Gullies connect directly with sinuous and continuous channels in front of the paleo-ice stream trough, whereas gullies only connect indirectly with relatively wider, less-continuous, and more prominent channels elsewhere on the slope (Figs. 5–7). The spatial variations in the form of the gully-channel systems may be explained by a combination of: (1) contrasts in downslope sediment gravity flow processes; (2) the nature and composition of sediments delivered to the

shelf edge from the ice margin and then transferred downslope, and (3) variations in the volume and rate of sediment delivered to the ice-sheet margin, where sediment delivery to the slope would be most significant in front of the paleo-ice stream at the trough mouth at 114°W compared to elsewhere along the margin. Lowe and Anderson (2003) have observed bedforms in Pine Island Bay, indicating the presence of abundant meltwater at the ice-sheet base. The source for large quantities of subglacial water remains unclear, however. Basal melting alone would produce little meltwater, and there is unlikely to

be major production of surface meltwater under full-glacial conditions, given that there is no surface melting in today's interglacial climate. However, meltwater production may have been enhanced at times of rapid ice-sheet retreat during deglaciation of the Pine Island Bay shelf. Sea-ice formation on the Amundsen Sea outer shelf during interglacials may also provide some downslope flow into the gullies, augmenting development of the gully-channel system, especially from the relatively deep cross-shelf trough observed between 113° and 114°W by J. Evans (2005, personal commun.).

Large-Scale Slope Morphology

The angle of the eastern Amundsen Sea continental slope, between $\sim 4^\circ$ and 7° (Figs. 2 and 3A), is lower than slopes over the vast bulk of the more easterly Bellingshausen Sea and Antarctic Peninsula margins. The continental slope varies from $\sim 6^\circ$ – 13° in the Bellingshausen Sea, and the angle of the Peninsula margin often exceeds 10° (e.g., Larter and Barker, 1991; Ó Cofaigh et al., 2003; Dowdeswell et al., 2004a). An exception to this is the area around $\sim 83^\circ\text{W}$, offshore of Eltanin Bay, where the slope is only 1° to 3° (Nitsche et al., 2000). A fan-shaped, low-gradient slope is also inferred from the free-air gravity anomaly map of the margin in the latter region (McAdoo and Laxon, 1997), and the presence of a submarine fan is confirmed for this area by core and acoustic data (Ó Cofaigh et al., 2005).

Swath bathymetric records show that the Amundsen Sea slope in front of the cross-shelf trough between 113° and $114^\circ 30'\text{W}$ is marked by a bulge in the bathymetric contours (Fig. 3). The longitudinal profiles in Figure 2 show that the gradient of the continental slope off Pine Island Bay is least steep offshore of the marked cross-shelf trough at $\sim 114^\circ\text{W}$, and that the bathymetric contours are convex downslope in this region (Fig. 3A). This suggests that a sedimentary depocenter could be present at this location. However, this interpretation is based on gross morphology alone. We do not see evidence of the debris flows that are often found in association with the buildup of glacier-influenced submarine fans (e.g., Anderson et al., 1986; Dowdeswell et al., 1996, 2002; Ó Cofaigh et al., 2003). Rather, limited seismic-reflection data show that the continental shelf has aggraded during its more recent history, with relatively minor slope progradation (Fig. 4). This is despite the evidence, in the form of megascala glacial lineations, that fast-flowing ice streams reached, or extended close to, the shelf edge, fed from the huge full-glacial Pine Island and Thwaites Glacier drainage basins (J. Evans, 2005, personal commun.). Progradation is certainly not on the scale commonly associated with the major fan-shaped depocenters, referred to as “trough-mouth fans,” that extend outward from the shelf edge on a number of other high-latitude margins (cf. Vorren et al., 1998; Dowdeswell et al., 2002; Ó Cofaigh et al., 2003).

A similar situation exists in the eastern Ross Sea (Anderson and Bartek, 1992) and on the Antarctic Peninsula continental margin (Bart and Anderson, 1995). Indeed, linked trough and trough-mouth fan complexes in West Antarctica appear to be the exception rather than the rule. This is also the case for some Northern Hemisphere high-latitude margins. For example, no

associated and clearly identified fans occur downslope of the Hudson Strait ice stream, which drained the vast Hudson Bay drainage basin of the Laurentide Ice Sheet (e.g., Hesse et al., 1997; Ó Cofaigh et al., 2003; Dowdeswell et al., 2004a). Here too, channel systems are prominent features of the continental slope.

Anderson (1999) pointed out that the major trough-mouth fans of Antarctica, including the Cray Fan in the Weddell Sea (Kuvaas and Kristoffersen, 1991; Moons et al., 1992; Bart et al., 1999), the North Victoria Fan in the Ross Sea (Bart et al., 2000), and the Amery Fan (Kuvaas and Leitchenkov, 1992; O'Brien, 1994) are long-lived features. This implies that, in these areas, ice streams have remained largely fixed in their locations since the continental shelves were first eroded by ice sheets. However, seismic data from the Antarctic Peninsula shelf show clearly that troughs, and therefore ice streams, have shifted in location from one glacial cycle to the next (Bart and Anderson, 1995). This is an important reason why the troughs of the Peninsula region are not linked to trough-mouth fans. The absence of a linked trough and trough-mouth fan in the Amundsen Sea area may also indicate, therefore, that the Pine Island Bay ice streams have shifted their locations on the shelf. Unfortunately, no strike-orientated seismic profiles exist for the area, so it is not possible to demonstrate that this is the case.

In addition, and by analogy with other ice-stream-influenced margins, the inference is that the rate of full-glacial sediment delivery to the shelf break in the eastern Amundsen Sea was probably very high (e.g., Dowdeswell and Siegert, 1999; Pollard and DeConto, 2003). More reasons for the lack of a trough-mouth fan are that channel systems and the turbidity currents associated with them act to transfer much of the ice-stream-derived sediment down the relatively steep upper slope, to be deposited, and in many cases reworked by along-slope currents, in deeper water.

CONCLUSIONS

The morphology and sedimentation of the eastern Amundsen Sea continental margin adjacent to Pine Island Bay was investigated using shipborne geophysical equipment and sediment cores (Fig. 1). Continental slope angles adjacent to a prominent bathymetric trough dissecting outer Pine Island Bay that opens at the shelf edge are typically 4° , and correspond with a bulge in bathymetric contours indicative of slope progradation (Fig. 3). The remaining continental slope away from the trough mouth is steeper, with slope angles of between 5° and 7° (Fig. 2). Seismic-reflection profiles in this

region show relatively minor slope progradation and mostly shelf aggradation.

The continental slope is dominated by gully-channel networks (Figs. 5–8). Channels occur along the entire continental slope (Figs. 2 and 11). They are most clearly developed and continuous in front of the cross-shelf bathymetric trough but are much wider, less sinuous, and have prominent elevated banks elsewhere. Gullies up to 120 m deep and 20 km in length are present on the uppermost slope that feed directly or indirectly into the larger channels further down the slope.

Sediments cored in the region of the gully-channel network on the continental slope comprise pebbly sand and ungraded gravel turbidites (Fig. 10). They represent channel-related deposits and diamicton facies deposited by debris flows, with sandy turbidites interbedded with hemipelagic and diatomaceous muds at the base of the continental slope, continental rise, and abyssal plain.

Elongate sedimentary bedforms in the outer shelf bathymetric trough indicate that the West Antarctic Ice Sheet extended to the shelf edge of Pine Island Bay under full-glacial conditions and was drained by an ice stream through this trough (Figs. 5 and 11). The gully-channel network is interpreted to have been produced in front of this extended ice sheet during the last glaciation, and possibly earlier full-glacial times.

The presence of turbidites on the slope and rise, and the fact that gullies cut back into the shelf, indicate that the formation and development of the gullies and channels are likely to have resulted from sediment gravity flows derived from the release of water-saturated till and turbid water directly to the continental slope along a line source corresponding to the ice-sheet margin. Downslope flow of dense cold and saline water due to rejection of brine associated with sea-ice freezing may also have augmented gully-channel formation.

The limited scale of progradation coupled with the absence of debris-flow deposits extending outward from the cross-shelf trough indicate an apparent absence of a paleo-ice stream-fed trough-mouth fan in the eastern Amundsen Sea (Fig. 11). Instead, the glacially influenced gully-channel sedimentary system and associated sediment gravity flows acted to transfer sediment through the upper continental slope to be deposited in the abyssal plain of the Amundsen Sea.

Regionally, the submarine channels imaged on the continental slope continue down to the abyssal depths of the Amundsen Sea as far north as 67°S , separated by sediment drifts and sediment waves (Fig. 11). This suite of sedimentary seafloor features is a result of the interaction between downslope turbidity current processes

and along-slope bottom currents. Similar deep-sea sedimentary processes operate along West Antarctica and the western side of the Antarctic Peninsula.

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REFERENCES CITED

- Alley, R.B., Blankenship, D.D., Bentley, C.R., and Rooney, S.T., 1986, Deformation of till beneath Ice Stream B: West Antarctica: *Nature*, v. 322, p. 57–59.
- Anderson, J.B., 1999, Antarctic marine geology: Cambridge, UK, Cambridge University Press, 289 p.
- Anderson, J.B., and Bartek, L.R., 1992, Cenozoic glacial history of the Ross Sea revealed by intermediate resolution seismic reflection data combined with drill site information, in Kennett, J.P., and Warnke, D.A., eds., *The Antarctic Paleoenvironment: A Perspective on Global Change I*: American Geophysical Union, Antarctic Research Series, v. 56, p. 231–263.
- Anderson, J.B., Wright, R., and Andrews, B., 1986, The Weddell fan and associated abyssal plain, Antarctica: Morphology, sediment processes, and factors influencing sediment supply: *Geo-Marine Letters*, v. 6, p. 121–129.
- Anderson, J.B., Shipp, S.S., Lowe, A.L., Wellner, J.S., and Mosola, A.B., 2002, The Antarctic Ice Sheet during the Last Glacial Maximum and its subsequent retreat history: A review: *Quaternary Science Reviews*, v. 21, p. 49–70, doi: 10.1016/S0277-3791(01)00083-X.
- Baegi, M., 1985, Turbidite deposition on the Bellingshausen Abyssal Plain: Sedimentologic implications [Ph.D. thesis]: Houston, Texas, Rice University, 109 p.
- Bamber, J.L., and Bindschadler, R.A., 1997, An improved elevation dataset for climate and ice-sheet modelling: Validation with satellite imagery: *Annals of Glaciology*, v. 25, p. 439–444.
- Bart, P.J., and Anderson, J.B., 1995, Sequence record of glacial events affecting the Pacific margin of the northwestern Antarctic Peninsula: *American Geophysical Union, Antarctic Research Series*, v. 68, p. 75–96.
- Bart, P.J., De Batist, M., and Jokat, W., 1999, Interglacial collapse of Cray trough-mouth fan, Weddell Sea, Antarctica: Implications for Antarctic glacial history: *Journal of Sedimentary Research*, v. 69, p. 1276–1289.
- Bart, P.J., Anderson, J.B., Trincardi, F., and Shipp, S.S., 2000, Seismic data from the Northern Basin, Ross Sea, record multiple expansions of the East Antarctic Ice Sheet during the late Neogene: *Marine Geology*, v. 166, p. 31–50, doi: 10.1016/S0025-3227(00)00066-2.
- Bromwich, D.H., and Kurtz, D.D., 1984, Katabatic wind forcing of the Terra Nova Bay polynya: *Journal of Geophysical Research*, v. 89, p. 3561–3572.
- Canals, M., Urgeles, R., and Calafat, A.M., 2000, Deep seafloor evidence of past ice streams off the Antarctic Peninsula: *Geology*, v. 28, p. 31–34, doi: 10.1130/0091-7613(2000)028<0031:DSFEOP>2.3.CO;2.
- Canals, M., Calafat, A., Camerlenghi, A., De Batist, M., Urgeles, R., Farran, M., Geletti, R., Versteeg, W., Ambias, D., Rebesco, M., Casamor, J.L., Sanchez, A., Willmott, V., Lastras, G., and Imbo, Y., 2003, Uncovering the footprint of former ice streams off Antarctica: *Eos (Transactions, American Geophysical Union)*, v. 84, p. 97–108.
- Clark, C.D., 1993, Mega-scale glacial lineations and cross-cutting ice-flow landforms: *Earth Surface Processes and Landforms*, v. 18, p. 1–29.
- Dowdeswell, J.A., and Elverhøi, A., 2002, The timing of initiation of fast-flowing ice streams during a glacial cycle inferred from glaciomarine sedimentation: *Marine Geology*, v. 188, p. 3–14, doi: 10.1016/S0025-3227(02)00272-4.
- Dowdeswell, J.A., and Siegert, M.J., 1999, Ice-sheet numerical modeling and marine geophysical measurements of glacier-derived sedimentation on the Eurasian Arctic continental margins: *Geological Society of America Bulletin*, v. 111, p. 1080–1097, doi: 10.1130/0016-7606(1999)111<1080:ISNMAM>2.3.CO;2.
- Dowdeswell, J.A., Kenyon, N.H., Elverhøi, A., Laberg, J.S., Hollender, F.-J., Mienert, J., and Siegert, M.J., 1996, Large-scale sedimentation on the glacier-influenced polar North Atlantic margins: Long-range side-scan sonar evidence: *Geophysical Research Letters*, v. 23, p. 3535–3538, doi: 10.1029/96GL03484.
- Dowdeswell, J.A., Ó Cofaigh, C., Taylor, J., Kenyon, N.H., Mienert, J., and 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., and Ó Cofaigh, C., eds., *Glacier-influenced sedimentation on high-latitude continental margins*: Geological Society [London] Special Publication 203, p. 33–54.
- Dowdeswell, J.A., Ó Cofaigh, C., and Pudsey, C.J., 2004a, Continental slope morphology and sedimentary processes at the mouth of an Antarctic palaeo-ice stream: *Marine Geology*, v. 204, p. 203–214.
- Dowdeswell, J.A., Ó Cofaigh, C., and Pudsey, C.J., 2004b, Thickness and extent of the subglacial till layer beneath an Antarctic palaeo-ice stream: *Geology*, v. 32, p. 13–16.
- Evans, J., Dowdeswell, J.A., Grobe, H., Niessen, F., Stein, R., Hubberten, H.W., and Whittington, R.J., 2002, Late Quaternary sedimentation in Keiser Franz Joseph Fjord and the continental margin of East Greenland, in Dowdeswell, J.A., and Ó Cofaigh, C., eds., *Glacier-influenced sedimentation on high-latitude continental margins*: Geological Society [London] Special Publication 203, p. 149–179.
- Gordon, A.L., 1971, Oceanography of Antarctic waters, in Reid, J.L., ed., *Antarctic oceanology I: Antarctic Research Series*, v. 15: New York, American Geophysical Union, p. 169–203.
- Heroy, D.C., and Anderson, J.B., 2005, Ice-sheet extent of the Antarctic Peninsula region during the Last Glacial Maximum (LGM)—Insights from glacial geomorphology: *Geological Society of America Bulletin*, v. 117, p. 1497–1512.
- Hesse, R., Klauke, I., Ryan, W.B.F., and Piper, D.J.W., 1997, Ice-sheet sourced juxtaposed turbidite systems in the Labrador Sea: *Geoscience Canada*, v. 24, p. 3–14.
- Hughes, T.J., 1981, The weak underbelly of the West Antarctic Ice Sheet: *Journal of Glaciology*, v. 27, p. 518–525.
- Kamb, B., 2001, Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion, in Alley, R.B., and Bindschadler, R.A., eds., *The West Antarctic Ice Sheet: Behavior and dynamics*: American Geophysical Union, Antarctic Research Series, v. 77, p. 157–199.
- Kellogg, T.B., and Kellogg, D.E., 1987, Recent glacial history and rapid ice stream retreat in the Amundsen Sea: *Journal of Geophysical Research*, v. 92, p. 8859–8864.
- Kenyon, N.H., 1987, Mass-wasting features on the continental slope of northwest Europe: *Marine Geology*, v. 74, p. 57–77, doi: 10.1016/0025-3227(87)90005-3.
- Kuvaas, B., and Kristoffersen, Y., 1991, The Cray Fan: A trough-mouth fan on the Weddell Sea continental margin, Antarctica: *Marine Geology*, v. 97, p. 345–362, doi: 10.1016/0025-3227(91)90125-N.
- Kuvaas, B., and Leitchenkov, G., 1992, Glaciomarine turbidite and current controlled deposits, Prydz Bay, Antarctica: *Marine Geology*, v. 108, p. 365–381, doi: 10.1016/0025-3227(92)90205-V.
- Larter, R.D., and Barker, P.F., 1991, Effects of ridge crest-trench interaction on Antarctic-Phoenix spreading: Forces on a young subducting plate: *Journal of Geophysical Research*, v. 96, p. 19,583–19,607.
- Larter, R.D., and Cunningham, A.P., 1993, The depositional pattern and distribution of glacial-interglacial sequences on the Antarctic Peninsula Pacific margin: *Marine Geology*, v. 109, p. 203–219, doi: 10.1016/0025-3227(93)90061-Y.
- Lawver, L.A., Gahagan, L.M., and Coffin, M.F., 1992, The development of paleoseaways around Antarctica: *American Geophysical Union, Antarctic Research Series*, v. 56, p. 7–30.
- Lowe, A.L., and 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: *Quaternary Science Reviews*, v. 21, p. 1879–1897, doi: 10.1016/S0277-3791(02)00006-9.
- Lowe, A.L., and Anderson, J.B., 2003, Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica: *Journal of Glaciology*, v. 49, p. 125–138.
- Lucchi, R., Rebesco, M., Camerlenghi, A., Busetti, M., Tomadin, L., Villa, G., Persico, D., Morigi, C., Bonci, M.C., and Giorgetti, G., 2002, Glaciomarine sedimentary processes of a high-latitude, deep-sea sediment drift (Antarctic Peninsula Pacific margin): *Marine Geology*, v. 189, p. 343–370, doi: 10.1016/S0025-3227(02)00470-X.
- Lucchitta, B., Rosanova, C., and Mullins, K., 1995, Velocities of Pine Island and Thwaites Glacier, West Antarctica, from ERS-1 SAR images: *Annals of Glaciology*, v. 21, p. 277–283.
- McAdoo, D., and Laxon, S., 1997, Antarctic tectonics: Constraints from an ERS-1 satellite marine gravity field: *Science*, v. 276, p. 556–560, doi: 10.1126/science.276.5312.556.
- Mienert, J., Kenyon, N.H., Thiede, J., and Hollender, F.-J., 1993, Polar continental margins: Studies off East Greenland: *Eos (Transactions, American Geophysical Union)*, v. 74, p. 225, 234, 236.
- Moons, A., De Batist, M., Henriot, J.P., and Miller, H., 1992, Sequence stratigraphy of Cray Fan, southeastern Weddell Sea, in Yoshida, Y., Kamunuma, K., and Shiraishi, K., eds., *Recent progress in Antarctic earth science*: Tokyo, Japan, Terra Scientific Publishing Co., p. 613–618.
- Nitsche, F.O., Gohl, K., Vanneste, K., and Miller, H., 1997, Seismic expression of glacially deposited sequences in the Bellingshausen and Amundsen Seas, West Antarctica: *American Geophysical Union, Antarctic Research Series*, v. 71, p. 95–108.
- Nitsche, F.O., Cunningham, A.P., Larter, R.D., and Gohl, K., 2000, Geometry and development of glacial continental margin depositional systems in the Bellingshausen Sea: *Marine Geology*, v. 162, p. 277–302, doi: 10.1016/S0025-3227(99)00074-2.
- Nürnberg, D., Wollenburg, I., Dethleff, D., Eicken, H., Kasens, H., Letzig, T., Reimnitz, E., and Thiede, J., 1994, Sediments in Arctic sea ice: Implications for entrainment, transport and release: *Marine Geology*, v. 119, p. 185–214, doi: 10.1016/0025-3227(94)90181-3.
- O'Brien, P.E., 1994, Morphology and late glacial history of Prydz Bay, Antarctica, based on echo sounder data: *Terra Antarctica*, v. 1, p. 403–405.
- Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., and Morris, P., 2002, Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf: *Geophysical Research Letters*, v. 29, doi: 10.1029/2001.GL014488.
- Ó Cofaigh, C., Taylor, J., Dowdeswell, J.A., and Pudsey, C.J., 2003, Palaeo-ice streams, trough-mouth fans and high-latitude continental slope sedimentation: *Boreas*, v. 32, p. 37–55.
- Ó Cofaigh, C., Dowdeswell, J.A., Kenyon, N.H., Evans, J., Taylor, J., Mienert, J., and Wilken, M., 2004, Timing and significance of glacially-influenced mass wasting in the submarine channels of the Greenland Basin: *Marine Geology*, v. 207, p. 39–54.
- Ó Cofaigh, C., Larter, R.D., Dowdeswell, J.A., Hillenbrand, C.D., Pudsey, C.J., Evans, J., and Morris, P., 2005, Flow of the West Antarctic Ice Sheet on the continental margin of the Bellingshausen Sea at the Last Glacial Maximum: *Journal of Geophysical Research*, v. 110, doi: 10.1029/2005JB003619.
- Pollard, D., and DeConto, R.M., 2003, Antarctic ice and sediment flux in the Oligocene simulated by a climate-ice sheet-sediment model: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 198, p. 53–67, doi: 10.1016/S0031-0182(03)00394-8.
- Powell, R.D., 1990, Glaciomarine processes at grounding-line fans and their growth to ice-contact deltas, in Dowdeswell, J.A., and Scourse, J.D., eds., *Glaciomarine environments: Processes and sediments*: Geological Society [London] Special Publication 53, p. 53–73.

- Pudsey, C.J., 2000, Sedimentation on the continental rise west of the Antarctic Peninsula over the last three glacial cycles: *Marine Geology*, v. 167, p. 313–338, doi: 10.1016/S0025-3227(00)00039-6.
- Rebesco, M., Larter, R.D., Camerlenghi, A., and Barker, P.F., 1996, Giant sediment drifts on the continental rise west of the Antarctic Peninsula: *Geo-Marine Letters*, v. 16, p. 65–75.
- Rebesco, M., Camerlenghi, A., and Zanolla, C., 1998, Bathymetry and morphogenesis of the continental margin west of the Antarctic Peninsula: *Terra Antarctica*, v. 5, p. 715–725.
- Rebesco, M., Pudsey, C., Canals, M., Camerlenghi, A., Barker, P., Estrada, F., and Giorgetti, A., 2002, Sediment drift and deep-sea channel systems, Antarctic Peninsula Pacific margin, in Stow, D.V.A., Faugeres, J.C., Howe, J., Pudsey, C.J., and Viana, A., eds., *Deep-water contourite systems*: Geological Society [London] Memoir 22, p. 353–371.
- Rignot, E., 2001, Evidence for rapid retreat and mass loss of Thwaites Glacier: *West Antarctica: Journal of Glaciology*, v. 47, p. 213–222.
- Shipp, S., Anderson, J.B., and Domack, E., 1999, Late Pleistocene–Holocene retreat of the West Antarctic Ice Sheet system in the Ross Sea: Part 1—Geophysical results: *Geological Society of America Bulletin*, v. 111, p. 1486–1516, doi: 10.1130/0016-7606(1999)111<1486:LPHROT>2.3.CO;2.
- Shreve, R.L., 1966, Statistical law of stream numbers: *Journal of Geology*, v. 74, p. 17–37.
- Syvitski, J.P.M., 1989, On the deposition of sediment within glacier-influenced fjords: *Oceanographic controls: Marine Geology*, v. 85, p. 301–329, doi: 10.1016/0025-3227(89)90158-8.
- Tomlinson, J.S., Pudsey, C.J., Livermore, R.A., Larter, R.D., and Barker, P.F., 1992, Long-range sidescan sonar (GLORIA) survey of the Antarctic Peninsula Pacific margin, in Yoshida, Y., et al., eds., *Recent progress in Antarctic earth science*: Tokyo, Terra, p. 423–429.
- Tucholke, B.E., and Houtz, R.E., 1976, Sedimentary framework of the Bellingshausen Basin from seismic profiler data, in Hollister, C.D., and Craddock, C., eds., *Initial Reports from the Deep Sea Drilling Project, Volume 35*: Washington, D.C., U.S. Government Printing Office, p. 197–228.
- Vaughan, D.G., Bamber, J.L., Giovinetto, M., Russell, J., and Cooper, A.P.R., 1999, Reassessment of net surface mass balance in Antarctica: *Journal of Climate*, v. 12, p. 933–946, doi: 10.1175/1520-0442(1999)012<0933:RONSMB>2.0.CO;2.
- Vaughan, D.G., Smith, A.M., Corr, H.F.J., Jenkins, A., Bentley, C.R., Stenoiien, M.D., Jacobs, S.S., Kellogg, T.B., Rignot, E., and Lucchitta, B., 2001, A review of Pine Island Glacier, West Antarctica: Hypotheses of instability vs. observations of change, in Alley, R.B., and Bindschadler, R.A., eds., *The West Antarctic Ice Sheet: Behavior and dynamics*: American Geophysical Union, Antarctic Research Series, v. 77, p. 237–256.
- Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J., and Werner, F., 1998, The Norwegian–Greenland Sea continental margins: Morphology and late Quaternary sedimentary processes and environment: *Quaternary Science Reviews*, v. 17, p. 273–302, doi: 10.1016/S0277-3791(97)00072-3.
- Wellner, J.S., Lowe, A.L., Shipp, S.S., and Anderson, J.B., 2001, Distribution of glacial geomorphic features on the Antarctic continental shelf and correlation with substrate: Implications for ice behaviour: *Journal of Glaciology*, v. 47, p. 397–411.
- Wright, R., and Anderson, J.B., 1983, The importance of sediment gravity flow to sediment transport and sorting in a glacial marine environment: Eastern Weddell Sea, Antarctica: *Geological Society of America Bulletin*, v. 10, p. 951–963.
- Wright, R., Anderson, J.B., and Fisco, P., 1983, Distribution and association of sediment gravity flow deposits and glacial/glacial-marine sediments around the continental margin of Antarctica, in Molnia, B.F., ed., *Glacial marine sedimentation*: New York, Plenum Press, p. 265–300.
- Yamaguchi, K., Tamura, Y., Mizukoshi, I., and Tsuru, T., 1988, Preliminary report of geophysical and geological surveys in the Amundsen Sea, West Antarctica: *Proceedings of the National Institute for Polar Research Symposia on Antarctic Geosciences*, v. 2, p. 55–67.

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