

Seismic morphology and distribution of inferred glaciomarine deposits along the East Antarctic continental margin, 20°E–60°E

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Abstract

Seismic-reflection profiles from the continental rise and abyssal plain along a nearly 2000-km long stretch of the East Antarctic margin have been studied, including the Cosmonaut Sea basin and adjacent parts of the Riiser-Larsen Sea to the west and the Cooperation Sea to the east. The recognition of glaciomarine deposits is based on their correlative basal reflector and acoustic characteristics. The lateral distribution of seismostratigraphic sediment thickness, internal architecture of reflectors and seafloor morphology reveal a number of deep-water depocentres with large paleo-channels. These main depocentres correspond to the coastal outlets of present-day ice streams and hence indicate longer-term stabilities in the ice-stream positions during the Neogene advance and retreat phases of the Antarctic Ice Sheet. Scattered paleo-channels and subordinate depocentres in the Cosmonaut Sea suggest that some of the ice streams might occasionally change their position or that also other ice streams were episodically involved during earlier glacial maxima.

Several paleo-channels are >30 km wide and >500 m deep, the largest one being approximately 40 km wide and 1000 m deep. These channels show evidence of multiple incisions and have prominent, multi-storey levees. The giant conduits are considered to be formed through several extensive phases of mass wasting from the shelf edge and upper slope to the continental rise and adjoining abyssal plain. Downslope transport by sediment gravity flows predominates with a subordinate role of along-slope sediment drift by circumpolar contour current.

The repetitive advances and retreats of the ice sheet and recharging of ice streams with terrigenous detritus allowed enormous amounts of glacial sediment to be transferred from the Antarctic interior to the shelf margin during glacial phases. It was probably a high rate of localized sediment supply by ice streams and a wide range of sediment grain sizes that promoted the long series of large and highly efficient turbidity currents. The study demonstrates that a seismostratigraphic mapping of deep-water depocentres and recognition of paleo-channels along a glaciated continental margin may provide important information on the long-term ice-sheet dynamics, particularly on the pattern of ice drainage represented by coastal ice streams.

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1. Introduction

The circum-Antarctic continental margin includes a range of glacial-marine sedimentary environments. Within relatively short lateral distances, the environments commonly range from areas of stationary polar ice to zones of diverging or converging ice streams. These environments have different capacities for offshore sediment transfer, often involve both sediment gravity flows and contour currents (Hollister and Elder, 1969; Anderson et al., 1979; Wright and Anderson, 1982), and are characterized by differing styles of sedimentation and sedimentary architectures (Kuvaas and Kristoffersen, 1991; Kuvaas and Leitchenkov, 1992; Rebesco et al., 1997; Barker et al., 1998; Escutia and Eitrem, 2000; De Santis et al., 2003; Kuvaas et al., 2004a,b, 2005).

The present paper reviews the results of a seismic-reflection study in the Atlantic and Indian Ocean sector of the East Antarctic continental margin (Fig. 1), focusing on the distribution and morphology of inferred glaciomarine deposits. Recent investigations in the region have found the sedimentary succession to be demarcated by a distinct change in acoustic character, and regional correlations with other parts of the East Antarctic margin suggest that this change represents the onset of glaciomarine sedimentation (Kuvaas et al., 2004b). The change commonly involves a basal unconformity, which has been variously referred to as the RLS-4 seismic marker in the Riiser-Larsen Sea (Kuvaas et al., 2004a), the CS-4 marker in the Cosmonaut Sea (Kuvaas et al., 2005) and the P1 marker in the Cooperation Sea (Kuvaas and Leitchenkov, 1992).

The aim of the present study has been to map the distribution of glaciomarine deposits and identify their main depocentres in the Atlantic- and Indian Ocean sectors (20°E to 60°E) of the East Antarctic continental margin (Fig. 2). Attributes like seabed morphology, internal seismic-reflection architecture and morphometric characteristics of the deposits are discussed, and their spatial distribution is compared with the present-day geographical pattern of local ice streams.

2. The seismic data

The seismic profiles come from an extensive database (>10000 km of seismic lines) acquired by the Russian Polar Marine Geosurvey Expedition (PMGE, 1998–2004) from the Riiser-Larsen Sea, the Cosmonaut Sea and the western part of the Cooperation Sea (Fig. 1). These multichannel seismic-reflection data include profiles perpendicular, parallel and oblique to the continental slope and rise. No profiles reach across the continental shelf, because of its ice cover.

The seismic source for these profiles consisted of two airguns with a total volume of 40 L, towed at a water depth of 4–6 m. The signal was recorded by a 72-channel (or 96-channel in 1998) hydrophone cable with 25-m group length. The shot point interval was 50 m. During adverse weather conditions, the cable was towed deeper, at ca. 12 m on the average, whereby the corresponding spectral notch from the surface ghost reflection limited the frequency content to less than 65 Hz. The data were edited and sorted, and velocity analysis was carried out at 7–10 km intervals. The stacked traces were mixed and the conventional zero-phase deconvolution, bandpass filter and automatic gain control were applied before the data display. Sonobuoy measurements collected by the PMGE (locations in Fig. 1) provide seismic velocities for the uppermost part of the sediment succession (Table 1).

The bathymetry of the continental margin is from a data grid with a 2' resolution and water depths predicted from satellite gravity measurements for short wavelengths, calibrated against ship track measurements for the longer wavelengths (Smith and Sandwell, 1997). Fledermaus software has been used for visualization.

3. Regional setting

The studied segment of the East Antarctic continental margin off the Dronning Maud Land and Enderby Land comprises three main depositional basins: the Riiser-Larsen Sea, the Cosmonaut Sea and the Cooperation Sea (Fig. 1). The passive margin is considered to have formed as a result of the Gondwana break-up in the Late Jurassic to Early Cretaceous time. Recent geodynamic models suggest that the Riiser-Larsen Sea is the oldest basin and began to develop at 155 Ma, about 20 Ma prior to the formation of the adjacent other deep-water basins (Ramana et al., 2001; Jokat et al., 2003).

The Riiser-Larsen Sea is confined to the east by a submarine basement ridge oriented perpendicular to the continental margin (Fig. 1). The Gunnerus Ridge follows the 34°E meridian and constitutes a topographic barrier between the Riiser-Larsen Sea and the Cosmonaut Sea. This ridge is considered to be a fragment of continental crust, isolated from the main Antarctic margin after the Gondwana break-up (Roeser, 1996). The steepest continental slope, locally exceeding 10°, is found in the proximity of this ridge.

The present-day pattern of oceanographic circulation around Antarctica is dominated by three main water masses: the Antarctic Surface Water, the Circumpolar Deep Water and the Antarctic Bottom Water. The Antarctic Surface Water encompasses the counter-clockwise flow of the Antarctic Coastal Current in the shelf and

upper slope zone, and the clockwise flow of the more distal Antarctic Circumpolar Current. The latter current occurs in a deep bathymetric zone, but may at least locally affect the entire water column (Foldvik and Gammelsrød, 1988). The Circumpolar Deep Water constitutes the largest water mass in the Southern Ocean (Carmack, 1990), extending from ca. 250 to 4000 m depth and

flowing generally from east to west near the continental margin. The Antarctic Bottom Water (ABW) is the densest water mass, flowing off the continental shelf, down the slope and into the basins. Most of the ABW production occurs in the Weddell Sea, but some originates in the Ross Sea and off Wilkes Land. The main factors controlling oceanic circulation are the distribution of land

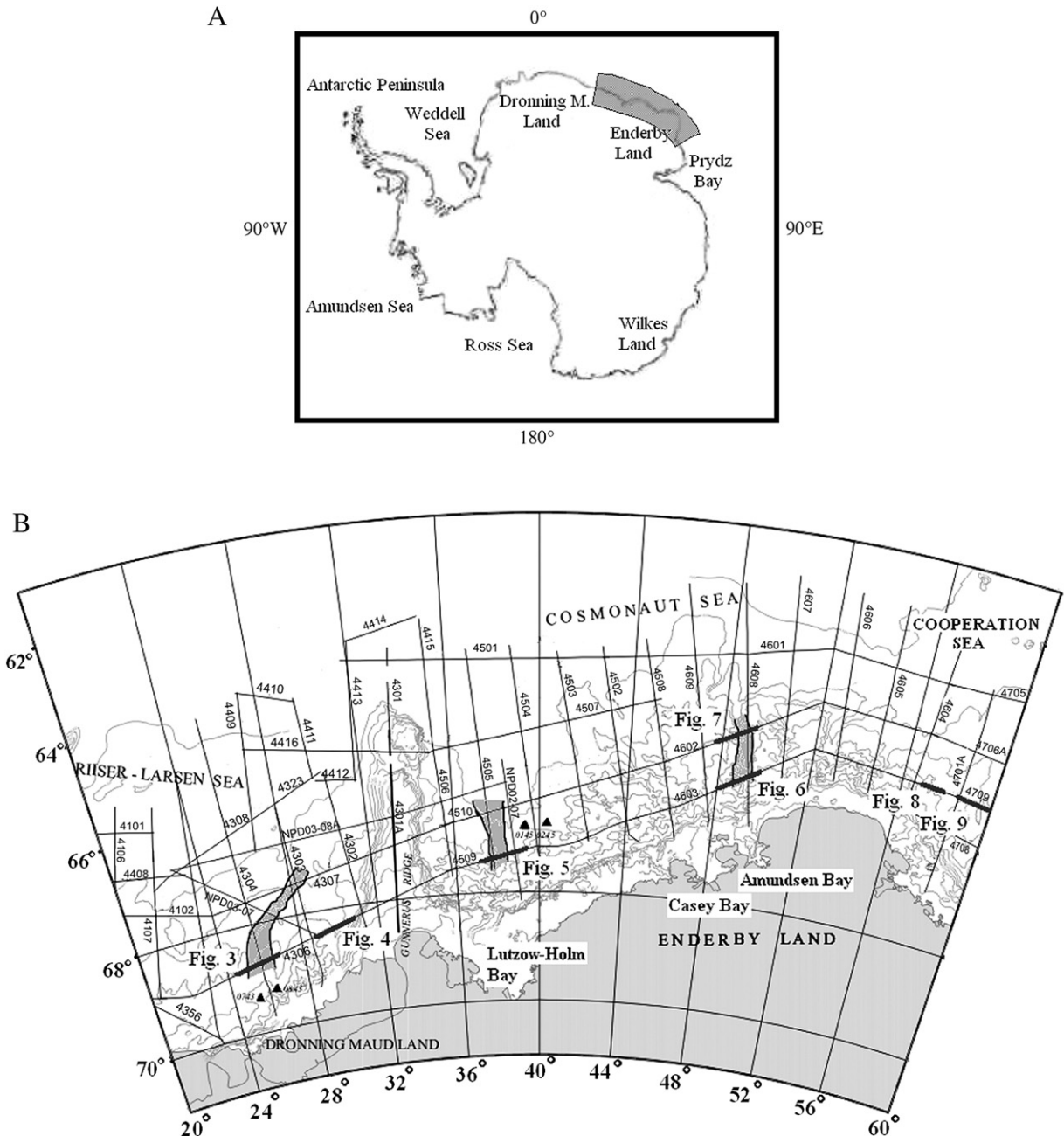


Fig. 1. Location of the study area (A) and a corresponding bathymetric map with the seismic sections (B). The margins of the three largest paleo-channels are outlined. The black triangles indicate sonobuoy locations. Bold lines indicate the location of figures.

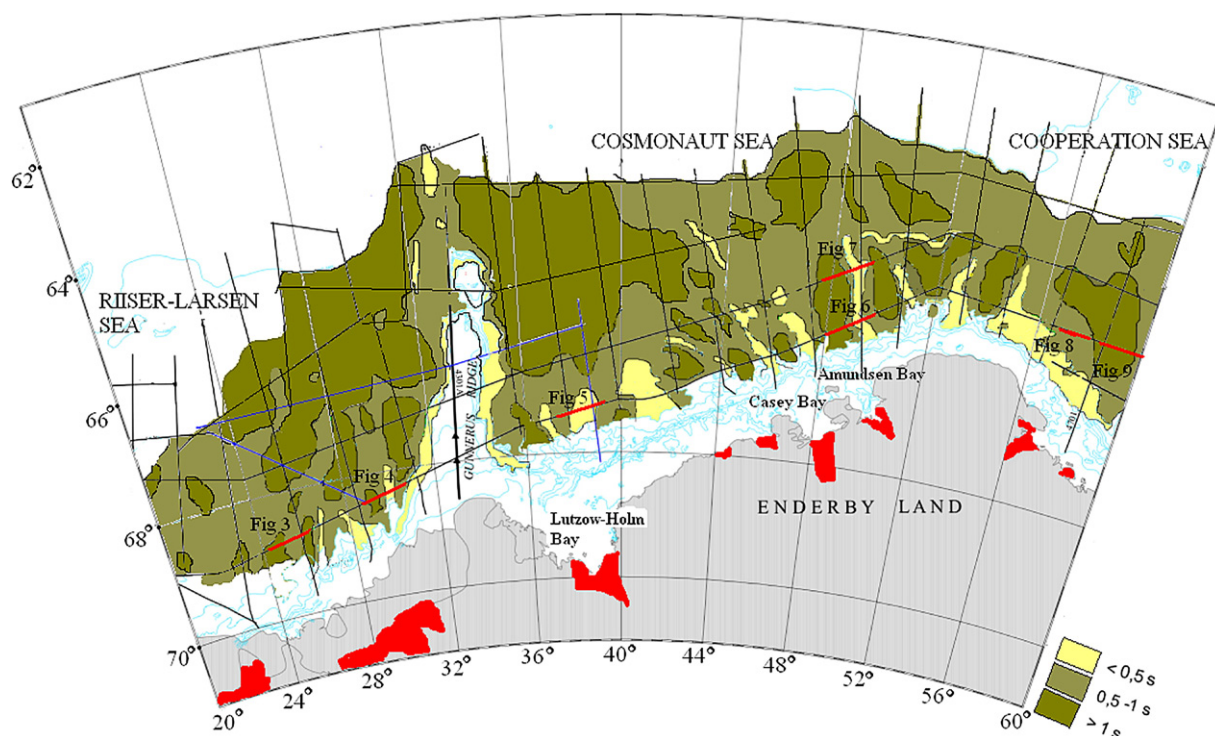


Fig. 2. Map of the continental margin in the study area showing the inferred glaciomarine sediment thickness. Sediment thickness is given in TWT (s). The coastal areas marked in red are characterized by high-rate ice movements (>1000 m/year); after Rignot and Thomas (2002).

masses and the global climate, and both these factors have changed considerably during the late Mesozoic and Cenozoic time with the development of seaways around Antarctica as a result of the Gondwana break-up. The growth of the first continental ice sheet is considered to have commenced about 34 Ma (Barrett, 2003; Macphail and Truswell, 2004; Cooper and O'Brien, 2004). Ice-sheet models by DeConto and Pollard (2003) suggest that the main cause for the inception and growth of the Antarctic Ice Sheet was decreasing levels of CO_2 in the atmosphere, with the opening of the Southern Ocean gateways playing a secondary role.

Ice streams, or corridors of relatively fast ice movement, are important features of the Antarctic Ice Sheet. In Swinbank's (1954) definition, they are "those parts of an inland ice sheet in which the ice flows more rapidly, and not necessarily in the same direction as, the surrounding ice". Ice streams are responsible for the majority of ice and sediment discharge within the ice sheet and at its margins. At present, over 90 vol.% of all the ice and sediment discharged by the Antarctic Ice Sheet flows within the ice streams (Bentley and Giovinetto, 1991; Bamber et al., 2000). The movement of ice and hence also the transport of sediment are slow outside the ice streams, which themselves are of limited net volume. Paterson

(1994) estimated that ice streams presently occupy only 13% of the Antarctic margin, although more recent satellite imagery (Showstack, 1997) indicates a slightly higher ice-stream proportion. Despite the small fraction of the ice-sheet front occupied by ice streams, the latter is considered the main mechanism for sediment supply to the continental margin. Most of this sediment supply to the Antarctic outer shelf and upper slope zone occurred during glaciations, when the ice sheet advanced across the continental shelf. The residence time of the sediment accumulated on the upper slope might have varied, but a large part of this unstable terrigenous material would eventually be transported as sediment gravity flows down

Table 1

The top-layer refraction velocity (V) and the corresponding sediment thickness (H) derived as a one-dimensional velocity/depth function from the PMGE measurements

Sonobuoy No.	Latitude (°S)	Longitude (°E)	Water depth (km)	V (km/s)/ H (km)
0743	69.18370	25.19170	2.704	2.0/1.49
0843	69.14190	26.22990	3.176	2.0/0.90
0145	66.47525	39.19422	4.170	2.0/1.58
0245	66.44359	40.24414	4.290	1.9/1.80

The locations of sonobuoys are indicated in Fig. 1.

to the continental rise and adjoining abyssal plain. The morphology and spatial distribution of glaciomarine deposits on the deep-seafloor thus provide important clues to the dynamic history of the Antarctic Ice Sheet (e.g., Kuvaas and Kristoffersen, 1991; Kuvaas and Leitchenkov, 1992; Barker et al., 1998; De Santis et al., 2003; Cooper and O'Brien, 2004; Rebesco et al., 2006).

4. Continental rise deposits of the East Antarctic margin

In this section, we review observational evidence with special emphasis on the seismic-reflection patterns and morphological characteristics of deposits in the continental rise zones of the East Antarctic margin. The locations of the seismic profiles selected for illustration are shown in Fig. 1. The ensuing description begins with the definition of two principal acoustic horizons used for seismostratigraphic subdivision of the sedimentary succession.

4.1. Acoustic interfaces

Two important seismic reflectors are highlighted in the seismic profiles: one corresponding to the base of the sediment succession and referred to as acoustic basement (AB), and the other defines an internal unconformity which is regional and considered to represent the base of glaciomarine deposits (BGD, see Kuvaas et al., 2004b).

Acoustic basement surface— A distinct, high-amplitude reflector appears at the base of the acoustically well-layered sedimentary succession in all seismic profiles (see horizon AB in Figs. 3–9). This seismic interface is characterized by a highly varied apparent morphological relief and shows a marked overall inclination both seawards (Fig. 10A) and away from the basin-separating Gunnerus Ridge (Fig. 4). The reflector morphology varies laterally from nearly flat to rugged, with rolling heights (Figs. 3–6) or narrow plateaux (Figs. 4 and 9), and locally shows prominent isolated ridges (Figs. 6 and 8). This marker surface separates the irregular and nearly transparent pattern of seismic reflections below from the well-defined pattern of sub-parallel reflections above (Figs. 3–9), and is thus interpreted to indicate acoustic basement (bedrock) beneath the overlying sedimentary succession.

Base of glaciomarine deposits — On the continental rise a distinct change in seismostratigraphic architecture is recognized, where uniform patterns of sub-parallel reflections pass upwards into more irregular patterns of uneven and commonly contorted reflections, including

scour-and-fill features, large sediment mounds and lens shaped features (see horizon BGD in Figs. 3–10). Similar upward changes in acoustic character are previously reported by Kuvaas et al. (2004a,b, 2005) in the eastern Riiser-Larsen Sea, the Cosmonaut Sea, the Weddell Sea and the eastern Cooperation Sea, and considered to be regionally correlative. The present study has identified the corresponding acoustic stratigraphic level also in central parts of the Riiser-Larsen Sea and in the western Cooperation Sea (Fig. 1).

The change in acoustic character is generally associated with a distinct unconformity, onto which overlying sedimentary units frequently show downlapping terminations (Figs. 3–9). Kuvaas et al. (2004a,b, 2005) found this laterally extensive surface to mark the shift from low-intensity sedimentation dominated by uniform aggradation to high-intensity sedimentation characterized by strong sediment fluxes and erosional slope adjustments, with the formation of turbiditic channels, levees and contouritic mounds. The distinct change in seismic-reflection pattern with an increase in channel related sedimentation occurring above this boundary (Kuvaas et al., 2005), is considered to reflect an increase in sediment input caused by glacial advances to the shelf edge. Detailed analyses of the seismic facies in comparison with data from other segments of the East Antarctic margin suggest that the marker horizon is stratigraphically representing the base of glaciomarine deposits (Kuvaas et al., 2004a,b, 2005). The interpretation is supported by DSDP and ODP drilling results from the Weddell Sea and Prydz Bay (Kuvaas and Kristoffersen, 1991; Shipboard Scientific Party, 2001; Kuvaas et al., 2004a). Albeit the seismic expression of deep-marine glaciomarine sediments is largely non-diagnostic, Stoker (1997) noted that exceptions may occur in areas of sediment drift accumulation and in deep-sea channel systems where the sediment supply is directly related to glaciations.

If this interpretation is correct, a seismostratigraphic mapping of the thickness maxima of glaciomarine deposits and/or recognition of major paleo-channels should allow the zones of greatest sediment flux to be identified along the continental margin. Under this premise, the distribution of glaciomarine deposits has been tentatively assessed from the seismic sections (Fig. 2).

4.2. Glaciomarine deposits

The Riiser-Larsen Sea — The seismostratigraphic signature attributed to the boundary between preglacial and glaciomarine deposits is recognizable throughout the studied areas of the Riiser-Larsen Sea (Figs. 3, 4; see

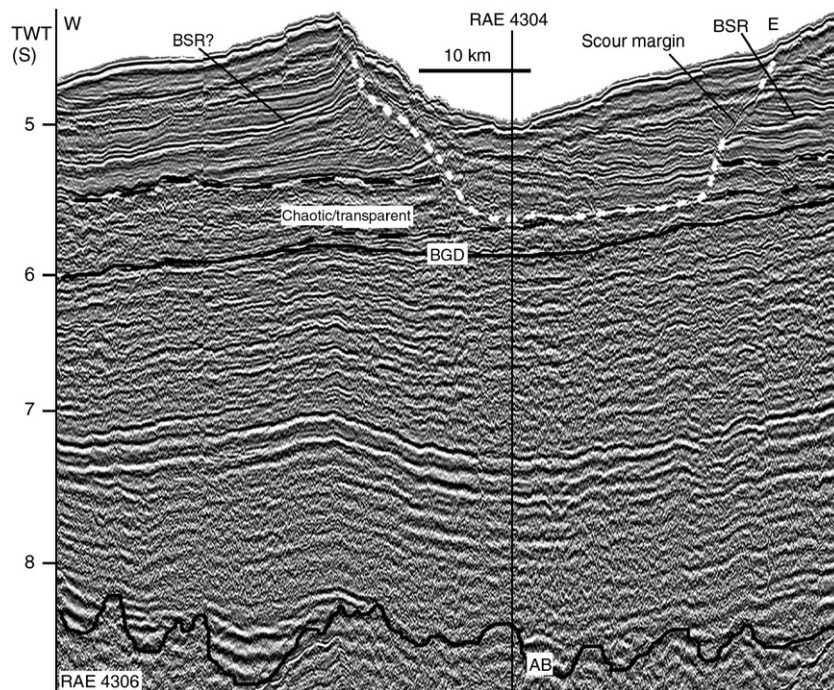


Fig. 3. Seismic image showing a large-scale scour and fill structure in the eastern part of the Riiser-Larsen Sea; for location, see Fig. 1. The white dashed line indicates the margin of the scour. The scale on vertical axis indicates the signal two-way travel time, TWT (s). Reflector labels: AB — acoustic basement; BGD — base of glaciomarine deposits; and BSR — bottom-simulating reflector. Note the upward transition from parallel and continuous reflectors in the lower part of the sediment succession, to a more complex architecture in the upper part.

also Kuvaas et al., 2004a). The produced thickness map indicates a prominent depocentre in eastern parts of the basin close to the Gunnerus Ridge (Fig. 2), where several large scour-and-fill features dominate the seismostratigraphic architecture (Figs. 3, 4). The apparent widths of the scours are in the order of a few tens of kilometres on upper parts of the continental rise. Distinct sediment ridges are commonly present on either side of the scours. The ridges are oriented almost perpendicular to the continental margin, and the ridges on the western side of the scours tend to be larger than the eastern (Fig. 4). The internal reflectors of the ridges are dipping tangentially and converging away from the scour, downlapping either underlying lens-shaped units with a chaotic to transparent internal facies (Figs. 3 and 4) or directly the preglacial substrate. The tangential reflectors terminate abruptly against the margins of the scours. The trajectory of the largest scour is indicated in Fig. 1. The scour has a width of approximately 40 km on the seismic line RAE 4306 (Fig. 3), which is oriented perpendicularly to the scour-axis. The depth, measured from the buried floor of the scour to the mean height of the flanking mounds, is around 1 km (assuming a sediment velocity of 2 km/s, as indicated by sonobuoy data; see Table 1).

Fig. 2 indicates a somewhat thinner succession of glaciomarine deposits in the westernmost area, which corresponds to central parts of the Riiser-Larsen Sea. Still, the seismic profiles and the seafloor bathymetry suggest the presence of distinct sediment mounds. However, we do not observe large-scale incisions with flanking ridges similar to the ones observed in the eastern part of the basin.

The Cosmonaut Sea — The glaciomarine unit in the Cosmonaut Sea area is separated from the underlying preglacial deposits by a regional sedimentary lens (Fig. 10; Kuvaas et al., 2005), which extends here along the whole length of continental margin (ca. 1200 km), is up to 250 km wide and mainly around 1 s (TWT) thick with relatively smooth, gently undulating boundaries. This unit is broadly lenticular, pinching out seawards (Fig. 10A) and also towards the basin western margin, but extending eastwards into the adjacent Cooperation Sea area. Kuvaas et al. (2005) have interpreted this extensive unit as a slope-plastered drift deposited prior to the main flux of glaciogenic sediment from the continental margin.

The bulk of glaciomarine deposits in the Cosmonaut Sea is accumulated in the western part towards the flank of the Gunnerus ridge (Fig. 2). The thickness map also

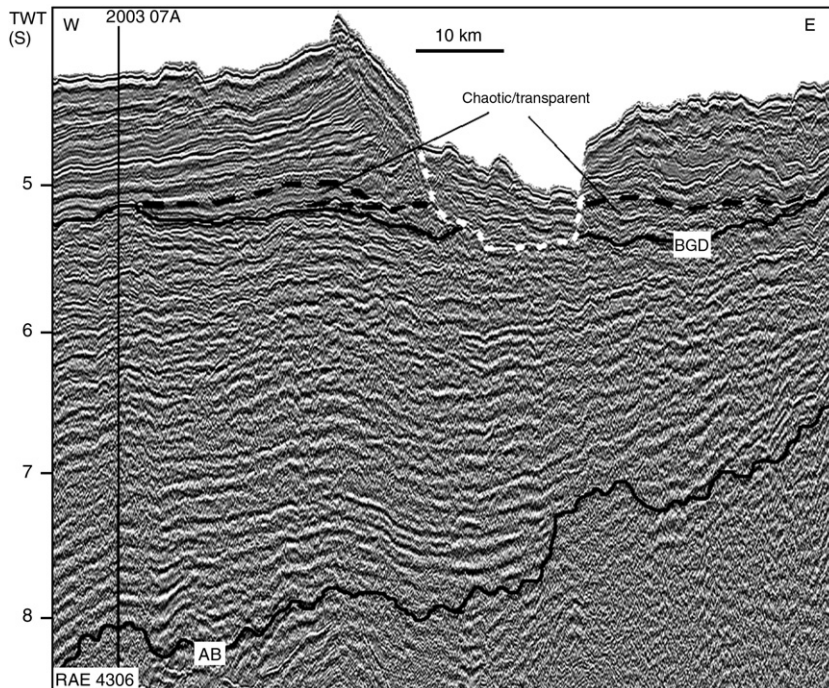


Fig. 4. The seismic profile reveals a westward dipping basement and lens shaped sedimentary units overlying the BGD. Note the scour is incised in pre-glacial deposits and partly filled. Several episodes of filling and rescouring can be observed (Fig. 1 for location).

reveals a thick succession of glaciomarine deposits seaward of Casey Bay and Amundsen Bay. In addition, we observe several sediment ridges oriented perpendicularly to the continental margin in the basin-margin

sector of 50–54°E. The relatively great thickness of glaciomarine deposits in this sector apparently does not correspond to the coastal outlets of any major present-day ice streams.

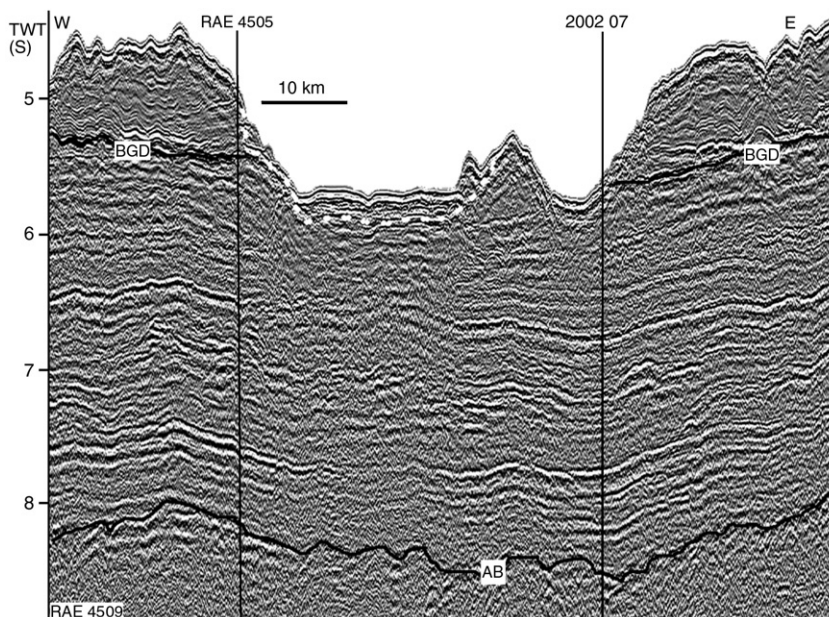


Fig. 5. Large scour and fill structure in the western part of the Cosmonaut Sea. The planar filling of the scour is indicative of turbidites. Notice also the small mound overlying the planar sediment fill near the eastern margin (see Fig. 1 for location).

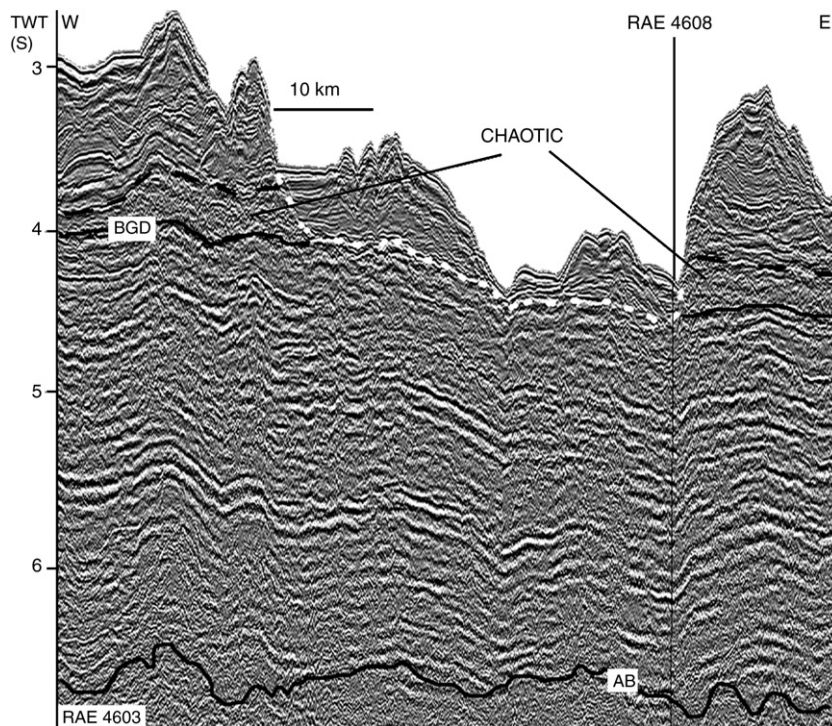


Fig. 6. Several of the large scour and fill structures show signs of rejuvenation, filling and rescouring (see Fig. 1 for location).

The seafloor surface in the Cosmonaut Sea is highly rugged (Fig. 10), incised by numerous scours and showing large sediment mounds in inter-scour areas. The mounds occur along the entire stretch of the continental margin and have varied shapes and sizes (Fig. 10). Their widths in sections parallel to the margin are mainly in the range of 40–120 km (Fig. 10B, C). The scours within this basin are widely scattered, rather than concentrated within the main depocentres, which contrasts with their distribution in the adjacent Riiser-Larsen Sea. The apparent widths of the scours range from a few hundred metres (Fig. 10B, C) to as much as 10–40 km (Figs. 5–7). The largest scours and greatest local thicknesses of glaciomarine deposits occur in front of the present-day ice-stream termini: directly eastwards of the Gunnerus Ridge and in the basin-margin sector of 46–50°E (Figs. 1, 2, 5, 6 and 7).

The Cooperation Sea — The regional sedimentary lens recognized in the Cosmonaut Sea extends into the adjoining western part of the Cooperation Sea, where it appears to pinch out eastwards (Fig. 8). Multiple scours and an irregular pattern of reflectors dominate in cross sections from upper parts of the continental rise. These scours are mainly 1–10 km wide, but relatively shallow and lacking prominent flanking ridges (Fig. 8).

The depocentre located in the region 55–60°E (Fig. 2) shows some important features not observed

elsewhere along the margin: 1. The large incisions with flanking ridges that appear to characterize the proximal parts of other depocentres, is not present. The depocentre is only flanked to the east by a relatively small scour (Fig. 9). 2. The depocentre appears to be aligned almost parallel to the continental margin (Fig. 2). The external shape of the mounded deposits is almost symmetrical and the internal pattern of reflectors appears to consist of parallel to sub-parallel reflectors. Notice also the sediment package leaning onto the small mound on the eastern side of the scour. The reflectors within this unit indicate progradation from east to west (Fig. 9).

5. Interpretation and discussion

Deep-sea research in the last two decades has demonstrated that: (1) the terrigenous sediment supply to continental-margin basins may involve point-type, multi-point or line-type sources (Reading and Richards, 1994); (2) both downslope and along-slope sediment transport processes may play important roles in these basins (Bouma et al., 1985; Viana et al., 1998; Wynn et al., 2000); and (3) it is often the interaction of the two dispersal modes that shapes the local seafloor morphology and determines sedimentary architecture (e.g., Cleary et al., 1985; Shanmugam et al., 1995; Carter

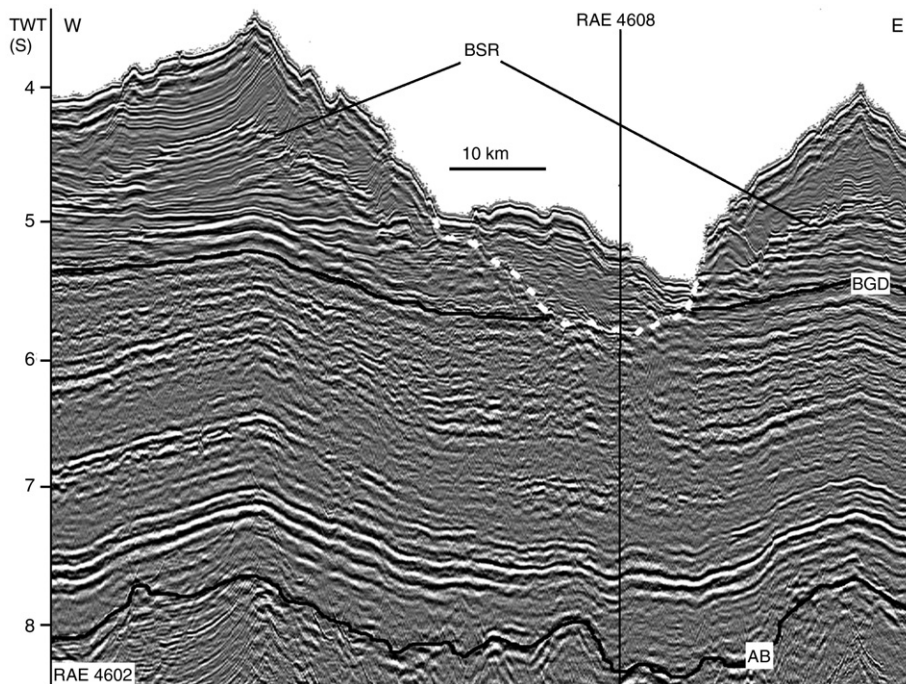


Fig. 7. Prominent sediment mounds are often developed on either side of the large scours. Their internal pattern of reflectors is sometimes disturbed by a strong BSR (see Fig. 1 for location).

and McCave, 1997; Kuvaas et al., 2005). However, the relative impact of these two dispersal modes is generally difficult to assess, especially from seismic sections alone (Weimer and Link, 1991; Faugeres et al., 1999; Posamentier and Kolla, 2003). For example, prominent sediment mounds can be formed both by contour currents and by slope-derived turbidity currents (Flood et al., 1993; Brew, 1995; Howe, 1996; Migeon et al., 2001; Nakajima and Satoh, 2001). Either of these processes, along with hemipelagic “background” sedimentation, can similarly deposit thick successions of flat-lying sediment sheets ranging from sandy to muddy (Stow and Lowell, 1978; Weimer and Link, 1991; Viana et al., 1998; Faugeres et al., 1999). In the absence of drill cores, sidescan sonograms and high-resolution sub-bottom acoustic profiles, the recognition of sediment dispersal processes is an uncertain task (cf. Rupke and Stanley, 1974; Stow, 1979; Piper et al., 1985; Brunner and Ledbetter, 1987; Porębski et al., 1991) and hence may in part be hypothetical in the present case.

5.1. Sediment dispersal pattern

Mapping of the inferred glaciomarine deposits (Fig. 2) along the east Antarctic continental margin shows prominent depocentres off the main coastal outlets of present ice streams. This spatial link suggests

a long-term stability in the drainage patterns and a predominance of downslope processes. The occurrence of large scours oriented transverse to the margin with flanking sediment ridges (in proximal parts of the depocentres in the Riiser-Larsen Sea and the Cosmonaut Sea) also supports these notions. We interpret these structures as channel-levee systems produced by turbidity currents. The larger western levee is attributed to the influence of the Coriolis force. In the Southern hemisphere, if the flow is directed downslope as for turbiditic systems, the turbidity systems are deflected to the left. Where they reach the continental rise or where channel relief has diminished sufficiently, they preferentially overflow the left flank of the channel and build up a prominent levee on this side (Faugeres, 1999). The layers within the sediment ridges converge away from the scours and terminate abruptly against their margins, implying levee growth accompanied by channel-bank erosion.

Also, the largest paleo-channels (>30 km wide) recognized in the seismic sections coincide with the areas of converging ice streams (Fig. 11). This further illustrates the importance of ice streams as principal sediment suppliers and suggests that their geographical positions in this part of the Antarctic margin would thus appear to have been quite stable during the Neogene time, probably constrained by upstream land

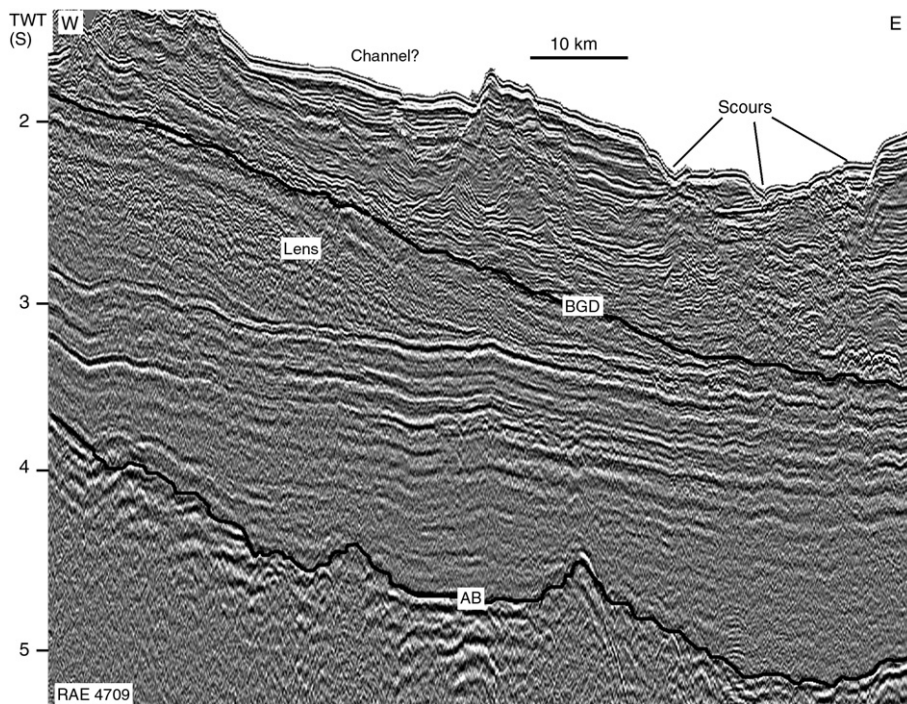


Fig. 8. The seismic image indicates that the regional sediment lens pinches out towards the east. Several small scale scours are observed near the seafloor surface (see Fig. 1 for location).

topography. Although the entire shelf edge was likely shedding sediment and at times may have acted as a line source, the multi-point supply from ice streams clearly dominated along the continental margin over a longer-term perspective, rendering it a combined-type sourcing system.

The episodic nature of ice-sheet advance and retreat phases would allow the delivery system to become recharged with sediment, ensuring high sediment supply for the next re-advance, although the ice sheet might not necessarily extend to the shelf edge. Sediment stored temporarily on the shelf would tend to be transferred farther towards its edge during the more extensive ice-sheet advances. Overall, the system would thus have the potential to deliver enormous amounts of sediment to the continental margin, as is clearly testified by the great sediment thickness and large paleo-channels in the continental rise zone.

The relatively thick succession of glaciomarine deposits in the sector 50–54° E cannot be directly linked to any of the present-day ice-stream outlets. Still, the depocentre is characterized by large paleo-channels oriented transverse to the margin and inter-channel ridges. The thickness of the glaciomarine deposits and the geometry of the deep-sea features indicate respectively, a significant delivery of sediments to this sector of

the continental shelf-edge and a predominance of downslope processes. This notion is also supported by the undulated morphology of the continental shelf (Fig. 12), which resembles the trough and bank morphologies off Lutzow Holm-, Casey- and Amundsen Bay where the present-day ice-stream outlets are located. The depressions in this region (50–54° E) are around 150 m deep and tens of km wide, oriented transverse to the margin and extending to the shelf edge. The sediment transport to this sector of the continental shelf is probably either related to palaeo-ice-streams migrating eastwards (when crossing the continental shelf) from the Amundsen Bay region or the presence of additional ice streams during previous glacial maxima. Based on the trajectory of the depressions, the latter option appears most likely. The continental shelf in the region is also relatively narrow (30–50 km), which means that even some smaller, secondary ice streams could have potentially reached the shelf edge. These notions might explain the scattering of smaller paleo-channels in such areas as the Cosmonaut Sea, where many channels show no apparent spatial link to the present-day ice streams.

The lack of large paleo-channels and the oblique orientation of the depocentre in the western part of the Cooperation Sea may be indications of a stronger influence from along-slope processes. This notion is also

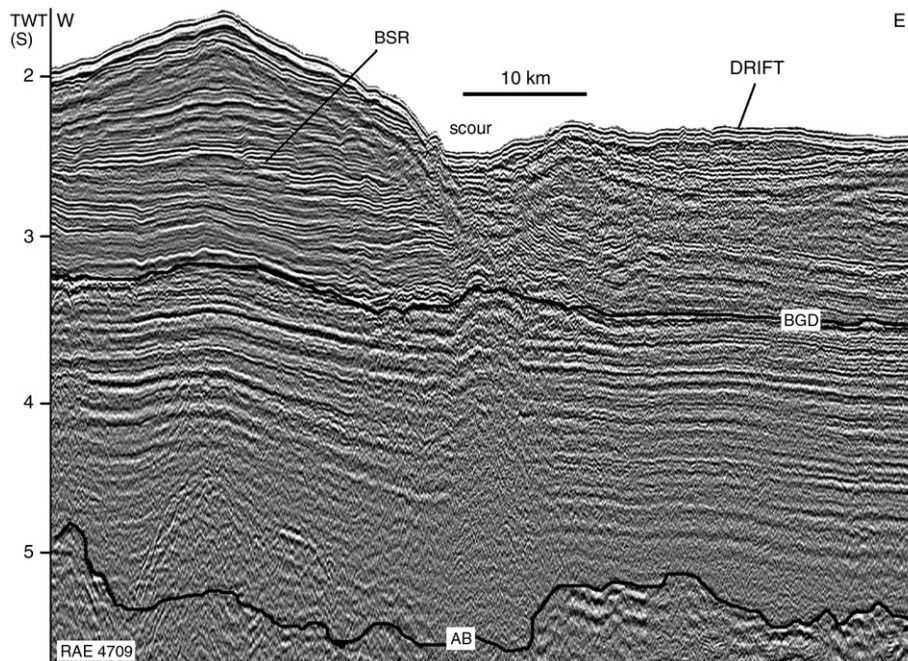


Fig. 9. The scour in the central part of the profile is flanked by a sediment mound on either side. Notice also the sediment package that has infilled a small seafloor depression to the east, having internal reflectors indicating migration from east to west (see Fig. 1 for location).

supported by the slight westward offset of the depocentre in relation to the corresponding ice-stream terminus (Fig. 2), the relative size of the flanking scour (which seems disproportionate with respect to a possible western levee, Fig. 9), the internal pattern of reflectors of the mounded deposits (which does not seem to be converging away from scour, Fig. 9) and by the east to west migration observed within the adjacent sediment package leaning onto the smaller eastern mound (Fig. 9). The observations are consistent with an influence from westward flowing contour currents within the Circumpolar Deep Water. We have hence interpreted the smaller sediment package as a sediment drift (Fig. 9) and the mounded deposits within the depocentre as mixed levee-drift deposits. The scour in Fig. 9 can be traced further upslope and appears to be incised by gravity flows. This suggests that sediments were supplied to the deep-sea through mass wasting and redeposited by westward flowing contour currents.

The deposits in the Cosmonaut Sea also reveal a component of westward flowing contour currents. Here the sediment drift was probably derived mainly by erosion of the high levee ridges and by stripping of turbidity currents (Shanmugam et al., 1995). This is supported by the rugged topography of some of the sediment ridges (Figs. 5, 7 and 10) and the occurrence of semicircular sediment mounds (Fig. 10, Kuvaas et al., 2005). Kuvaas et al. (2005), also identified elongated

moats interpreted to represent areas of erosion or non-deposition beneath the margin-parallel system of contour currents. Nevertheless, the channel-dissected topography of the Cosmonaut Sea is far from having been “healed” by the along-slope sediment drift, which indicates that the overall effect of contour currents has been limited throughout the glacial period.

5.2. The paleo-channels

As pointed out by Escutia and Eitrem (2000), channels are among the characteristic features of glaciated continental margins. The inferred glaciomarine succession discussed here is characterized by the occurrence of large paleo-channels, which:

- are trending away from the continental margin and generally lack a radial pattern typical of submarine fans (Fig. 12);
- are generally associated with the local depocentres and linkable to the present-day ice-stream termini (Figs. 1 and 2);
- have widths and depths at the upper extreme range of values reported from modern and ancient submarine channels (Fig. 13);
- occur in the upper part of the succession, show evidence of rejuvenation (filling and rescouring) and

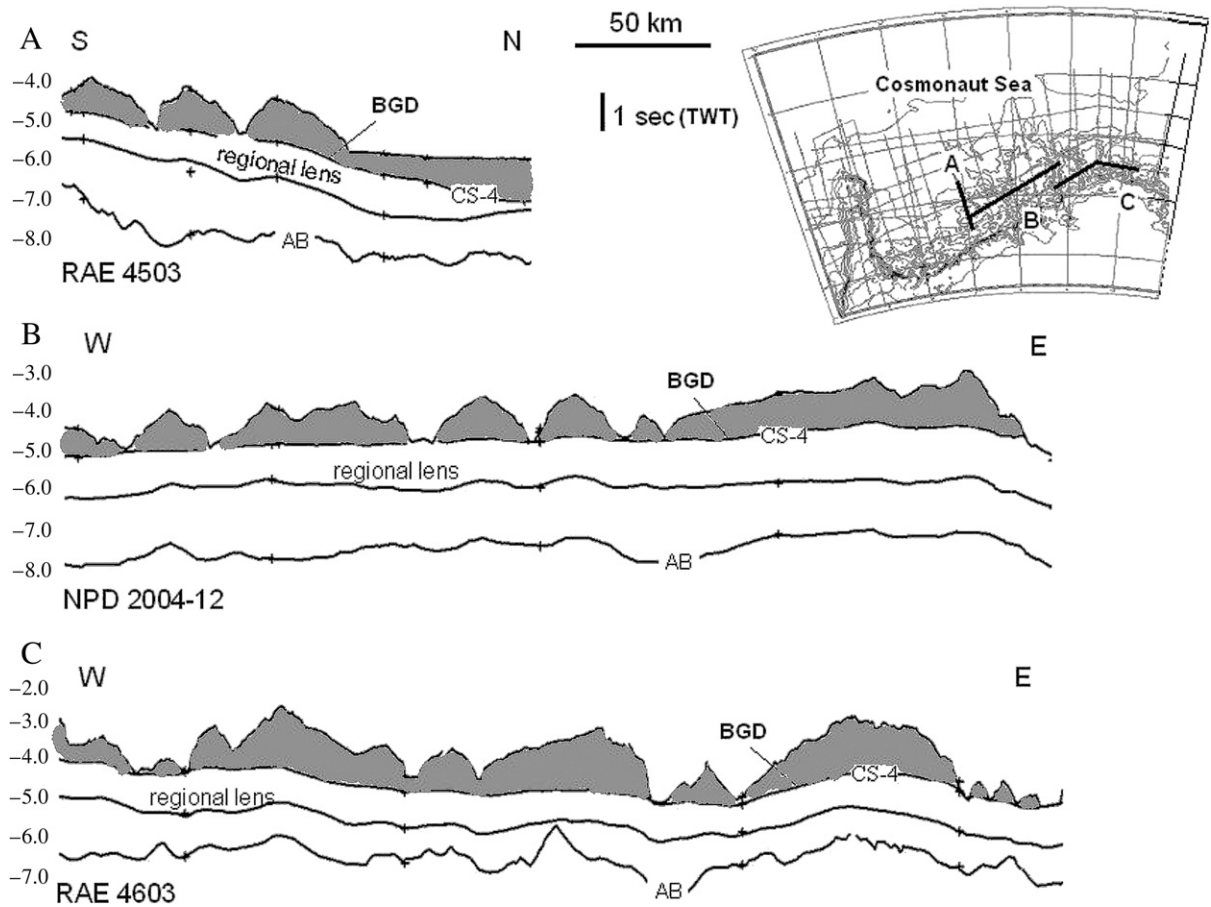


Fig. 10. Seafloor morphology and key reflectors in selected seismic profiles from the Cosmonaut Sea (see locations in the inset map). The CS-4 marker is the boundary between the lower, parallel-layered sedimentary unit (northward-inclined regional lens) and the upper sedimentary unit characterized by numerous incisions. Reflector labels as in the caption to Fig. 3. Slightly modified from Kuvaas et al. (2005).

are mainly half-filled with sediment (Figs. 3–7; see also the indication of a lateral slumping of undercut channel-fill in Fig. 5);

- are in some cases incised all the way down to the base of the inferred glaciomarine succession or even somewhat deeper (Figs. 4–7); and
- are flanked by prominent levees in most cases, but by no means universally.

The observed spatial link between the glaciomarine depocentres and the location of present-day ice streams implies a long-term stability in ice-stream trajectories. If so, the large widths and depths of the paleo-channels may be attributed to the long-lived, polyphase activity of these mass-flow conduits. Glacigenic sediment would tend to accumulate on the shelf and upper continental slope during the ice-sheet advances (Anderson et al., 1979; Alley et al., 1989), leading to intense resedimen-

tation by gravity flows to the continental rise and abyssal plain.

The large paleo-channels, with or without major levees, are most commonly oriented transverse to the margin (Fig. 12) and indicate sediment transport by long series of powerful, highly efficient turbidity currents. Although major sites of bottom-water formation can have the potential to generate flows scouring channels on the lower slope and upper continental rise (Futterer and Melles, 1990), there is no reported evidence of such phenomena in the study area. The non-leveed small scours may be bottleneck slump scars or mass-flow gullies (Prior and Coleman, 1984). The turbidity currents were almost certainly evolving from and/or accompanied by debris flows. The occurrence of slump and/or debris-flow deposits can be suspected in the lens shaped chaotic to transparent portions of the glaciomarine succession (Figs. 3, 4 and 6).

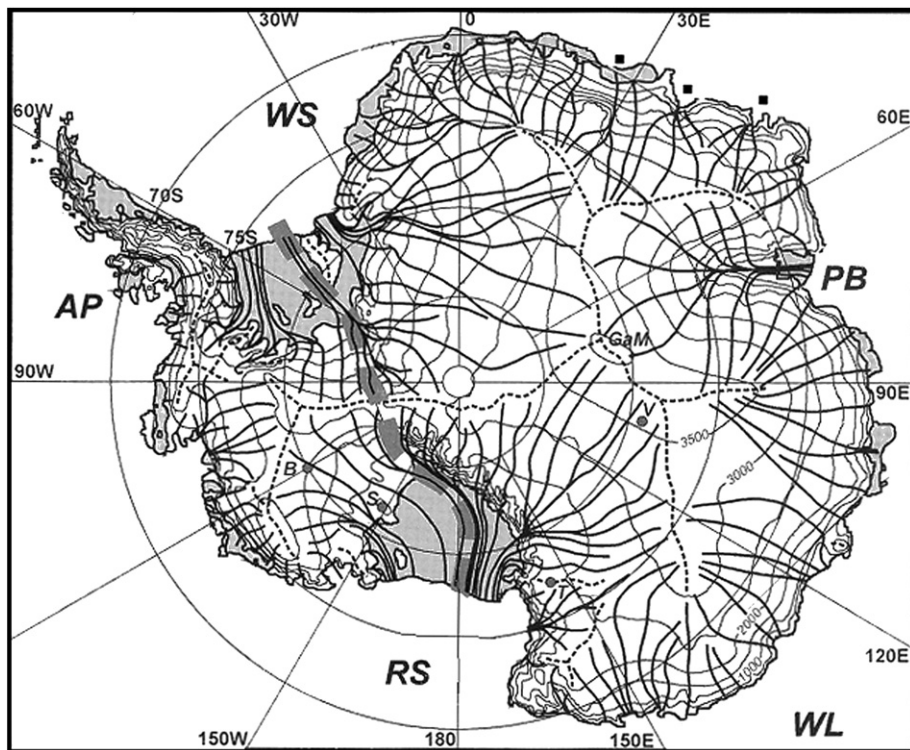


Fig. 11. Generalized map of the present-day extent of the Antarctic Ice Sheet, showing surface elevation (500-m topographic contours) and hypothetical ice-flow lines. Dashed grey line is boundary between ice flow from West and East Antarctic Ice Sheets. Letter symbols: AP — Antarctic Peninsula; WS — Weddell Sea; PB — Prydz Bay; WL — Wilkes Land; and RS — Ross Sea. The black rectangles indicate locations of the three largest paleo-channels recognized from seismic section in the present-study area. Modified from [Barker et al. \(1998\)](#).

The presence of giant paleo-channels at the Antarctic continental margin has been known since the 1970's from the work of people like [Tucholke and Houtz \(1976\)](#). Seismic sections from the Weddell Sea and off the Prydz Bay respectively show buried channels with widths of 70 and 80 km ([Kuvaas and Kristoffersen, 1991](#); [Kuvaas and Leitchenkov, 1992](#)). These paleo-channels, as well as the widest channels (>30 km) in the present-study area, are among the largest submarine conduits thus far recognized at the bases of continental slopes, almost incompatible with the channel sizes reported from modern and ancient non-glaciated margins (Fig. 13) ([Clark and Pickering, 1996](#); [Damuth et al., 1998](#); [Cronin et al., 2000](#); [Kolla et al., 2001](#); [Deptuck et al., 2003](#)). Their closest modern analogue might be the gravel-paved valleys, each >20 km wide, recognized on the Laurentian fan at the eastern continental margin of Canada ([Piper et al., 1985](#)).

The “outsized” character of these seismic structures may justify the question as to whether their origin can actually be attributed exclusively to turbidity currents. As pointed out by [Rebesco et al. \(1997\)](#), the spill-over of flows and overbank sedimentation are unlikely to occur

once the channel bank or levee crest becomes elevated several hundred metres above the channel floor. This might suggest that the channel-levee structures are “too deep” and/or “too wide” to have been formed solely by turbidity currents, and that other processes such as contour currents must have contributed to the overbank sedimentation. Such reasoning does not however, take into account the dynamics of a turbiditic channel, including its equilibrium profile ([Ross et al., 1994](#); [Pirmez et al., 2000](#)) and possible polyphase activity.

In a long-term series of turbidity currents, the largest flows will likely determine the maximum size of the channel perimeter. Main overflow will occur at the early stage of channel incision and during the infilling stage of channel-floor aggradation, when the channel capacity is relatively low. As long as large and highly efficient currents occur, these will flush the channel and transfer the sediment far in the basin, thus lowering the local base level and allowing deeper incision. Alternatively, the channel may, instead, be considerably widened to maintain its capacity, as the incision cannot significantly exceed the depth of an equilibrium profile. When the magnitude and transport efficiency of currents decline,

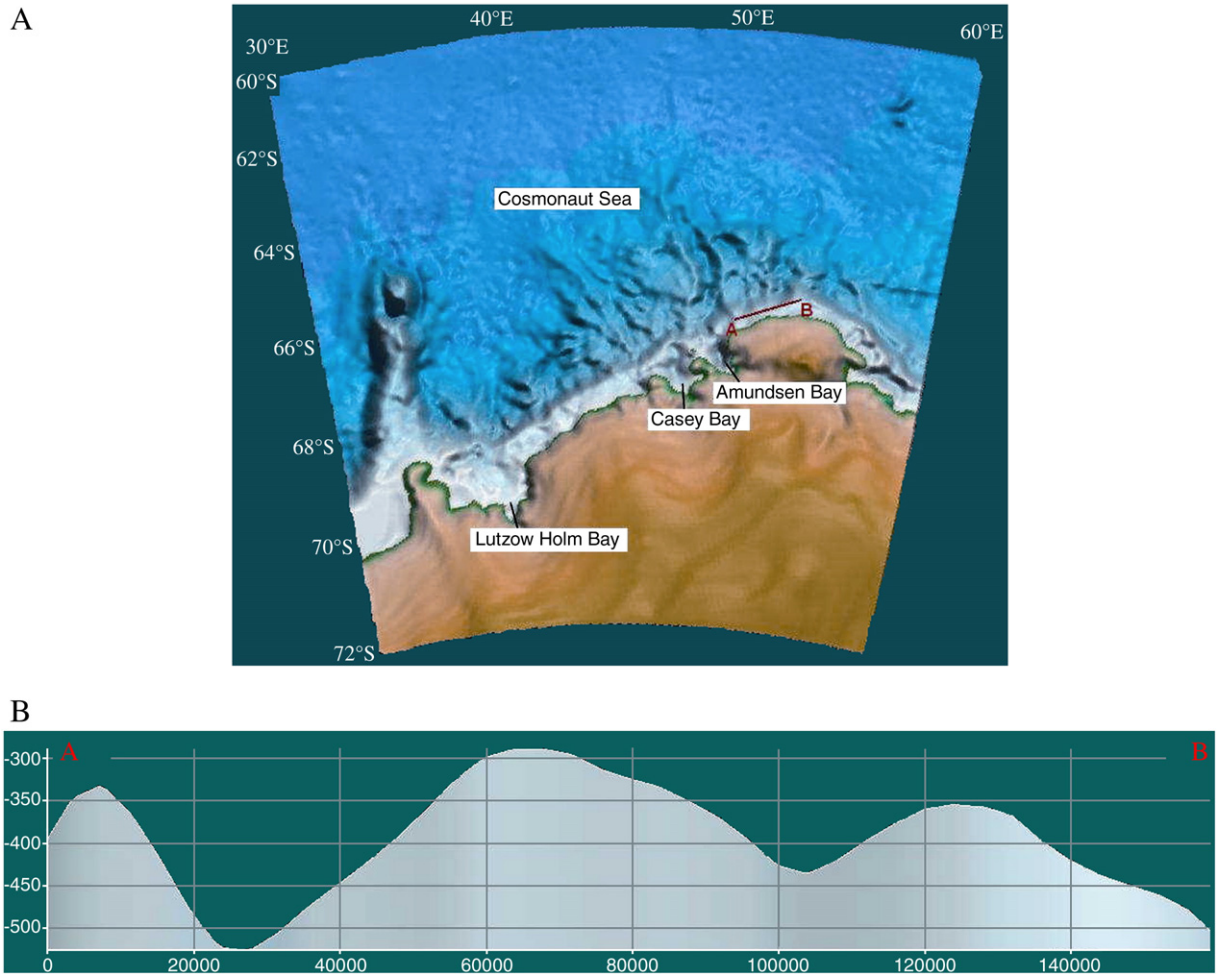


Fig. 12. Bathymetric map of the Cosmonaut Sea (upper part) and a seafloor profile from the continental shelf area east of the Amundsen Bay (lower part; both scales in metres). Note the undulated topography of the continental shelf far outside the sites of present-day ice streams (see also Figs. 2 and 11).

the base level rises and the channel becomes subject to back-filling, accompanied by renewed overflow. In this way, the growth of levees may bear little or no relationship to the channel stage of maximum deepening and/or widening.

Turbidity currents carrying a wide spectrum of grain sizes tend to be strongly density-layered, with the lower part of the flow moving through the channel and scouring its floor/banks, and the upper part spilling out and contributing to the overbank sedimentation (Stow, 1981). A relatively deep channel will minimize the overflow and maximize the current transport efficiency, and may thus remain nearly empty for considerable periods, acting chiefly as a sediment bypass conduit. The high-amplitude subsurface reflectors at the bottoms of many channels suggest coarse-grained deposits, which would be consistent with the wide size range of sediment particles supplied by glacial sources.

A polyphase activity of the same routes of mass-flow transport, as in the present case, may have rescored or virtually erased earlier channels, whereas the levees would bear a cumulative record of the entire overflow history. Notably, many of the levee ridges seem to consist of several storeys (Figs. 3–7), supporting the notion of polyphase channel activity. Successive phases of mass-flow transport could be characterized by an approximately constant maximum depth of channel incision depending on the local slope-to-basin topographic profile, or might alternatively involve its progressive increase or decrease. The levee record of overflows associated with the large, polyphase channels may thus range from very thick to sparse, as observed in the seismic sections.

The presence of high-amplitude reflectors that mimic the seafloor morphology often complicates the interpretation. These prominent changes in reflectivity parallel to the seafloor are widespread (Figs. 3, 7 and 9) and

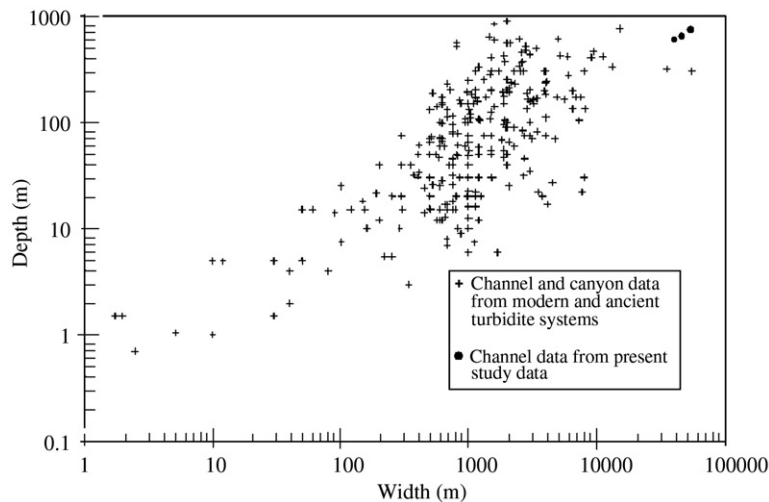


Fig. 13. Plot of the width and depth data from various modern and ancient submarine channels; modified from Clark and Pickering (1996). Since the width/depth aspect ratio commonly varies along the channel axis, the width and depth for the largest cross-sectional area are used to characterize each channel. Channel depth is measured as relief from a mean levee height to the channel floor. The circles represent width/depth data of the three largest paleo-channels identified in the present-study area.

probably a result of diagenetic change deep in the sediments. Such Bottom Simulating Reflectors (BSRs) are commonly found in sub-seafloor deposits of polar regions (Shipboard Scientific Party, 2001; Rebesco et al., 2002; Kuvaas et al., 2004a).

6. Conclusions

The morphology and thickness distribution of inferred glaciomarine deposits in the continental rise zone along the East Antarctic continental margin have been studied from seismic-reflection profiles, and their relationship to the spatial pattern of present-day ice streams has been established. The evidence indicates largely stable coastal positions of the main areas of local ice-stream convergence throughout the Neogene period of the Antarctic Ice Sheet advances and retreats, which resulted in distinct deep-water depocentres with large paleo-channels. Scattered paleo-channels and subordinate depocentres in the Cosmonaut Sea indicate that some of the coastal ice streams occasionally changed their position or that the ice-sheet margin episodically involved also other ice streams during the earlier glacial maxima.

Several paleo-channels have prominent levees and are >30 km wide and >500 m deep. The largest paleo-channel, found in the Riiser-Larsen Sea, is about 40 km wide and 1000 m deep. These giant structures are considered to be formed by a polyphase activity of the same mass-flow routes for glaciogenic sediment transport

from the shelf edge and upper slope to the base of slope and adjoining abyssal plain.

The continental margin apparently acted as a line-type sediment source with a strong multi-point supply from ice streams. Downslope transport by sediment gravity flows predominated at the margin, with a subordinate role of along-slope sediment drift by contour currents. In the western part of the Cooperation Sea the seafloor morphology and associated sedimentary structures may possibly indicate a stronger influence from along-slope processes.

It was probably the wide grain-size range of glaciogenic sediment and the high rate of the sediment supply by ice streams to the shelf edge that resulted in the long series of large and highly efficient turbidity currents. Recharging of ice streams with terrigenous detritus allowed enormous amounts of glaciogenic sediment to be transferred from the Antarctic interior to the adjacent deep-water basins through successive glacial and interglacial phases.

The study demonstrates that a seismostratigraphic mapping of deep-water depocentres and recognition of paleo-channels along a glaciated continental margin may be an important source of information on the ice-sheet dynamics, especially on the coastal pattern of ice drainage represented by ice streams. The largest channels may indicate outlets of the largest local ice streams, whereas the main depocentres with polyphase channels can serve as an indication of a long-term stability of the ice-stream position during the successive ice-sheet advances. Drill cores from the highest, multi-storey levees, rather than

from channel-fill deposits, might provide a high-resolution stratigraphic record of the resedimentation pulses and ice-front behaviour.

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