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A seismo-stratigraphic analysis of glaciomarine deposits in the eastern Riiser-Larsen Sea (Antarctica)

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Abstract Multichannel seismic data from the eastern parts of the Riiser-Larsen Sea have been analyzed with a sequence stratigraphic approach. The data set covers a wide bathymetric range from the lower continental slope to the abyssal plain. Four different sequences (termed RLS-A to RLS-D, from deepest to shallowest) are recognized within the sedimentary section. The RLS-A sequence encompasses the inferred pre-glacial part of the deposits. Initial phases of ice sheet arrival at the eastern Riiser-Larsen Sea margin resulted in the deposition of multiple debris flow units and/or slumps on the upper part of the continental rise (RLS-B). The nature and distribution of these deposits indicate sediment supply from a line or a multi-point source. The subsequent stage of downslope sediment transport activity was dominated by turbidity currents, depositing mainly as distal turbidite sheets on the lower rise/abyssal plain (RLS-C). We attribute this to margin progradation and/or a more focussed sediment delivery to the continental shelf edge. As the accommodation space on the lower rise/abyssal plain declined and the base level was raised, the turbidite channels started to backstep and develop large channel–levee complexes on the upper parts of the continental rise (RLS-D). The deposition of various drift deposits on the lower rise/abyssal plain and along the western margin of the Gunnerus Ridge indicates that the RLS-D sequence is also associated with increased activity of contour currents. The drift deposits overlie a distinct regional unconformity which is considered to reflect a major paleoceanographic event, probably related to a Middle Miocene intensification of the Antarctic Circumpolar Current.

Keywords Antarctica · Debris flows · Deep-sea deposits · Riiser-Larsen Sea · Seismics · Turbidites

Introduction

The eastern Riiser-Larsen Sea constitutes a relatively ''new'' region of the circum-Antarctic margin in terms of seismic data availability. Recent efforts in the area (Kuvaas et al. 2004a, b) have mainly focussed on the description of main morphological elements and the interpretation of prominent seismic facies in terms of processes. These initial studies emphasized a need for further seismic investigations in order to improve the spatial stratigraphic resolution of the sedimentary record and to increase our understanding of the dynamics of deep-marine sedimentation in the region.

In this paper, we perform a more detailed subdivision of the seismic stratigraphic record, studying the depositional patterns in the eastern part of the Riiser-Larsen Sea. Here we focus on the inferred glacial part of the depositional evolution and provide inferences about the nature and timing of the Cenozoic events. The seismo-stratigraphic setting in the Riiser-Larsen Sea is compared to adjacent regions of the circum-Antarctic margin in order to highlight

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similarities/differences in the development of the respective sediment records.

A distinct regional unconformity termed Riiser-Larsen Sea-4 (RLS-4) is believed to represent the boundary between glacial- and pre-glacial deposits. The seismic character of the deposits stratigraphically above this surface indicates a higher energy environment and enhanced terrigenous supply from the continent when compared to the deposits below (Kuvaas et al. 2004a, b). The sedimentary growth patterns of the margin are considered to be closely related to the glacial history of the adjacent continent from the time of the formation of this unconformity, and may hence improve our understanding of the Antarctic ice sheet history.

The seismic data

This study is based on approximately 5000 km of multi-channel seismic data available in the eastern part of the Riiser-Larsen Sea (Fig. 1). The data were acquired by the Polar Marine Geoscience Expedition (PMGE) in 1998 and through a joint project between PMGE, the Norwegian Petroleum Directorate and the University in Bergen from 2002 to 2004. The seismic source con-

sisted of two airgun arrays with a total volume of 40 l towed at 4–6 m depth. The signal was recorded by a 72-channel (96 in 1998) hydrophone cable with 25 m group length, at an average water depth of ca. 12 m. The cable was towed deep due to frequent adverse weather conditions and the corresponding spectral notch limited the frequency content to less than 65 Hz. The shot point interval was 50 m. The data were edited and sorted and their velocity analysis carried out at 7–10 km intervals. The stacked traces were mixed and zero-phase deconvolution, bandpass filter and automatic gain control were applied before data display.

The prevailing sea-ice conditions resulted in limited seismic coverage of the continental shelf and the upper continental slope. The study thus focuses on the deposits located on the lower continental slope, the continental rise and the abyssal plain of the eastern Riiser-Larsen Sea (Fig. 1).

Regional setting

The Riiser-Larsen Sea passive continental margin segment is situated off the Princess Ragnhild Coast of East Antarctica and is bounded to the east and west by prominent basement ridges (Fig. 1). The Astrid Ridge
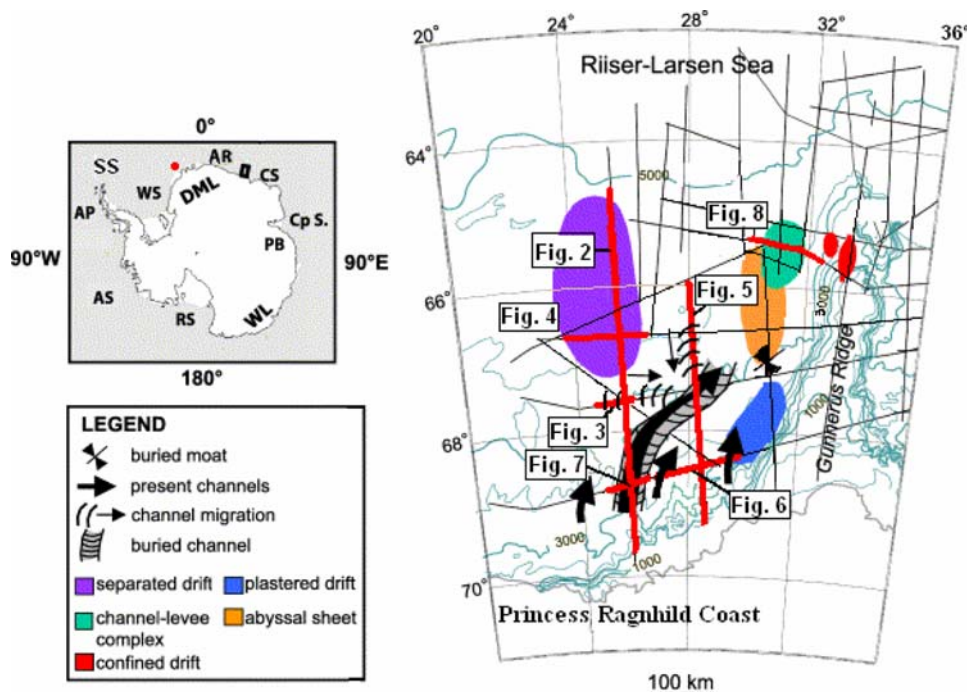

Fig. 1 Bathymetry map of the study area showing some of the main sedimentary units and the location of the seismic lines. Bold red lines correspond to the multi-channel seismic sections illustrated in Figs. 2–8. Subset map to the left indicates the location of the study area (black rectangle). The red circle in the subset map indicates the location of Site 693. AP: Antarctic Peninsula, SS: Scotia Sea, WS: Weddell Sea, DML: Dronning Maud Land, AR: Astrid Ridge, CS: Cosmonaut Sea, Cp S: Cooperation Sea, PB: Prydz Bay, WL: Wilkes Land, RS: Ross Sea, AS: Amundsen Sea. (Modified from Kuvaas et al. 2004a)

constitutes the western demarcation of the depositional basin and is located at 10–15°E longitudes off Dronning Maud Land. The Gunnerus Ridge, roughly aligned following the 34°E meridian, marks the eastward extent of the depositional basin (Fig. 1). The ridge has a water depth of 500–1500 m and is considered to be a fragment of continental crust (Roeser 1996), isolated from the main Antarctic continental margin after the Gondwana break-up, during the Cretaceous. The Riiser-Larsen Sea and the Mozambique Basin were created as conjugate spreading compartments in the Late Jurassic to the Early Cretaceous time (Marks and Tikku 2001).

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 includes the westward circumpolar flow of the Antarctic Coastal Current and the eastward flow of the more distal Antarctic Circumpolar Current. Despite occurring in a deep bathymetric zone, the latter current may at least locally affect the entire water column (Foldvik and Gammelsrød 1988). The Circumpolar Deep Water represents the dominant water mass in the Southern Ocean (Carmack 1990), extending from ca. 250 to 4000 m depth and flowing around the continent in a counter clockwise direction. The Antarctic Bottom Water encompasses dense water masses produced on the continental shelf that spills over the shelf-edge and into the basins. Significant production of Antarctic Bottom Water is to the best of our knowledge not reported in the Riiser-Larsen Sea. Neelov et al. (1998), identified westward flowing bottom waters along the continental slope of the eastern Riiser-Larsen Sea.

Although recent studies (Barrett 2003; Macphail and Truswell 2004; Cooper and O'Brien 2004) indicate an age of 34 Ma for the first inception of an Antarctic Ice Sheet, we know little about the nature and timing of the first arrival of ice sheets to the different sectors of the Antarctic continental shelf. In addition, the Late Paleogene and Neogene general cooling period did not proceed uniformly; with the δ^{18} O record exhibiting a number of steps and peaks reflecting episodes of global warming and cooling (Grützner et al. 2005; Zachos et al. 2001). Ice sheet models presented by Huybrechts (1993) and DeConto and Pollard (2003), indicate that the Riiser-Larsen Sea would have been one of the first marginal basins to be affected by an expanding ice sheet. This implies that a long-term record of the East Antarctic ice sheet history can be expected in the study area.

Seismic sequences

The seismo-stratigraphic subdivision is based upon acoustic character and stratal geometry. We recognize four different sequences within the sedimentary succession below the sea floor (Figs. 2–8). The sequences are termed RLS-A–RLS-D, from the deepest to the shallowest. The unconformities bounding these sequences are termed RLS-4–RLS-6, from the deepest to the shallowest. The lowermost sequence (RLS-A) encompasses all sediments situated between the acoustic basement and a distinct unconformity marking the base of glaciomarine deposits (RLS-4) (Kuvaas et al. 2004a, b). This sequence, which is considered to be of pre-glacial origin, will be treated as one unit. Detailed seismic analyses in this part of the sedimentary succession are not considered within the scope of the study (see introduction).

RLS-A

At the base of the sequence we observe discontinuous infilling between basement highs (Figs. 2–5). The infill is sometimes faulted (Fig. 3), but mostly occurs as well-stratified units that onlap the sides of isolated basement highs or wider basement plateaus. Sub-parallel, low and high amplitude reflectors that can be traced over long distances dominate the internal acoustic character in the middle and upper parts of the sequence (Figs. 2–5). The continuity of the reflectors decreases somewhat towards the top. Tracing of the high-amplitude reflectors outlines a laterally extensive tabular unit overlain by more irregular reflector configurations (Figs. 3 and 4). The upper parts of the sequence also contain sedimentary units with a convex shape. The convex units display radial thinning towards the north, east and west (Figs. 2–4), with local evidence of internally downlapping reflectors (Fig. 4). The thickness of the sequence gradually decreases from the upper part of the continental rise to the abyssal plain (Figs. 2 and 5). There are no clear indications of scour-and-fill features within this seismic sequence.

RLS-B

Overlying the RLS-4 unconformity we observe a number of lens shaped sedimentary units at the base of the continental slope and on the upper/middle part of the continental rise (Figs. 2–6). The lenses display aggradational to progradational stacking patterns (Figs. 2, 5) and are quite variable in size. The widths of these depositional structures are usually in the range of 10–50 km, but the down-slope length of some of the most elongated features may exceed 100 km (Fig. 5).
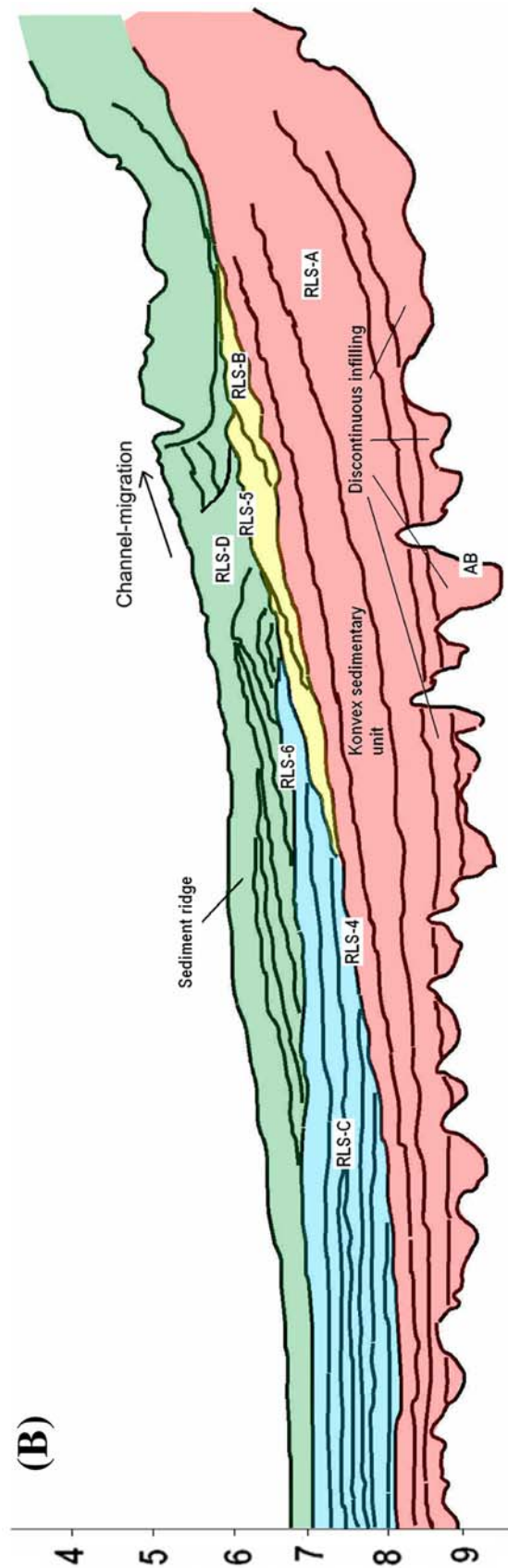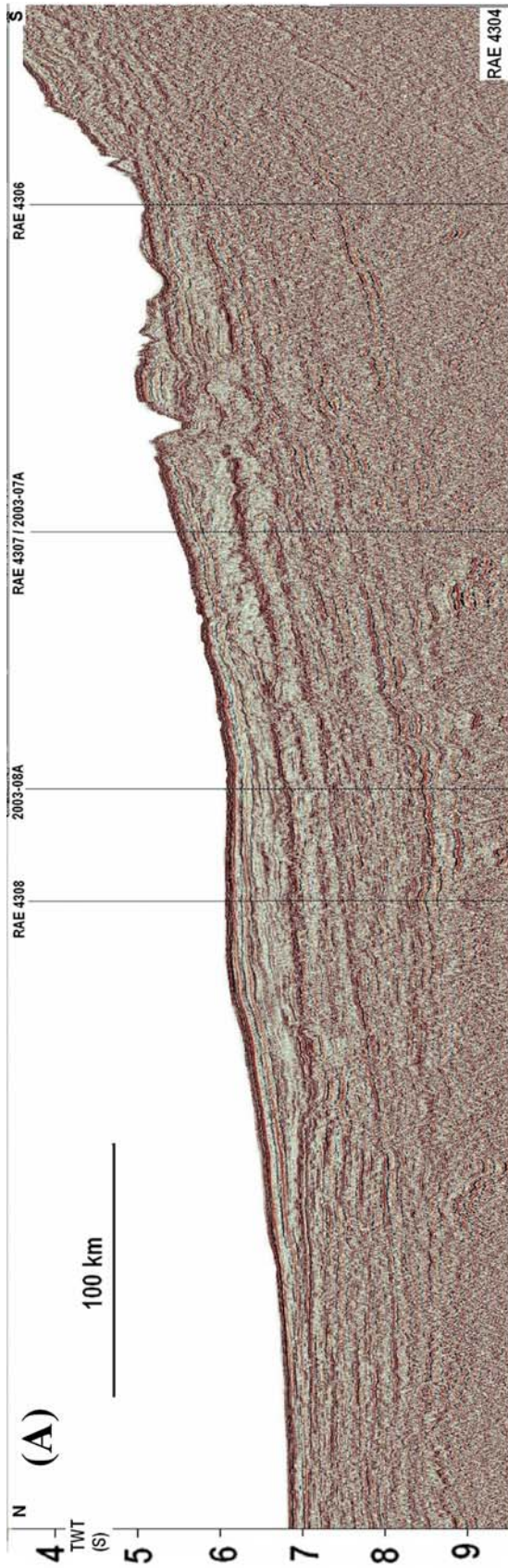
Fig. 2 (**A**) The seismic profile RAE 4304 oriented perpendicular to the continental margin (for location, see Fig. 1). (**B**) Line drawing of profile RAE 4304. Sequence RLS-A (red), sequence RLS-B (yellow), sequence RLS-C (blue) and sequence RLS-D (green)
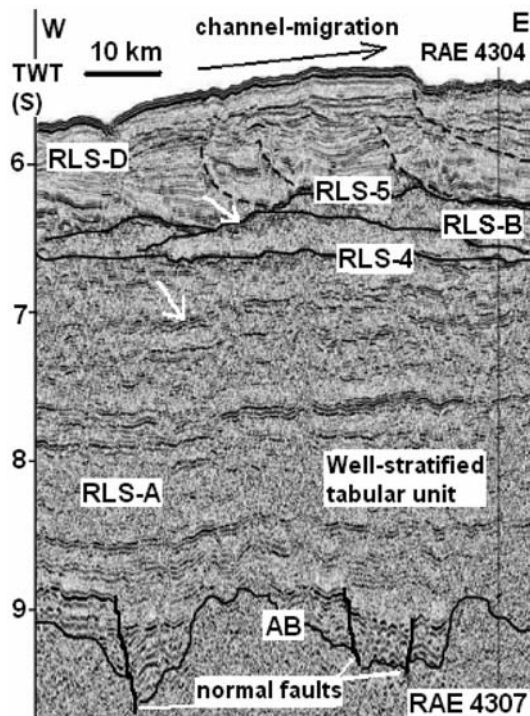
Fig. 3 The seismic profile RAE 4307 oriented sub-parallel to the continental margin (for location, see Fig. 1). Dashed black lines indicate the margins of fragmented scour-and-fill facies. The uppermost white arrow indicates a chaotic facies near the top of a lens shaped unit. The lowermost white arrow indicates a westward dipping reflector, corresponding to the top of a convex sedimentary unit

Strike parallel profiles on the upper and middle part of the continental rise reveal both larger mounds with overlapping lens-bodies and isolated lens features. A semi-transparent to transparent internal acoustic character predominates (Figs. 2–6), but chaotic facies are also locally present. The chaotic facies occurs directly below the base of scour-and-fill features (see RLS-D) and at the top of the transparent facies (Fig. 3).

The top of the sequence is marked by a highly reflective seismic interface (RLS-5), which onlaps the underlying (RLS-4) unconformity at the base of the continental slope and appears to be terminated by downlap onto the same unconformity in the distal parts (Figs. 2, 5). A highly irregular apparent morphological relief characterizes this seismic interface and the thickness of the sequence varies laterally from 0 to 0.5 (s) TWT (Figs. 3, 4, 6).

RLS-C

Extensive well-stratified units dominate the deposits that overlie the RLS-4 unconformity on the lower continental rise and the abyssal plain. Internal reflectors are of low to medium amplitude, and tracing of the reflectors in a landward direction indicates onlapping terminations (Figs. 2 and 5). The reflectors within the lower part of the succession onlap the RLS-4 unconformity, while reflectors in the

Fig. 4 The seismic profile NPD 2003-08 oriented sub-parallel to the continental margin (for location, see Fig. 1). The grey lines outline the konvex sedimentary unit. Internal reflectors are well-stratified on the eastern side, but show downlapping terminations towards the west
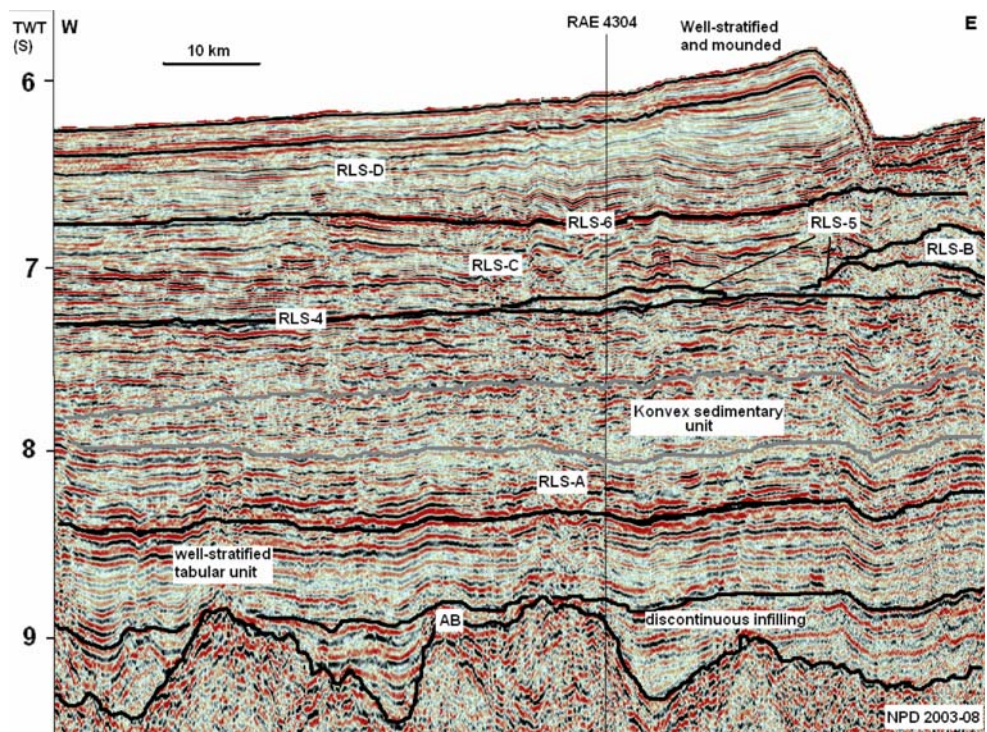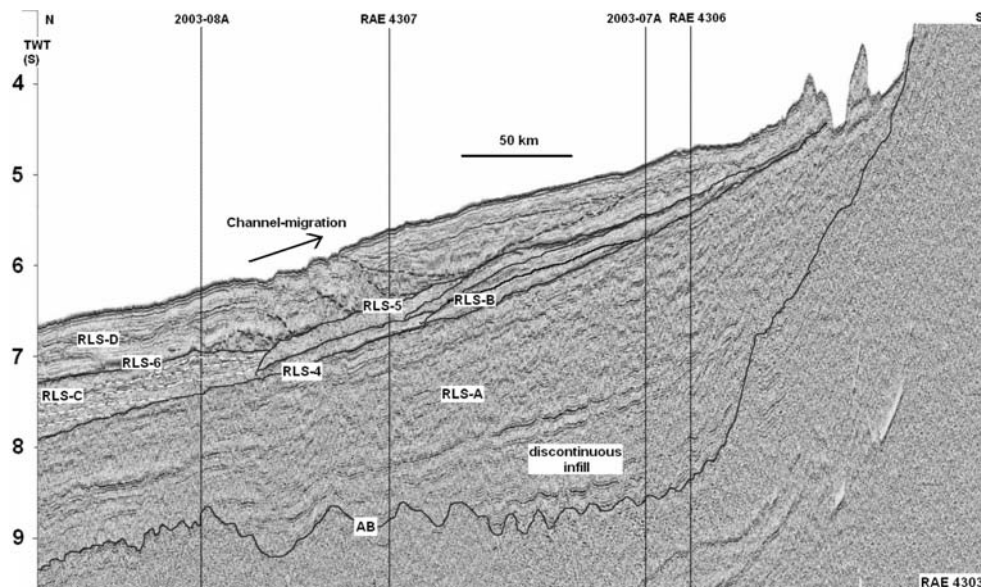
Fig. 5 The seismic profile RAE 4303 oriented transverse to the continental margin (for location, see Fig. 1). Dashed black lines indicate the margins of scour-and-fill facies. Dashed white lines indicate sub-parallel reflectors within the RLS-C unit

upper part onlap the lens shaped structures within the RLS-B sequence (Figs. 2 and 5). The units are relatively uniform, but locally reflections may be undulating or nearly transparent. In a few locations we observe scours (width around 100 m, Fig. 4). The unconformity formed at the top of this succession (RLS-6) is either dipping gently or nearly flat (Figs. 2, 4 and 5).

RLS-D

The uppermost unit displays a mixture of seismic facies, where well-stratified units predominate. The well-stratified units are often mounded and may be categorized based on their association to scour-and-fill features.

On the upper/middle part of the continental rise, two types of high amplitude well-stratified facies occur in direct association with large scour-and-fill features: (i) non-parallel or sub-parallel stratified facies and (ii) parallel stratified facies (Fig. 7). The non-parallel facies occur on either side of the scours and show reflectors that converge away from the scour-margins (Fig. 7A). The margins are outlined by erosive and diachronous seismic surfaces and often develop U-shapes that can be tens of km wide (Figs. 6, 7A). In some zones the scour-and-fill features appear to be fragmented (Figs. 2, 3, 5). The largest mounds are usually observed on the western side of the scours (Fig. 6).

In distal parts of the margin we recognize well-stratified facies unrelated to scour-and-fill features. These seismic facies overlie the nearly flat RLS-6 unconformity, which is characterized by minor local erosion (Figs. 2, 4, 5), and are sometimes organized
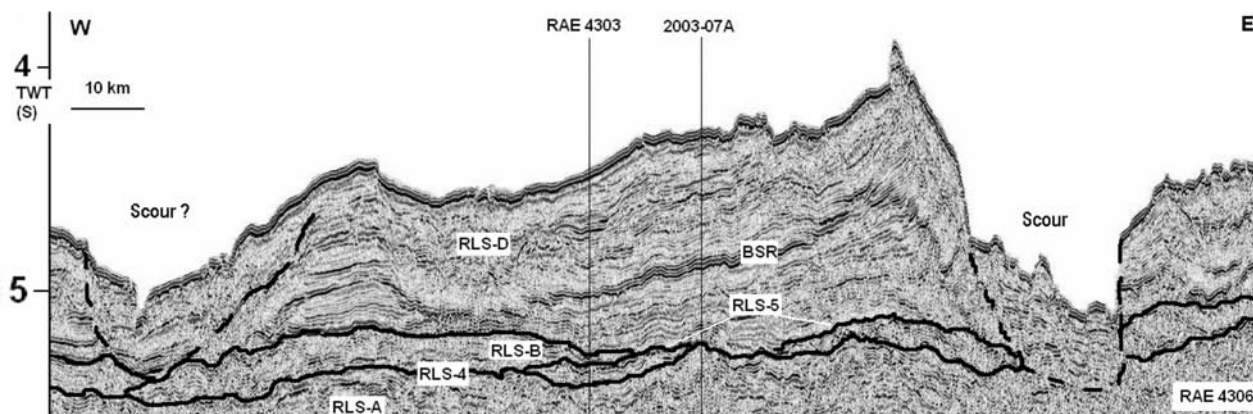
Fig. 6 The seismic profile RAE 4306 oriented sub-parallel to the continental margin (for location, see Fig. 1). Dashed black lines indicate the margins of large U-shaped scours. BSR: Bottom Simulating Reflector

Fig. 7 Large channel–levee complex in the Riiser-Larsen Sea. (**A**) Well-stratified non-parallel reflectors indicating levee deposition. (**B**) Well-stratified parallel reflectors indicating channel fill deposits. LAP: Lateral Accretionary Package. BSR: Bottom Simulating Reflector (for location, see Fig. 1)
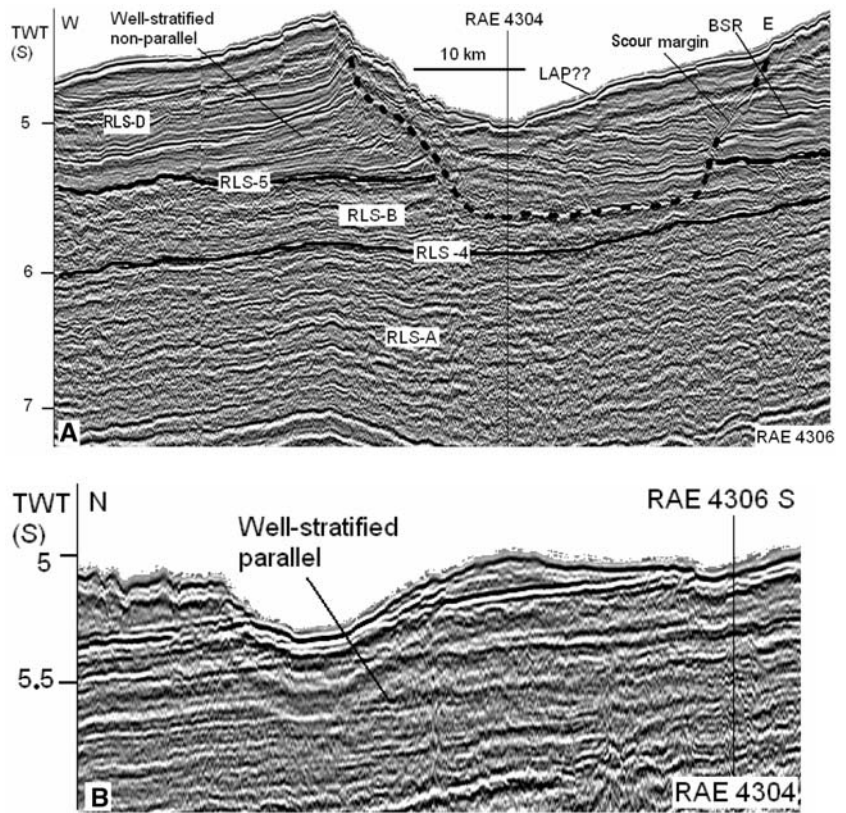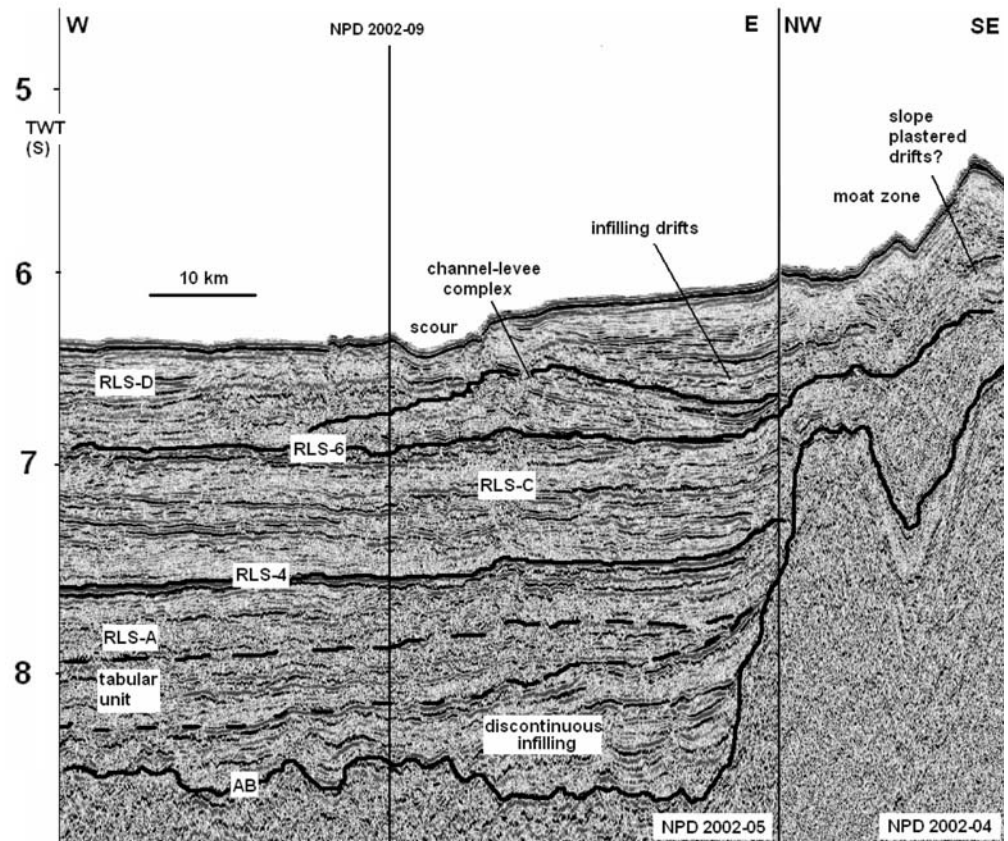

Fig. 8 The seismic profiles NPD 2002-05 and NPD 2002-04 (for location, see Fig. 1), showing the depositional features along the western margin of the Gunnerus Ridge

into larger sediment mounds. The giant sediment ridge situated on the abyssal plain of the eastern Riiser-Larsen Sea (Figs. 1, 2, 4) rises up to ca. 850 m above the surrounding seafloor surface (Kuvaas et al. 2004a). It is elongated in a north-south direction and shows an internal seismic pattern of parallel to sub-parallel reflectors. The stacking pattern of the internal layers indicates northward progradation (Fig. 2). The ridge is asymmetrical, with a steeper eastern side (Fig. 4).

Several of the sediment mounds display a strong discontinuous reflection ca. 0.4–0.5 s (TWT) below the seafloor. The reflection follows the topography of the sea-bottom. This Bottom Simulating Reflector (BSR) is of the same polarity as the seafloor surface and appears to cut through the internal layering of the mounds (Figs. 6, 7A).

Interpretation and discussion

The seismic stratigraphy of deposits across the continental margin of the eastern Riiser-Larsen Sea indicates a stepwise development in which a range of seismic facies is identified. The distribution and character of these facies suggest influence from various depositional processes throughout the evolution of the margin. The significance of the seismic sequences and bounding unconformities is evaluated in a four-step model:

The four-step model

Step 1: deposition of the pre-glacial unit

Continental break-up leads to formation of a highly irregular acoustic basement and control pathways of initial sediments supplied to the evolving basin. This is reflected by the strong discontinuity observed within the lowermost deposits. Gravity flows, probably with contribution from hemipelagic deposition, infilled topographic lows and covered successively deeper regions (Figs. 2, 5). Locally, the well-stratified units were affected by subsequent faulting (Fig. 3). Following this stage of infilling and smoothing of the margin relief, we observe a transition into more continuous reflector configurations. The well-stratified, sheeted deposits (laterally extensive tabular unit) may either correspond to the distal parts of a turbidite system or sheeted contourite drifts (Faugeres et al. 1999; Maldonado et al. 2005). The main way to distinguish seismic reflections of these types of contourite and turbidite deposits is with their associated depositional bodies (Maldonado et al. 2005). While turbidite basin plain deposits have associated feeder channels (Twichell et al. 1992; Nelson et al. 1992), the sheeted contourite drifts are flanked by other contourite drifts such as elongate-mounded drifts and plastered drifts (Maldonado et al. 2005).

At this stratigraphic level (RLS-A), the sheeted deposits show onlapping terminations against the western margin of the Gunnerus Ridge (Fig. 8). The deposits do not appear to be associated with well-developed moats or mounded depositional bodies elongated along the continental slope. This suggests that the well-stratified seismic reflection pattern corresponds to distal turbidites, probably alternating with hemipelagic deposits. The transition into more irregular reflection patterns (stratigraphically above) with slightly convex sedimentary units may hence reflect progradation of the continental margin and the deposition of turbidite lobes. Due to a sparse seismic coverage of the continental slope we have not been able to determine if these deposits can be associated with feeder channels.

Step 2: Onset of glacially derived sedimentation

The distinct RLS-4 unconformity marks an upward transition from parallel and sub-parallel reflector configurations to a much more diversified reflection pattern above (Figs. 2–6). This prominent change is considered to reflect the enhanced terrestrial input to the deep-sea from erosion by a growing East Antarctic Ice Sheet (Kuvaas et al. 2004a, b). The accumulation of lens shaped deposits on upper parts of the continental rise indicates that large volumes of sediment were delivered to the outer shelf and upper continental slope during this early phase of ice sheet expansion on the continent. This led to slope instability and triggered numerous gravity flows. The transparent facies is interpreted as debris flows or slumps, whereas the chaotic facies is interpreted as the acoustic image of the top of these sedimentary units, as described elsewhere along the Antarctic margins (Michels et al. 2002; Melles and Kuhn 1993).

The recognition of several local depocentres of variable size indicates that the sediment supply was laterally variable. We hence suggest that the ice sheet acted as a multi-point source during this initial phase (Reading and Richards 1994). Alternatively, if the ice sheet acted more as a line source, some sections of the continental slope would have to be more failure prone than others. The widespread distribution of lens shaped units across the upper part of the continental

rise is considered to reflect sediment input from an immature and highly dynamic Antarctic Ice Sheet, in which large parts of the ice sheet front expanded to the shelf edge during glacial periods. Even though the upward change in acoustic character suggests a significant increase in the supply of sediments to the shelf edge, the subsequent gravity flows settled in rather proximal parts as the upper/middle part of the continental rise and the lower slope. The acoustic character of the deposits indicates that the gravity flows did not evolve into organized turbidity flows. This observation supports the impression of a scattered sediment supply to the outer shelf and upper slope during the early stages of the glaciation. The RLS-4 unconformity that was developed during this phase is characterized by widespread erosion on the proximal margin and non-deposition in the distal parts.

Step 3: An organized sediment supply to the shelf edge?

The up-slope onlapping terminations of the thick RLS-C sequence indicate that the accumulation of debris-flow deposits (and/or slumps) on the upper rise was followed by a period with significant deposition in the distal parts of the continental margin, rendering the RLS-4 unconformity a time transgressive surface. The continuous and slightly sub-parallel reflector configurations are incised by small scours and can be associated with much larger scour-and-fill structures on upper parts of the continental rise (see step 4). These deposits were probably emplaced over a period when persistent turbidity flows dominated the depositional setting. The irregular surface topography of the lower slope/upper rise is considered to have played an important role in constraining these initial turbidity currents. This is suggested by the formation of large channel–levee structures (see step 4) in between the previously deposited lenses (Fig. 6). The added effect of erosion and initial overflow allowed most of the sediment to be spilled out as broad sheets on the lower rise where there was an abundance of accommodation space. As long as there was accommodation space available, highly efficient turbidity currents flushed the channels and transferred sediment far in the basin. The deep incision of some of the channels (eastern part of Fig. 6) is probably related to this stage characterized by polyphase activity and a high channel capacity.

The seismo-stratigraphic framework indicates that the continental margin underwent a major architectural change from step 2 to step 3, which is considered to reflect the transition towards a more organized sediment supply from the interior of the continent to the shelf edge. Progressively colder climatic conditions

(Barrett 1996) may have led to decreasing amounts of subglacial meltwater and less dynamic conditions within the Antarctic Ice Sheet. The net result of which is a more restricted type of ice flow. We speculate that sediment transport within ice streams was dominant during this phase and that the sediment supply from the continent to the outer shelf/upper slope was focussed within such corridors of rapid ice movements (Bentley and Giovinetto 1991; Bamber et al. 2000). This caused local slope instabilities and triggered gravity flows that evolved into larger volume turbidity currents and settled mainly as distal turbidite sheets. Alternatively, the initial glaciation (Step 2) was associated with a significant progradation of the continental shelf-edge that allowed subsequent gravity flows to reach the distal parts of the margin. Regrettably, no seismic profile in the eastern Riiser-Larsen Sea crosses the continental shelf, and hence it is not possible to verify the presence of such a progradational pattern of reflectors typical of many Antarctic margins (Solheim et al. 1991; Eittreim et al. 1995).

Step 4: Channel-backstepping and increased bottom current activity

The mapping and spatial association of the well-stratified facies directly associated with scour-and-fill features in sequence RLS-D indicate that they are deposited as parts of large channel–levee complexes (Kuvaas et al. 2004a). The common attributes of such structures involve both (i) non-parallel layers that thicken towards the channel axes (levees, Fig. 7A.) and (ii) well-stratified, parallel units that may signal channel-fill (Fig. 7B). Notably, many of the levee ridges seem to consist of several storeys (Figs. 6, 7), supporting the notion of a polyphase channel activity. Such a polyphase activity of the same routes of mass-flow transport, may have rescoured or virtually erased earlier channels, whereas the levees would bear a cumulative record of the entire overflow history. The infilling is often planar (Fig. 7, eastern side of Fig. 3) and indicative of turbidites.

We infer that the transport efficiency of the turbidity currents declined in response to the infilling of accommodation space on the lower rise. Raised base levels forced the equilibrium profile of the channels to readjust and subjected the channels to back-filling and renewed overflow. A high percentage of the deposition was relocated to the upper/middle part of the continental rise and resulted in the development of large levees (preferentially to the west of the channels) and widespread channel migration. The fragmentation of scour-and-fill features is considered a result of channel

migration (Kuvaas et al. 2004a). The larger western levees and the eastward migration of channels can be attributed to the influence of the Coriolis force (Gill 1973). In the southern hemisphere, if the flow is directed downslope as for turbiditic systems, the turbidity currents are deflected to the west. Where they reach the continental rise or where channel relief has diminished sufficiently, they preferentially overflow the western flank of the channel and build up a prominent levee on this side. With continued preferential deposition to the west, the channel and levee both tend to migrate towards the east so that the channel–levee system becomes oriented more and more oblique to the margin (Faugeres et al. 1999). The internal package of laterally-inclined reflectors within the channel in Figure 7A may be similar to the Lateral Accretionary Packages (LAPs) of Abreu et al. (2003) and indicate a bending channel (see also Fig. 1).

The well-stratified facies on the lower rise/abyssal plain overlie a more or less flat, erosion surface (RLS-6) and cannot exclusively be attributed to downslope processes. These deposits show features consistent with an influence from topographically controlled bottom currents:

The giant elongated sediment ridge was initially formed near the western margin of a large channel–levee complex (Figs. 1, 2), and it is possible that the uppermost parts of the ridge represent abandoned levees. The two sedimentary features were however gradually separated as the channel–levee system migrated eastwards and the sediment ridge was built out towards the north (Figs. 1–3). We hence suggest that contour currents controlled the deposition of the elongated sediment ridge, pirating sediment load from coeval turbidity currents. The steeper eastern side of the sediment ridge indicates that westward flowing bottom currents are being deflected northwards along this side. Following the definitions of Stow et al. (2002), Kuvaas et al. (2004a) interpreted the giant elongated sediment ridge as a separated drift. They also recognized other drift structures along the western slope of the Gunnerus Ridge such as plastered drifts and confined drifts (Fig. 1). These deposits also overlie the laterally extensive RLS-6 surface.

The well-stratified deposits filling in the topographic depression between a channel–levee complex (see Fig. 1 and Kuvaas et al. 2004a) and the RLS-6 surface are truncated to the southeast by a moat-zone (Fig. 8). The deposits show a north to south direction of progradation, consistent with southward flowing bottom currents. We hence interpret these deposits as infilling drifts (Stow et al. 2002). On the eastern side of the moat-zone (Fig. 8) we observe mounded deposits with an internal

pattern of reflectors indicating upslope migration. These deposits may represent slope plastered drifts.

Based on these observations the RLS-6 surface is interpreted to correspond to an important hydrological event which accompanied the initiation of active bottom-water circulation in the basin. The surface is considered to be the same age over its full extent. Suspended materials from turbidity currents were probably abundant at this stage and promoted the growth of various drift structures. Such basal erosion surfaces overlain by mounded drifts are reported from several continental margins. Good examples include the Hatteras, Blake, Feni, Faro, Guadalquivir and Marion Drifts in the Atlantic Ocean (Faugeres et al. 1999). This also suggests that the increased activity of bottom currents on the lower rise/abyssal plain and along the western margin of the Gunnerus Ridge was coeval with the main phase of levee formation and channel migration on the middle/upper rise. Consequently, the hydrological event and subsequent formation of drifts may at least be partially responsible for modifying turbidity current deposition by inducing release of a relatively larger part of their load in more proximal regions as well as enforcing new pathways in response to the changing sea-floor topography. This is supported by the findings of Kuvaas et al. (2004a). Their bathymetry map of the study area, which also contains the main sedimentary units (Fig. 1), clearly indicates that one of the channel–levee systems may have migrated eastwards in response to the growth of the large separated drift.

The Bottom Simulating Reflector (BSR)

The strong reflector that appears to cut through the internal layering of several mounds and follows the sea-floor topography represents a bottom simulating reflector (BSR). Bottom simulating reflectors may indicate gas hydrate or the diagenetic transformation of opal A to opal CT (Hammon and Gaither 1983).

Gas hydrates are commonly found in sub-seafloor deposits in polar regions, where the pressure and temperature combine to render them stable (Andreassen et al. 2003). The hydrates are crystalline compounds in which ice expands to form cages containing methane gas molecules (Grauls 2001). The BSR in such a case would occur at the base of the hydrate bearing sediments with weaker reflections above due to cementation by the gas hydrate. This characteristic weakening of reflectors above the BSR is not observed in the present case. The BSR should also have a phase inversion (Andreassen et al. 2000), which is not observed. We therefore attribute this feature to the dia-

genetic change of biogenic silica rather than gas hydrates.

Ocean Drilling Program Leg 188 at Site 1165 drilled a sediment ridge in the Cooperation Sea off Prydz Bay (Fig. 1) with a strong BSR ca. 600 m below the seafloor. An excellent record of siliceous microfossils was found down to this transition, where biogenic opal disappears because of an opal A to opal CT diagenetic transition (Shipboard Scientific Party 2001).

Comparison to other continental margin segments

The stratigraphic evolution of Cenozoic deposits along segments of the Antarctic continental margin is considered to be closely related to the history of the adjacent Antarctic Ice Sheet (Barker et al. 1998). However, in remote regions such as Antarctica where the continental margin is still sparsely sampled, it is especially challenging to decipher the geological and geophysical observations in terms of climatic or tectonic processes. Under this premise we have compared the stratigraphic development in the Riiser-Larsen Sea to other key segments of the Antarctic continental margin and tentatively estimated a relative age for some of the main events.

The eastern Weddell Sea

The depositional patterns observed in the eastern part of the Weddell Sea (Fig. 1) stands out as an important analogue for several reasons:

(1) The ice sheet model by DeConto and Pollard (2003) indicates a contemporaneous glacial onset in the two regions. If this model holds true the RLS-4 unconformity might have been formed approximately at the same time as a major (Early Oligocene) unconformity in the Weddell Sea. This unconformity, which was labelled W4 (after Miller et al. 1990), represents the transition from pre-glacial to glacial sediments and is associated with a reflection that can be traced over large areas (Kuvaas and Kristoffersen 1991). The timing of the RLS-4 event must however be regarded as highly uncertain. Given that the global deep-sea δ^{18} O record indicates the occurrence of two important cooling events during the Oligocene (Zachos et al. 2001). Also, the regional stratigraphic correlations of Kuvaas et al. (2004b) suggested that the RLS-4 unconformity might not have been formed until the Middle Miocene.

(2) The seismic stratigraphies on the two margins share many of the same characteristic acoustic and geometric features and the deposition on the respective continental rises appear to have progressed in a similar manner. The early glaciomarine deposits in the eastern Weddell Sea are characterized by the occurrence of numerous lenticular bodies that are acoustically transparent, mixed with high-amplitude, moderately continuous reflectors (Michels et al. 2002). This seismic reflection pattern verifies the notion of widespread activity of debris flows during the early stages of the Antarctic glaciation. The mixing with high-amplitude, moderately continuous reflectors might suggest that the debris flows were accompanied by the deposition of turbidite sheets and/or hemipelagic deposits.

(3) The regionally extensive reflector (W5), formed (in the Weddell Sea) at the top of the early glaciomarine deposits, is correlated with a Middle Miocene unconformity at ODP Site 693 (Fig. 1, Kuvaas and Kristoffersen 1991) and marks an increased influence from contour currents (Miller et al. 1990). Its position at the base of several wedge-shaped levees suggests that the bottom-current activity was accompanied by turbidity flows. The deposition above W5 is similar to sequence RLS-D in the Riiser-Larsen Sea and indicates an interplay between along-slope and downslope processes. We speculate that the W5 unconformity in the Weddell Sea and the RLS-6 unconformity in the Riiser-Larsen Sea might be directly or indirectly related to a Middle Miocene intensification of the Antarctic Circumpolar Current (ACC). The exact cause and timing of this intensification is however uncertain.

Lawver and Gahagan (1998, 2003) suggested that collision of the Australia–New Guinea block with Southeast Asia around 15 Ma was an important tectonic event with respect to ocean circulation. Among other global causes, they indicated that the blocking of substantial equatorial transport of water from the Pacific into the Indian Ocean enhanced the driving forces of the Antarctic Circumpolar Current and led to the Middle-Late Miocene expansion of the East Antarctic ice-sheet.

A Middle Miocene change in the driving forces of the Circumpolar Current may on the other hand also be related to the evolution of the Scotia Sea region (Fig. 1). The ridges and basins that were active during the early stages in the evolution of the Scotia Sea controlled the development of the Antarctic Circumpolar Current and the circumpolar deep water flows (Barker 2001; Maldonado et al. 2003, 2005 and 2006).

In this region, a major paleoceanographic event is recorded by a reflector c (estimated age of 12.1–12.6 Ma), which represents the connection between the Scotia Sea and the Weddell Sea (Maldonado et al. 2006). The deposits overlying this reflector record the initial incursions of Weddell Sea Deep Water into the Scotia Sea (Maldonado et al. 2006). This westward escape of Weddell Sea Deep Water towards the Pacific is considered to have controlled the stages of drift growth observed on the western side of the Antarctic Peninsula (Fig. 1, Camerlenghi et al. 1997; Rebesco et al. 1997). Michels et al. (2001) compared these drift growth stages with the seismo-stratigraphic units overlying the W5 unconformity on the eastern side of the Antarctic Peninsula (in the Weddell Sea). The correlation of the seismic sequences allowed an analogous dating of corresponding stages. This might suggest that the reorganization of bottom currents in the Scotia Sea region initiated a stronger bottom current circulation within several adjacent sectors of the circum-Antarctic margin. The event coincides with a major lowering of the global temperature (Maldonado et al. 2006).

Other sectors of the circum-Antarctic margin

Other Antarctic continental rise settings exhibit similar processes and a similar sequence of events to the ones observed in the eastern Weddell and Riiser-Larsen Seas (De Santis et al. 2003; Kuvaas and Leitchenkov 1992). The timing of some of these events may vary from region to region, but on a long-term basis the sediment records appear to develop a more or less consistent pattern with the following characteristics:

Firstly, in a deep sea depositional setting the first signs of deposition under a fully continental glacial regime is often associated with the formation of a distinct regional unconformity. The seismic character of the deposits stratigraphically above this surface indicates a higher-energy environment and enhanced terrigenous supply from the continent when compared to the deposits below. Kuvaas et al. (2004a) proposed that the RLS-4 surface corresponds to the surfaces W4 (Weddell Sea), P1 (Prydz Bay) and WL-U4 (Wilkes Land). All of these surfaces are regional in extent and have been related to the advances of ice sheets, delivering huge amounts of sediment to the shelf edge and upper slope (Kuvaas and Kristoffersen 1991; Kuvaas and Leitchenkov 1992; De Santis et al. 2003). The instability generated erosive gravity flows that settled in deeper parts of the margin. In the eastern Riiser-Larsen Sea, the deposits directly above the RLS-4

unconformity on the continental rise appears to be dominated by debris flows and/or slumps. In the eastern Weddell Sea, the deposits that overlie the W4 unconformity indicate the presence of multiple debris flows (Michels et al. 2002). On the continental rises outside Prydz Bay and Wilkes Land, the seismic character above the respective unconformities is largely indicative of turbidite lobes (Kuvaas and Leitchenkov 1992; De Santis et al. 2003). A few localities in Prydz Bay reveal a chaotic reflection pattern that may represent slumps and/or debris flows.

Secondly, the lenticular bodies (turbidite lobes, debris flow units and/or slumps) on the continental rise typically underlie larger sediment ridges. This is observed in the Riiser-Larsen Sea, in the Weddell Sea (Michels et al. 2002; Kuvaas and Kristoffersen 1991), in Prydz Bay (Kuvaas and Leitchenkov 1992) and at the Wilkes Land margin (DeSantis et al. 2003; Escutia et al. 2005). Turbidity currents and/or bottom-water currents and their interaction develop these sediment ridges. While the early glaciomarine deposits consist of a whole range of different types of gravity flows, turbidity currents often dominate the subsequent stage of downslope activity. This might suggest that the delivery of sediments to the shelf edge gradually became more organized in response to a progressively cooler climate. In the eastern Weddell Sea (Kuvaas and Kristoffersen 1991) and on the Wilkes Land margin (DeSantis et al. 2003; Escutia et al. 2005), the formation of large channel–levee structures on top of lenticular units has been explained by margin progradation. This would allow sediments to be transported further into the basin and explain the observed morphologies.

Thirdly, the Middle to Late Miocene period represents a time of significant ice sheet expansion in Antarctica with a Middle Miocene "climatic optimum" at about 15 Ma (Zachos et al. 2001; Barker et al. 1998), and is often recognized as the main phase of ridge growth on the continental rise (DeSantis et al. 2003; Escutia et al. 2005; Rebesco et al. 1997; Michels et al. 2002). The inferred Middle-Miocene age of the RLS-6 unconformity indicates that the main growth of sediment ridges in the Riiser-Larsen Sea should also be assigned to this period.

Fourthly, the seismic stratigraphy along other segments of the circum-Antarctic margin indicate that the end of the Middle-Miocene "climatic optimum" was associated with a change from subpolar regimes with dynamic ice sheets (i.e., ice sheets come and go) to regimes with persistent but oscillatory ice sheets (Escutia et al. 2005). This notion is based on an observed shift in depocentres to more proximal parts of the margin, in which the deposits are characterized by

steeply dipping foresets. Even though a similar change in regional geometry is not prominent within the eastern Riiser-Larsen Sea and the exact timing and nature of such an event is widely debated (Rebesco et al. 2006; Flower and Kennett 1994; Hambrey and McKelvey 2000), sedimentological data from the northern part of the Gunnerus Ridge support the idea. A general increase in the concentrations of ice rafted debris and illite after 8.7 Ma indicates stronger glacial conditions on a long-term time scale (Hillenbrand and Ehrmann 2003). The clay mineral assemblage deposited between 8.7 and 6.5 Ma suggests that a dry polar weathering regime had ultimately been established in the East Antarctic source areas (Hillenbrand and Ehrmann 2003).

Conclusions

The seismo-stratigraphic analysis of deposits in the eastern Riiser-Larsen Sea indicates the presence of four main sequences. The lowermost (oldest) sequence, RLS-A, is interpreted to be of pre-glacial origin and mainly consists of turbidites and hemipelagic deposits. We postulate that the initial transfer of sediments to the shelf edge by an expanding ice sheet was associated with the triggering of multiple debris flows/slumps and the development of a regional unconformity (RLS-4). The mass wasting products are manifested as lenticular and seismically transparent sedimentary units (RLS-B) scattered along upper parts of the continental rise, suggesting that the ice sheet initially acted as a line or a multi-point source. At a later stage of the glaciation the centre of deposition is relocated to the lower rise and the abyssal plain. We attribute this to margin progradation and/or a more focussed delivery of sediments to the shelf edge. This allowed large volume turbidity currents to reach distal parts of the margin, where there was an abundance of accommodation space, and spill out as broad sheets (RLS-C). As a critical level was reached, the rising base levels forced turbidity channels to backstep. This promoted widespread channel migration and the development of large levees on the upper rise. In distal parts of the margin and along the western margin of the Gunnerus Ridge we observe various drift deposits overlying a distinct unconformity (RLS-6). The unconformity corresponds to a hydrological event, which is considered to be related to a Middle Miocene intensification of the Antarctic Circumpolar Current. The main stage of drift/levee growth within sequence RLS-D is tentatively estimated to the Middle-Late Miocene. Sedimentological data from the northern

part of the Gunnerus Ridge indicate that a dry polar weathering climate had ultimately been established in the East Antarctic source areas by the Late Miocene.

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