Marine Geophysical Researches **22:** 465–485, 2001.

Recognition of contour-current influence in mixed contourite-turbidite sequences of the western Weddell Sea, Antarctica

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Received 17 July 2001; accepted 4 December 2001

Key words: Antarctica, channel levees, contourites, turbidites, contourite-turbidite interaction, drifts, multichannel seismic data, Parasound, Weddell Sea

Abstract

Sedimentary processes and structures across the continental rise in the western Weddell Sea have been investigated using sediment acoustic and multichannel seismic data, integrated with multibeam depth sounding and core investigations. The results show that a network of channels with associated along-channel ridges covers the upper continental slope. The seismic profiles reveal that the channels initially developed as erosive turbidite channels with associated levees on their northern side due to Coriolis force. Later they were partly or fully infilled, probably as a result of decreasing turbidite activity. Now the larger ones exist as erosive turbidite channels of reduced size, whereas the smaller ones are non-erosive channels, their shape being maintained by contour current activity. Drift bodies only developed where slumps caused a distinctive break in slope inclination on the upper continental rise, which served to initiate the growth of a drift body fed by contour currents or by the combined action of turbidites and contourites. The history of sedimentation can be reconstructed tentatively by correlation of seismo-stratigraphic units with the stages of evolution of the drifts on the western side of the Antarctic Peninsula. Three stages can be distinguished in the western Weddell Sea after a pre-drift stage, which is delimited by an erosional unconformity at the top: (1) a growth stage, dominated by turbidites, with occasional occurrence of slumps during its initial phase; (2) during a maintenance stage turbiditiy-current intensity (and presumably sedimentation rate also) decreased, probably as a result of the ice masses retreating from the shelf edge, and sedimentation became increasingly dominated by contour current activity; and (3) a phase of sheeted-sequence formation. A southward decrease in sediment thickness shows that the Larsen Ice Shelf plays an important role in sediment delivery to the western Weddell Sea. This study shows that the western Weddell Sea has some characteristics in common with the southern as well as the northwestern Weddell Sea: contour currents off the Larsen Ice Shelf have been present for a long time, probably since the late Miocene, but during times of high sediment input from the shelves as a result of advancing ice masses a channel-levee system developed and dominated over the contour-current transport of sediment. At times of relatively low sediment input the contour-current transport dominated, leading to the formation of drift deposits on the upper continental rise. Seaward of areas without shelf ice masses the continental rise mainly shows a rough topography with small channels and underdeveloped levees. The results demonstrate that sediment supply is an important, maybe the controlling factor of drift development on the Antarctic continental rise.

Introduction

The formation of sediment bodies at oceanic margins is most often controlled by both gravitational processes and processes related to alongslope currents. The result of this combined action are interbedded and mixed sediment sequences showing a variety of structures, which cannot always be assigned unequivocally to turbidity or contourite current origin.

A basic shortcoming is the lack of clear sedimentological characteristics for contourites. Whereas turbidites are generally related to channel-bound deposition, the possible range of settings and appearances of contourites is much broader. Furthermore, compared to turbidites, contourites are less studied and described.

A number of publications dealing with a basic description of contourite characteristics and numerous examples from different areas and settings document an increasing interest in this topic during recent years (e.g. Faugères and Stow, 1993; McGinnis and Hayes, 1995; Rebesco et al., 1997; Massé et al., 1998; Stoker, 1998; Faugères et al., 1998, 1999). This paper presents a case study dealing with multichannel seismic and Parasound data obtained from the western Weddell Sea. The seismic data from this area are unique because of the difficult access due to the permanent sea ice cover. Our special interest in this area is based

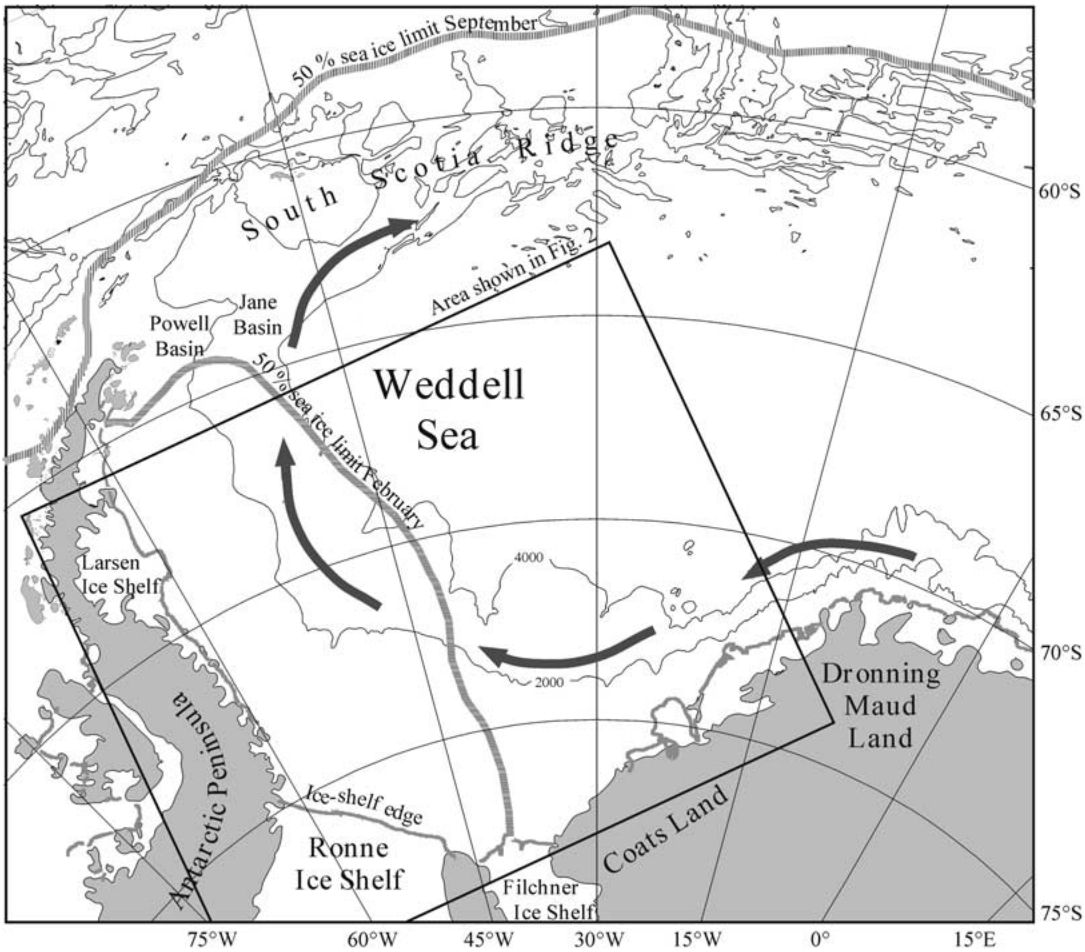


Figure 1. Map of the Weddell Sea with main geographic features, ocean surface circulation (arrows), and maximum and minimum sea-ice coverage indicated by mean 50% February and September sea-ice limits (data from Zwally et al., 1985). Water depth indicated by 2000 m and 4000 m isobaths. Box marks area shown in Figure 2.

on the glacimarine setting combined with the circulation system of the Weddell Gyre, which qualify drift development in this region as highly potential.

Setting

The Weddell Sea is a large marginal basin of the Southern Ocean, bound by glaciated coasts and ice shelves of Antarctica to the southeast and of the Antarctic Peninsula to the southwest, and by the South Scotia Ridge to the north. To the northeast it opens to the South Atlantic (Figure 1). The general oceanographic circulation in the Weddell Sea is dominated by the cyclonic Weddell Gyre, which affects all water masses down to the seafloor (Carmack and Foster, 1975; Deacon, 1979; Gordon et al., 1981). Deep and bottom water formation in the southern and western Weddell Sea is the major source of the bottom water in the world ocean (Carmack, 1977; Foldvik and Gammelsrød, 1988; Hellmer and Beckmann, 2001), favoured by the large-scale cyclonic circulation of the Weddell Gyre. Temperature/salinity characteristics are used to define four dominant water masses in the Weddell Sea (Carmack, 1974, 1977; Fahrbach et al., 1995). The uppermost Surface Water consists of Winter Water, Antarctic Surface Water and shelf waters of low temperature (−1.6 to −1.8 °C) and low salinity (34.3–34.5‰). Underneath follows the warmest water mass, Warm Deep Water (temperature 0.0 to 0.8 °C, salinity 34.64 to 34.72‰). The water mass below has the characteristics of Antarctic Bottom Water (temperature 0.0 to −0.7 °C, salinity 34.64 to 34.68‰), and is here named Weddell Sea Deep Water, following the nomenclature of Fahrbach et al. (1995). The deepest water mass is formed by Weddell Sea Bottom Water (temperature −0.7 to −1.4 °C, salinity 34.64 to 34.68‰).

Major sources of the Weddell Sea Deep and Bottom Water are water masses formed on the Filchner-Ronne and Larsen Ice shelves (Foldvik et al., 1985; Foster et al., 1987; Gordon et al., 1993; Fahrbach et al., 1995). Following the Weddell Gyre these water masses slowly flow down the continental slope and intensify the clockwise circulation there. During their descent from the shelf down the continental slope the water masses mix with various intermediate water masses to ultimately reach the temperature-salinity characteristics of Weddell Sea Deep and Bottom Water. In the western Weddell Sea these water masses move obliquely down the continental slope under the influence of the western boundary current (Fahrbach et al., 1995). Sea ice generally covers more than 80% of the Weddell Sea in the austral winter (Sea Ice Climatic Atlas, 1985). In the western Weddell Sea the sea-ice coverage still makes up about 50% during the minimum ice extent. This extensive sea ice coverage is one reason for difficult access to this area for research cruises. Sediments on the continental rise consist of terrigenous, mainly silt- and clay-sized particles with low biogenic carbonate and opal contents. Coarse silt and sand layers occur as a result of resuspension and winnowing (Gilbert et al., 1998). Gravel and pebbles are interspersed in the sediment by ice rafting.

The dominant processes of sediment supply on the continental slope and rise of the western Weddell Sea are (1) deposition of resuspended and winnowed particles from bottom currents or formation of residual sediments; (2) turbidites and other gravity flows, especially gravitationally sinking dense water masses formed on the Larsen Shelf; (3) ice rafting.

Previous work

Weddell Sea

Contour currents in the Weddell Sea were described as early as 1969 by Hollister and Elder (1969). They inferred a strong current influence on the sediments in the western Weddell Sea along the continental slope from visual inspection of bottom photographs. Based on a 'representative set of cores' lying on two transects from the central to northwestern Weddell Sea (Jane Basin region) Pudsey et al. (1988) found evidence for an increasing influence of bottom currents on sedimentation from the centre to the north of the Weddell Sea. They located the northern margin of the Weddell basin as the area of fastest flow of the western boundary undercurrent, where little deposition, but winnowing and even erosion takes place. A stratigraphic interpretation of the cores revealed that the Weddell Gyre existed throughout the last few glacial and interglacial stages, but during the Late Pliocene to Early Pleistocene the circulation was extremely sluggish (Pudsey et al., 1988). Further geophysical investigations with seismic and swath bathymetry methods in the northwestern Powell Basin documented a mudwave field near the base of the continental slope in water depths of 2,800–3,100 m, along the pathway of Antarctic Bottom Water from the Weddell Sea (Howe et al., 1998). It remains unclear from the data, however, whether original wave construction was initiated by turbidity currents from the basin floor channels or by contour currents. It is suggested that the waves are presently active, maintained by lateral transfer of distal turbidite suspension through contour currents (Howe et al., 1998). The study of sediment cores (max core length 280 cm) and 3.5 kHz sub-bottom profiles on the continental slope southwest of Powell Basin also revealed transport and depositional processes in a high-energy environment, where deposition is controlled by channel and bottom current-related processes including suspension in a distinct benthic nepheloid layer (Gilbert et al., 1998). A cyclicity between winnowed, better-sorted deposits implying warmer climatic conditions and stronger current activity and mud dominated poorly sorted sediment barren of fauna, resulting from cold climate and low bottom current strength, is attributed to climatic fluctuations of shorter duration than the main 100 ka glacial-interglacial cycle, though absolute chronology is missing (Gilbert et al., 1998).

The western boundary current system of the northern Weddell Gyre has been investigated in current meter moorings. A profile of current meter moorings deployed in 1989 to 1993 across the continental slope in the northwestern outflow region shows that the core of the western boundary current is located in water depths ranging from 2,300 m to 3,700 m (Fahrbach et al., 1994). Pudsey and King (1997) report on four current meter moorings in Jane Basin and just to the south, where during a period of 760 days the maximum current speed was 30 cm/s and mean current speed was 9.7 and 10.8 cm/s in 3,800 m and 4,500 m water depth, respectively.

Western margin of Antarctic Peninsula

A series of nine sediment mounds, aligned along the western margin of the Antarctic Peninsula continental rise, were interpreted as hemipelagic sediment drifts (Rebesco et al., 1994, 1996). Interpretation of seismic reflection profiles, combined with long-range side scan sonar images suggested an construction of the drift bodies by deposition of fine-grained sediments from a suspension layer, generated by small but highly energetic turbidity currents, within a general southwestward directed thermohaline bottom current (Rebesco et al., 1997).

McGinnis and Hayes (1995) and McGinnis et al. (1997) emphasised the overbank deposition along the channels and canyons between and within the mounds. They concluded on a basically turbidity-current origin of the mounds, reflecting the sedimentary record of the waxing and waning of ice sheets on the western side of the Antarctic Peninsula. Three main stages were identified for the formation of the sedimentary sequences in this area (Rebesco et al., 1997): An Oligocene to mid-Miocene ‘Pre-drift Stage’, which does not show indication of strong bottom current activity and predates the extension of grounded ice to the continental shelf on the western Antarctic Peninsula; a mid to late Miocene ‘Drift-growth Stage’, showing evidence of increased bottom current activity and drift development (during this stage conditions were changing from pre-glacial to fully glacial, with regular extension of grounded ice to the shelf edge); and a Plio-Pleistocene ‘Drift-maintenance Stage’, which is characterised by preservation and enhancement of the elevation of the drift.

Data and methods

The data for this study were collected during RV Polarstern cruise ANT XIV/3 in austral summer 1997 (Jokat and Oerter, 1998). Multichannel seismic data were obtained using a 24 l airgun array and an 800 m long 96-channel streamer. Digital high-resolution sediment acoustic data were recorded with the narrow-beam echosounder system Parasound (Grant and Schreiber, 1990). The water depth was recorded with the multibeam system Hydrosweep DS-2.

The ship’s track was northwestward from the southern Weddell Sea to the lower continental rise of the Antarctic Peninsula at about 66 °S (Figure 2), on the whole following the large-scale topography with water depths of 3,500 to 4,000 m. From there it leads westward up to the shelf. On the way back it largely followed the same course and sediment samples were retrieved at positions selected on the basis of the collected sediment acoustic data (Jokat and Oerter, 1998).

Results and interpretation

Parasound profile AWI-97050 runs north-south parallel to the contours in the western Weddell Sea (Figure 2). The profile shows cross-sections of several channels separated by ridges (Figure 3a). The deepest-lying group of channels in the centre of this profile shows a prolonged bottom reflection, low penetration and rough topography, which clearly indicate an erosional-constructional origin (after Nelson and Kulm, 1973; Carter, 1988). They probably represent a ‘braided’ channel system or two separated channels right upstream of their confluence. Southward follows a mound-like rise almost 200 m high characterised by sharp continuous parallel subbottom reflectors with penetration depths of about 30 m. The reflectors slightly diverge southward indicating an increasing sedimentation rate. A depression showing slightly condensed sedimentation forms the southern boundary of this mound.

To the north of the channel system in the centre the topography rises in two 200-m high steps with steep southern and flat northern flanks, which are separated by an asymmetric little-pronounced channel. The flat sides of the steps are characterised by sharp continuous parallel reflectors and deep penetration in the Parasound record; the steeper sides have strong semi-prolonged to parallel reflectors with low penetration.

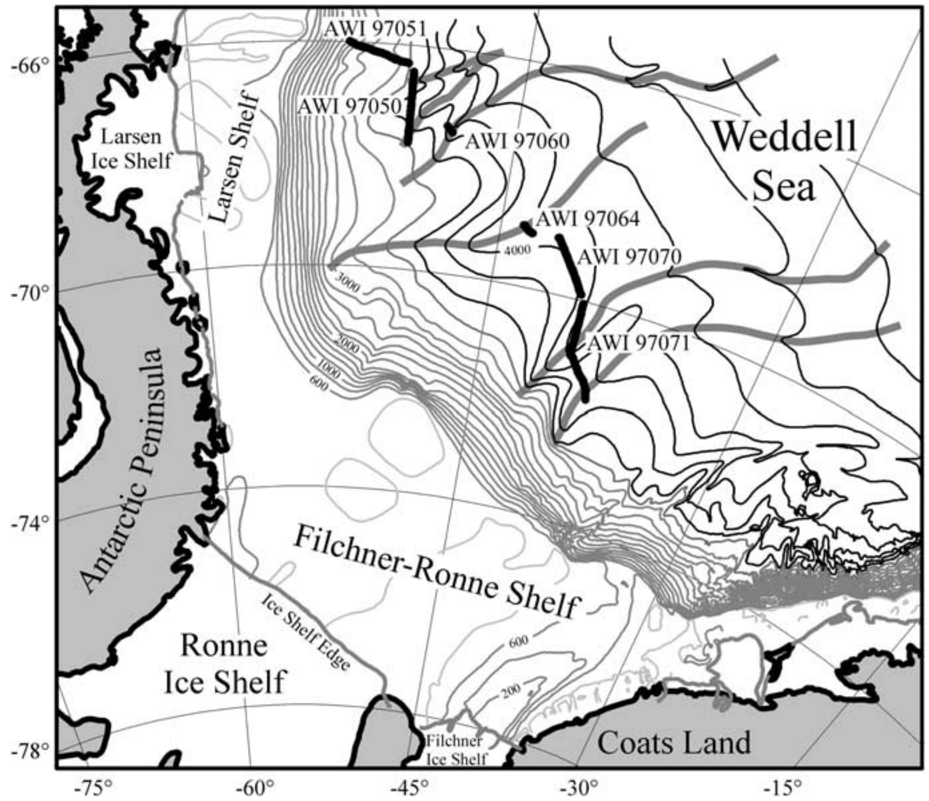


Figure 2. Map of the western and southern Weddell Sea with main geographic features, courses of channel-levee/drift body systems as can be inferred from the topography (grey lines), and seismic and Parasound profiles (dark lines). Bathymetry is indicated by isobaths in 200-m steps (after Schenke et al., 1998).

The channel between the steps forms a non-erosive, undisturbed transition between the steep side of the upper and the flat side of the lower step. The reflection pattern shown in the enlargement of this profile suggest that minimum sedimentation rates occur at the steeper flank significantly above the channel bottom (Figure 3a insert). This feature is not typical of channel levees along turbidity pathways but characteristic of sedimentation in the presence of contour currents. We therefore interpret the minimum in sediment thickness to indicate the position of the core of a local contour current. If turbidity-current activity would be responsible for the shaping of this channel, one would expect an erosive channel base, which is clearly not the case.

Seismic line AWI-97050 along the same track shows the deeper substructure (Figure 3b). Here it becomes evident that the group of channels in the centre of the Parasound profile developed from a larger erosive channel, which subsequently has been reduced in size by filling with coarser sediments.

The base of the large-scale depositional features, which determine the recent topography is a strong reflector at about 5.3 s Two-Way Traveltime (TWT), which is interpreted as a major (regional) unconformity (termed W5). It discordantly truncates the underlying sequences and separates them from units showing a regular and thin-bedded pattern of mostly parallel, continuous reflections above. A tentative correlation with seismic profiles in the southern Weddell Sea, where reflectors could be dated using ODP Site 693, suggests that this unconformity corresponds to a hiatus at the base of the Late Miocene (Miller et al., 1990).

This reflector has also been identified in numerous other profiles of channel levees in the southern Weddell Sea (Oszkó, 1997; Michels et al., in press). The seismic facies above reflects the increased role played by glacial marine sedimentation as a result of renewed cooling and major expansion of the East Antarctic Ice Sheet (Miller et al., 1990). In its southern part profile AWI-97050 shows a debris-flow deposit, following above reflector W5. The sequence shows that at an early stage (late Miocene) sedimentation was strongly related to channel-bound turbidites, which in some

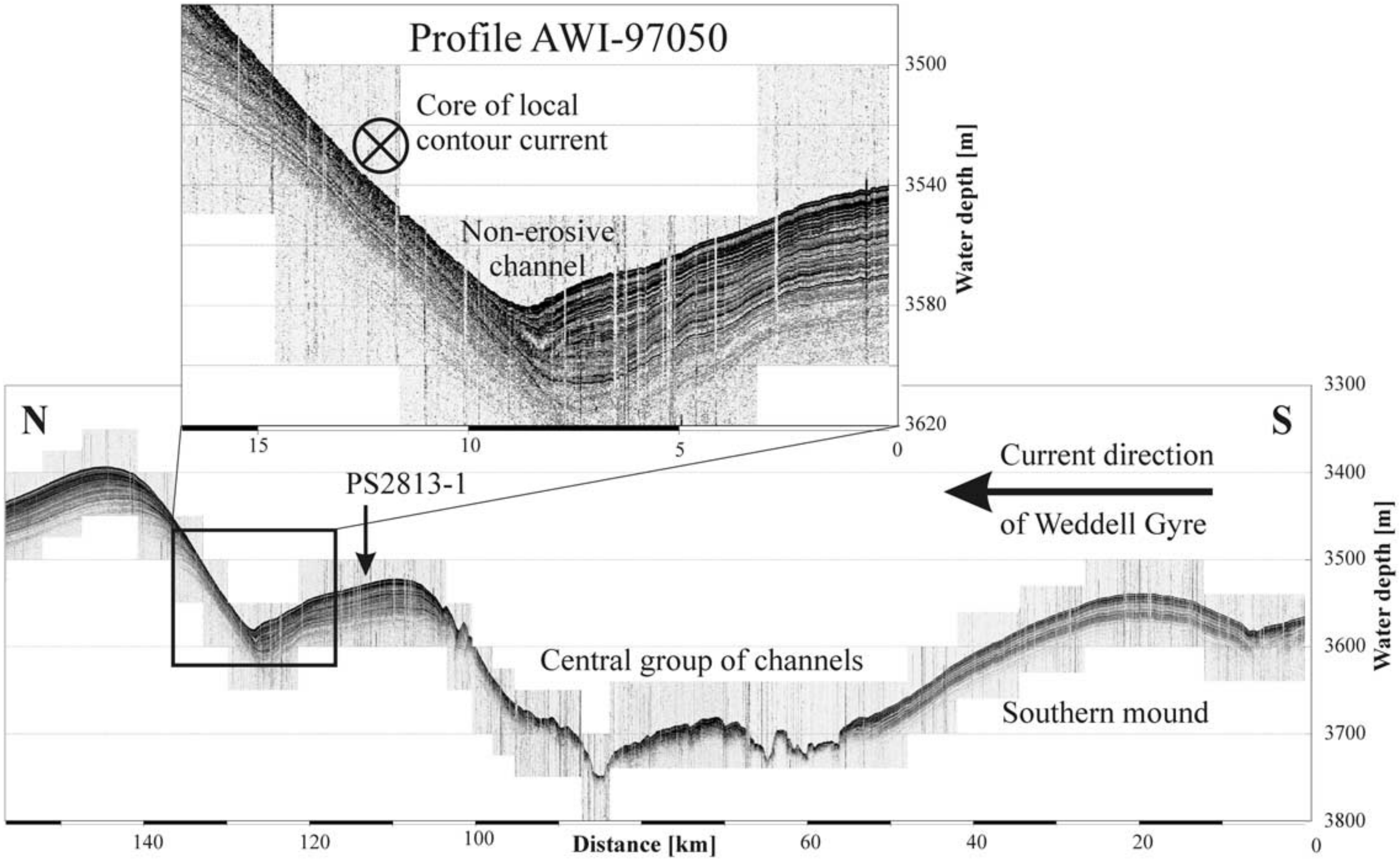


Figure 3. (a) Parasound profile AWI-97050 along the continental rise in the western Weddell Sea (for location of the profile see Figure 2); (b) Multichannel seismic profile AWI-97050 (same location) and its interpretation. The sequence above unconformity W5 represents late Miocene to Recent sediments deposited under an increased influence of contour currents.

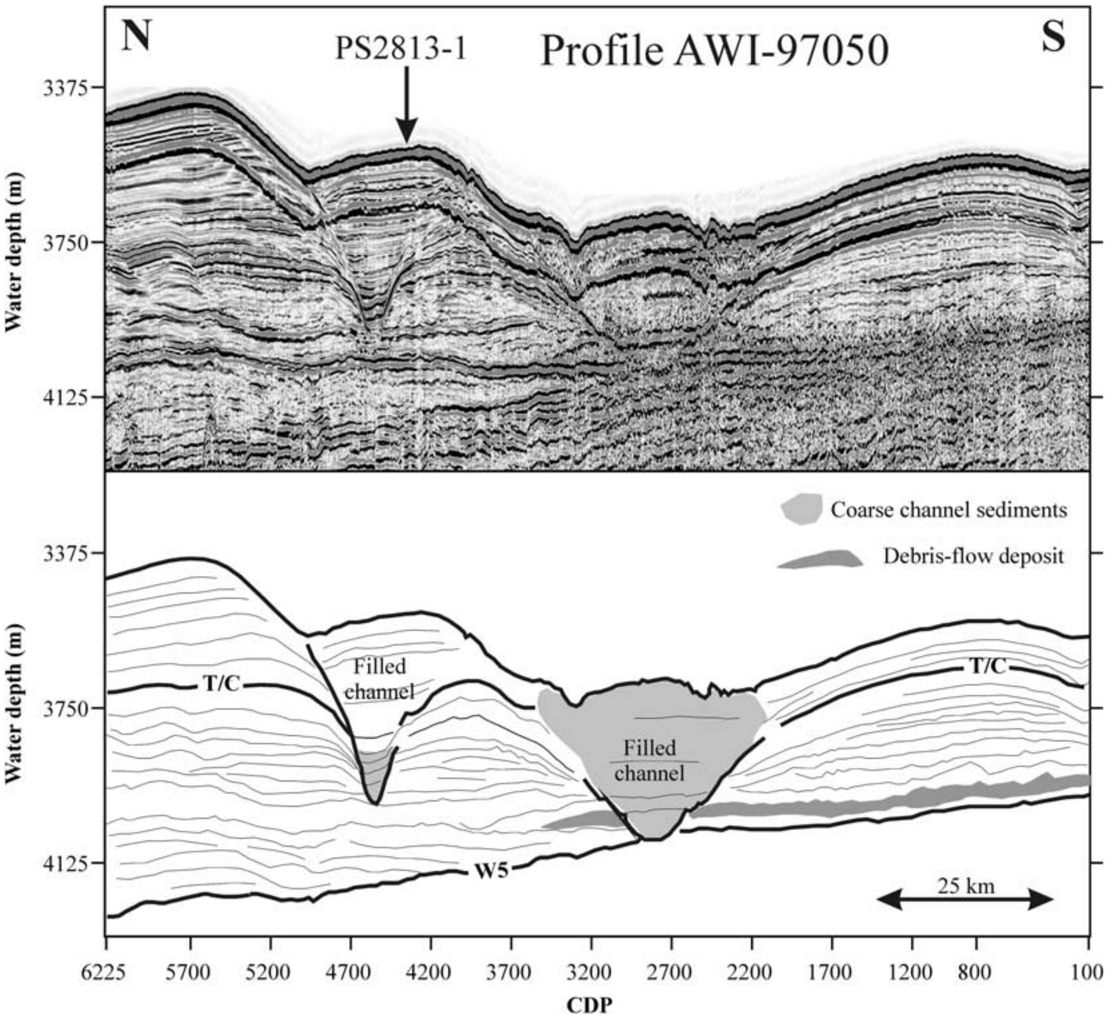


Figure 3. Continued..

places cut through reflector ‘W5’ into the underlying units. Levees grew up along the channels by overbank deposition of fine sediment.

At a stage roughly marked by reflector marked ‘T/C’ a transition occurred from a more turbidite- to a more contourite-related sedimentation (Figure 3b). At this reflector sedimentation seems to have changed from building up levee-shaped ridges along the channels to a draping and filling of the morphology.

The northern channel in profile AWI-97050 has been abandoned and completely filled in, whereas the cross section of the southern channel was reduced, splitting it up into several smaller gullies (Figure 3a). These are probably still maintained by a strongly reduced turbidity-current activity or by downstreaming cold and dense water masses formed on the shelf. Diminished turbidity-current activity can be ascribed to reduced sedimentation rates on the shelf and at the continental slope. In the Weddell Sea this generally is related to a major retreat of the ice sheets (Weber et al., 1994). Nowadays turbidity-current influence is probably largely restricted to the channels and their immediate vicinity.

A 10.64-m long core, PS2813-1, has been obtained from the first step-like rise north of the channel (Figure 3b). It revealed sequences of fine-grained, often laminated sediments (C. Holz, personal communication, 2001), which are typical of contourite deposits. An occasional influence of turbidites is rarely documented by coarser-grained layers.

A recent reduction in turbidite channel size and channel filling can be observed in Parasound profiles

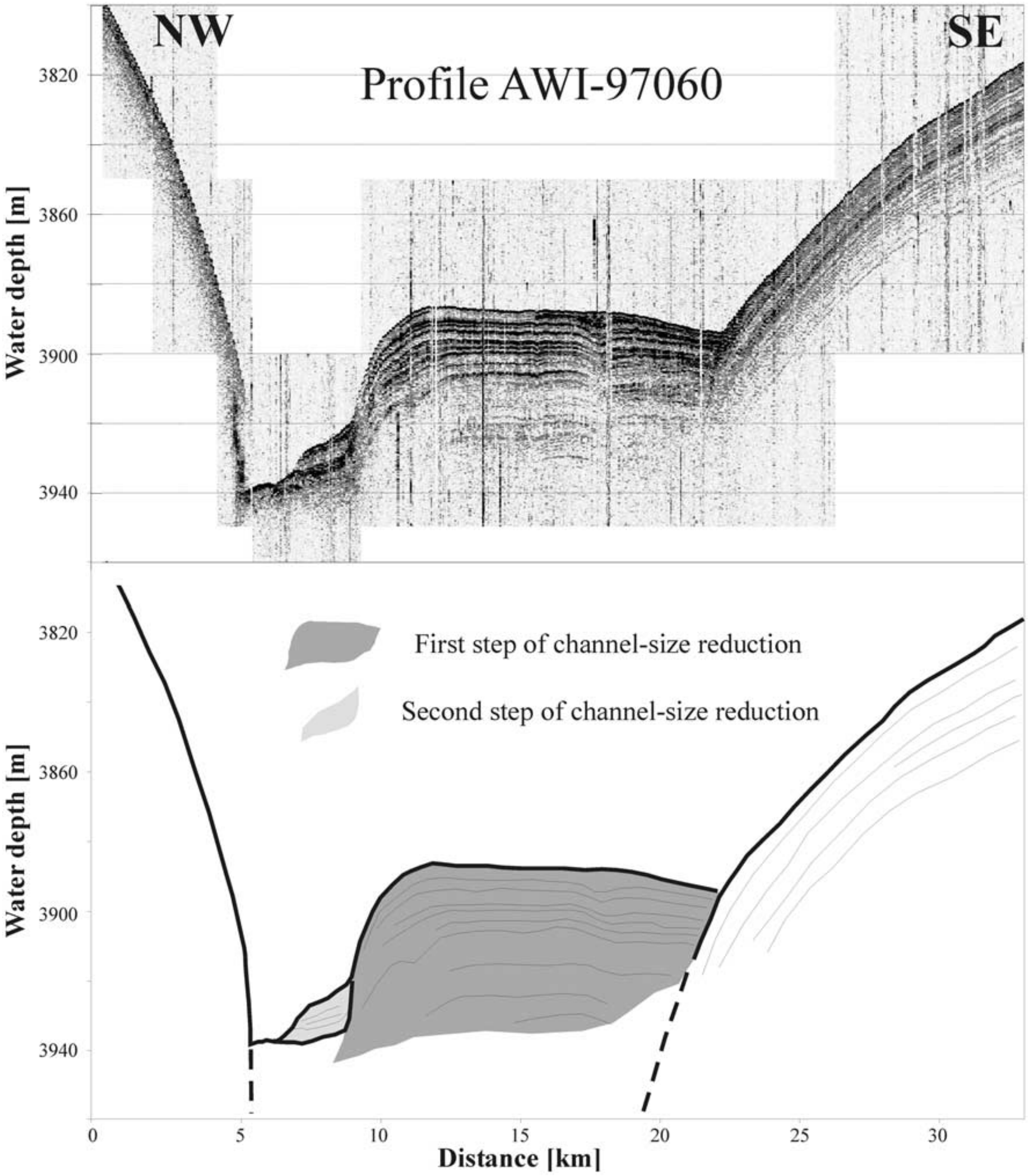


Figure 4. Parasound profile AWI-97060 across a channel in the western Weddell Sea and its interpretation (for location of the profile see Figure 2).

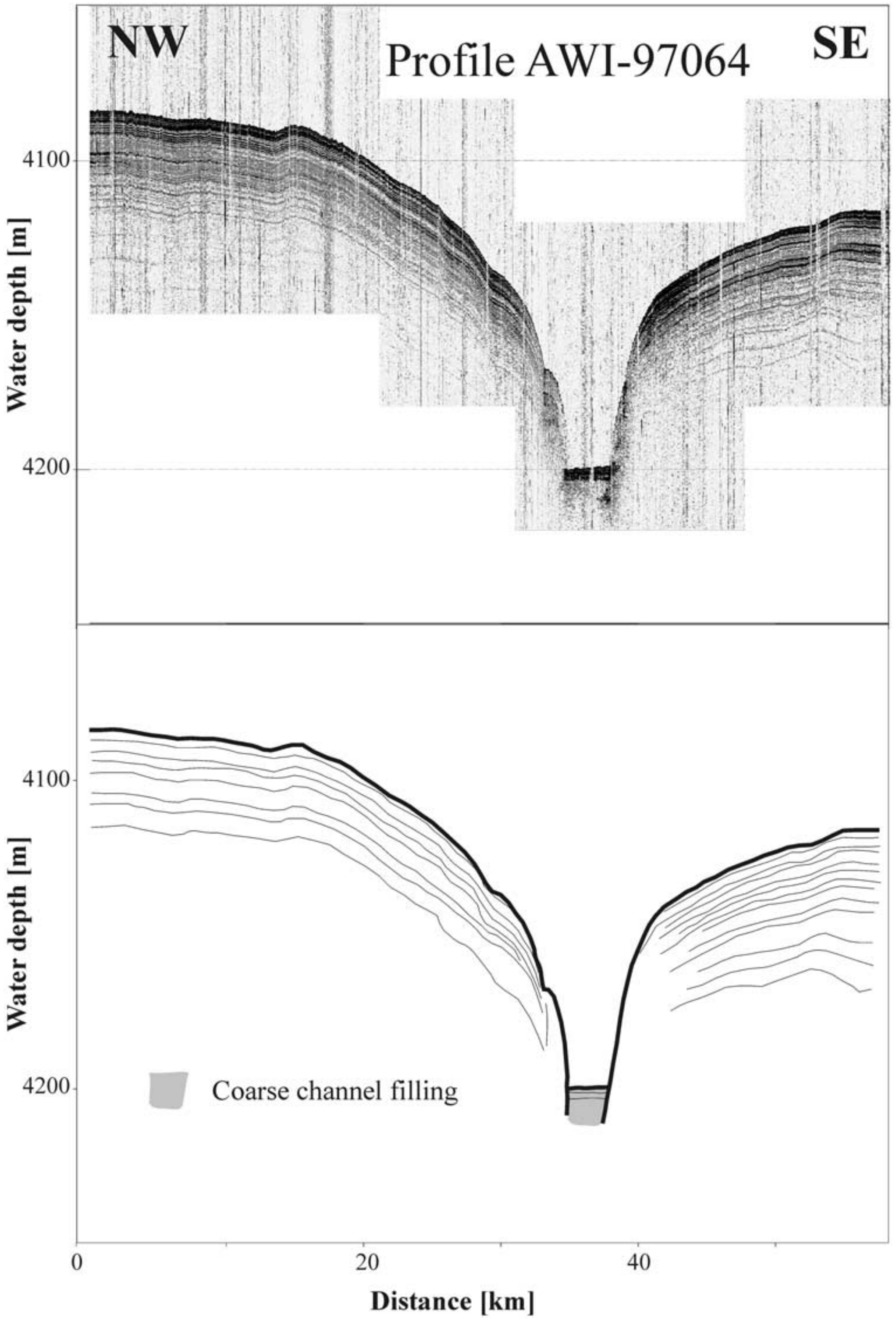


Figure 5. Parasound profile AWI-97064 across a channel in the western Weddell Sea and its interpretation (for location of the profile see Figure 2).

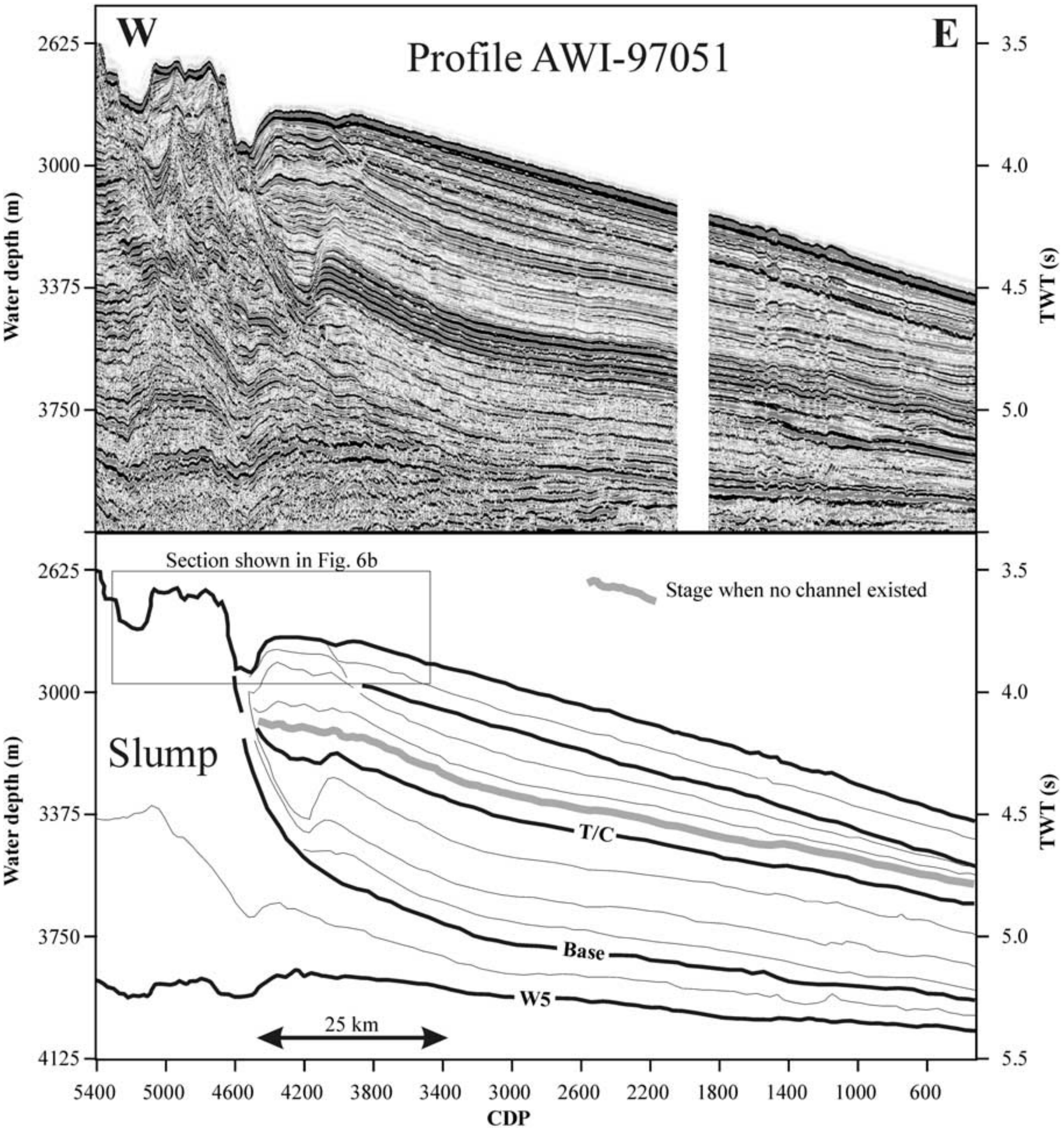
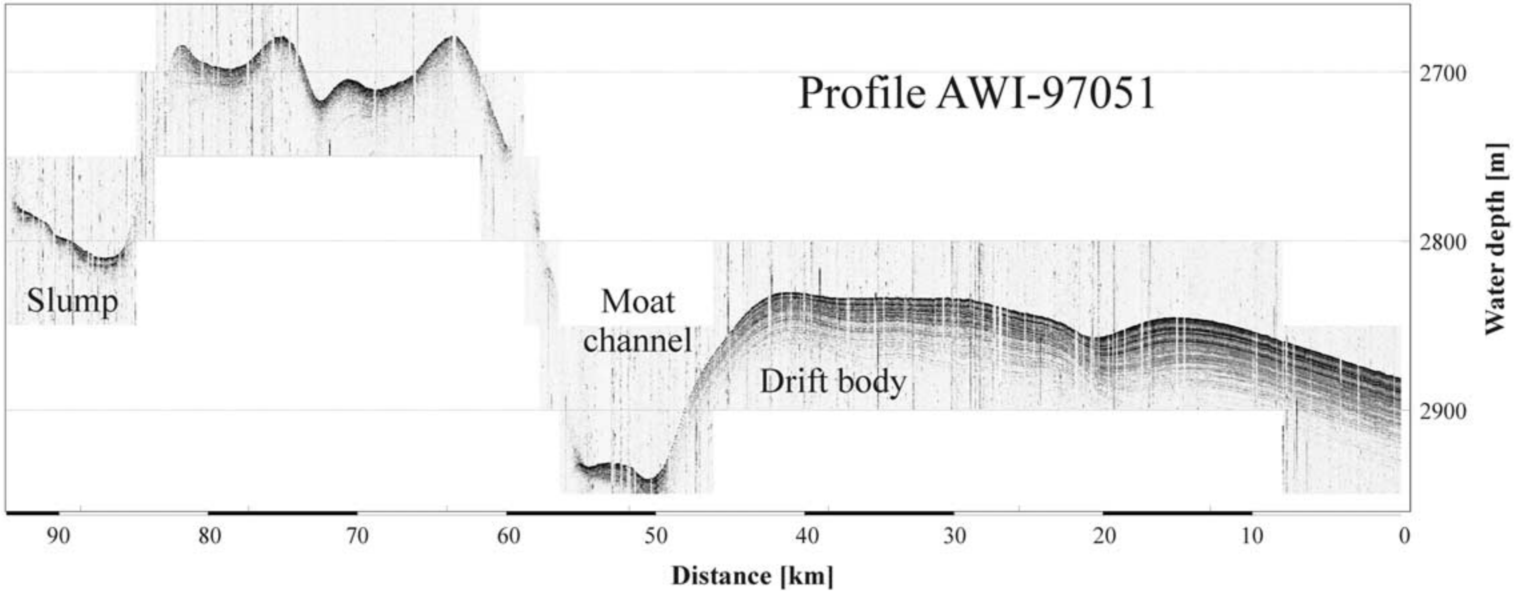


Figure 6. (a) Multichannel seismic profile AWI-97051 crossing the lower continental slope and upper rise in the western Weddell Sea and its interpretation (for location of the profile see Figure 2). Box marks Parasound section shown in Figure 6b, (b) Parasound profile AWI-97051 (same location). The sequence above unconformity W5 represents late Miocene to Recent drift sediments deposited under an increased influence of contour currents. Location of available cores is also shown.



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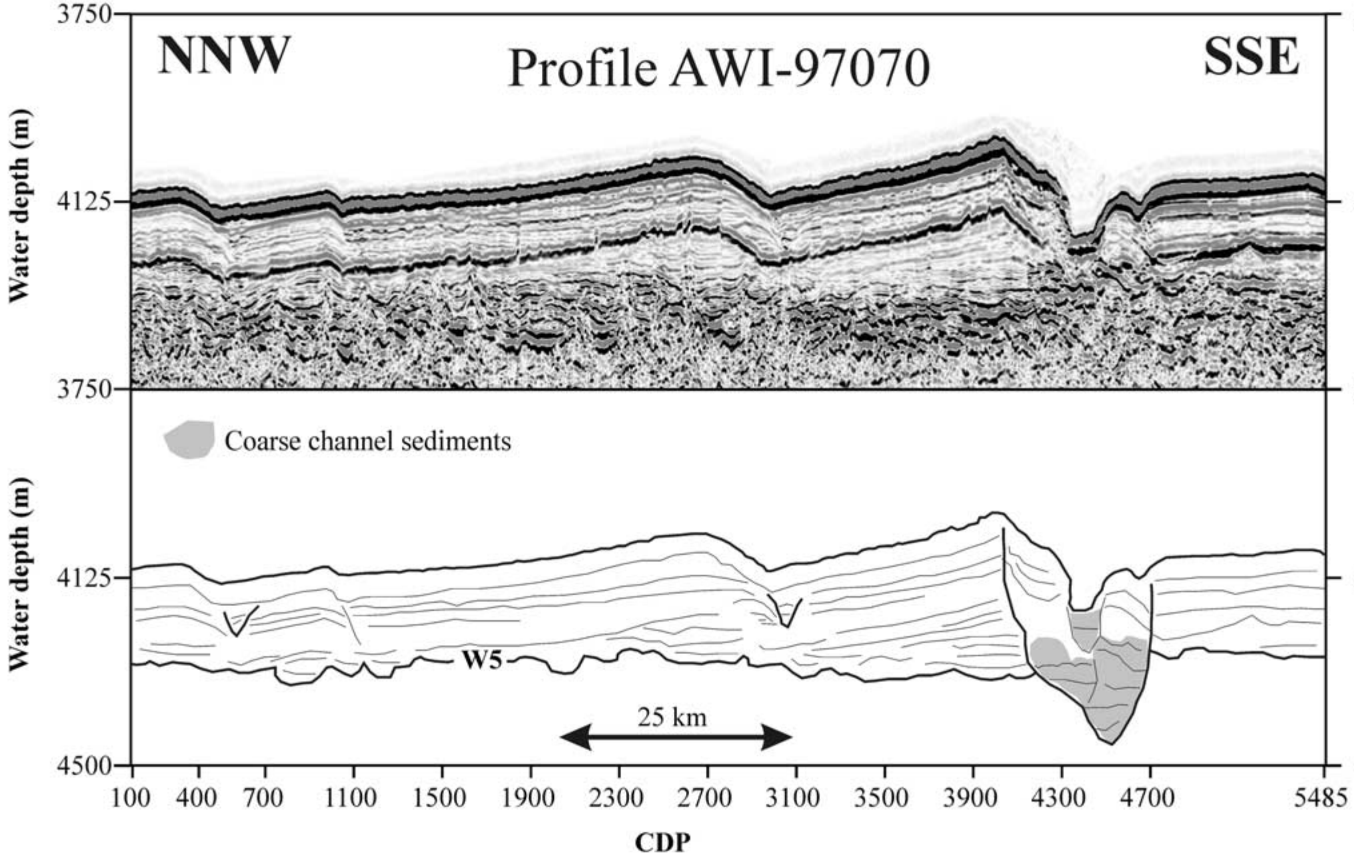

Figure 7. (a) Multichannel seismic profile AWI-97070 along the continental rise in the southwestern Weddell Sea and its interpretation (for location of the profile see Figure 2), (b) Parasound profile AWI-97070 (same location).

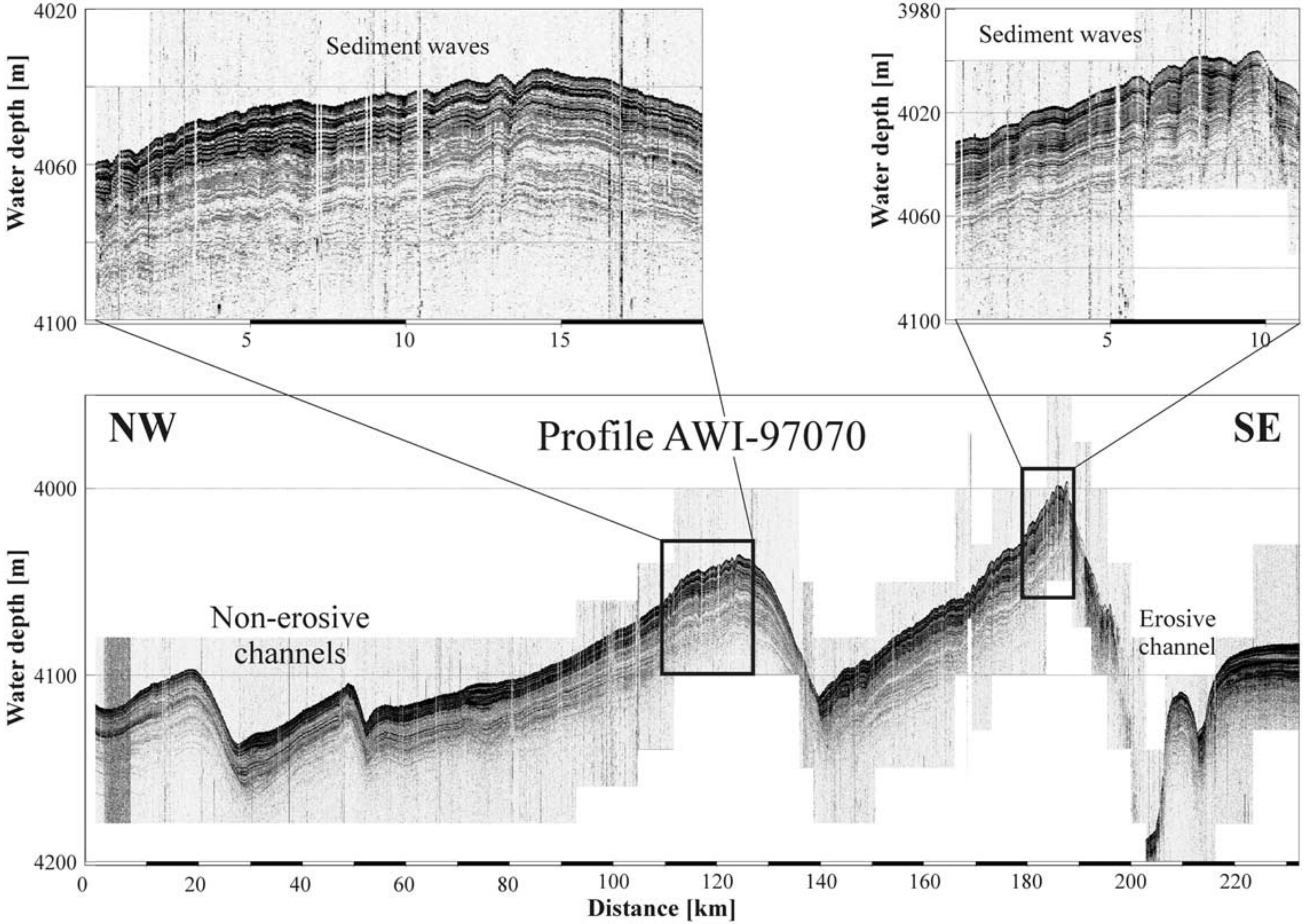

Figure 7. Continued.

AWI-97060 (Figure 4) and AWI-97064 (Figure 5). Profile AWI-97060 reveals that an originally about 15 km wide channel has been reduced in a first step by two thirds on its southeastern side by a filling with sediments showing parallel-bedded high-amplitude reflectors. In a second step the remaining channel again halved its size by accumulation of a 2 to 3 km wide and 10 m thick sediment sequence. The remaining channel is erosive in its deepest part and has a strongly asymmetric shape. The filling indicates a significant reduction in turbidity-current strength and frequency.

Profile AWI-97064 (Figure 5) shows an originally V-shaped channel, which has been filled in its deepest part. The filling has a flat surface and shows a high-amplitude, prolonged reflector. It suggests that turbidity-current activity ceased or decreased significantly in strength and frequency. Another possible interpretation would be that non-erosive turbidity currents fill this channel completely when active, and the bottom layer represents a residual of the turbidite suspension. Thus an interpretation of reduced turbidity-current activity in this case is less convincing compared to the example shown in Figure 4.

Seismic line AWI-97051 (Figure 6a) connects at its eastern end to the northern end of line AWI-97050, and leads to the west up the continental slope. The western part of the profile is dominated by a large block of sediments displaying irregular and distorted bedding. This feature has been interpreted as a slump by Rogenhagen and Jokat (2000; complete profile is shown in their Figure 3). Seaward of this block follows a channel, which separates the slump from a more than 1 s TWT thick seaward thinning sequence of largely parallel, thin-bedded, continuous reflections. Most of this sequence has been built up after slumping occurred. It is interpreted as a separated drift body, which formed at the slope break newly created by the slump. In its upper part at the contact with the slump, the drift body shows a filled-channel structure. Regarding the question whether the channel is of turbidity current or contourite (moat) origin, three arguments can be listed for a contourite-current origin: (a) The bathymetry at this location shows that the channel follows a course along the foot of the slump; (b) The low-amplitude, continuous reflectors of the channel filling (similar to the filling of the northern channel in AWI-97050, Figure 3b), indicating fine-grained sediments, suggest that contourite currents deposited these sediments; a gravitational channel filling would be expected to be coarse grained at its base; (c) The reflector marked with a thick grey line in the interpretation of AWI-97051 (Figure 6a bottom) represents a stage in the development of the sequence when no channel existed. Since levee development always involved a turbidity-current channel, this points to a contourite origin of the sequence.

The seismic reflection pattern of channel changes indicates a reduction in the size of the moat channel after the channel-less stage rather than an upslope migration (faulting may have been contributed to this process). In a preliminary interpretation this size reduction indicates a decrease in contour current speed.

The Parasound profile of the upper part of seismic line AWI-97051 (Figure 6b) reveals that at the bottom of the moat channel the surface reflector shows enhanced amplitudes indicating a thin veneer of coarser sediments. A small lens-shaped sediment body can be identified in the channel, covering most of its bottom. It probably represents an elongated sediment body along the main path of the contour current in the moat channel. As indicated already in the multichannel seismic data of this location, the convergence of reflectors toward the channel bottom implies that the channel has not migrated upslope, but is more or less stable in its present position.

Three major phases can be identified in the development of the sedimentary sequence shown in seismic line AWI-97051 above reflector W5 (the hiatus of mid Miocene age): (1) an initial phase of drift-body formation with the growth of a sheeted sequence. During this phase a pronounced moat channel developed at the foot of the slump. By correlation with profile AWI-97050 a turbidite-related component in sedimentation can be suggested, though there is no obvious indication of this in profile AWI-97051. The end of the initial phase of drift-body formation is marked by reflector 'T/C'. Early in this phase the area was subject to slumping. The surface created by the slumping process is termed 'Base' in Figure 6a. It does not show up as a strong reflector but is more characterised by discordant bedding. There is no obvious indication for slumping in other profiles; (2) During the next phase (above reflector 'T/C') turbidite-related sedimentation decreased and changed to a more contourite-current-related sedimentation. The large moat channel filled in, then levelled the topography, before it grew to a ridge, by this forming a smaller moat channel higher up at the slump foot; (3) a last phase is characterised by the formation of a sheeted sequence seaward of the moat channel.

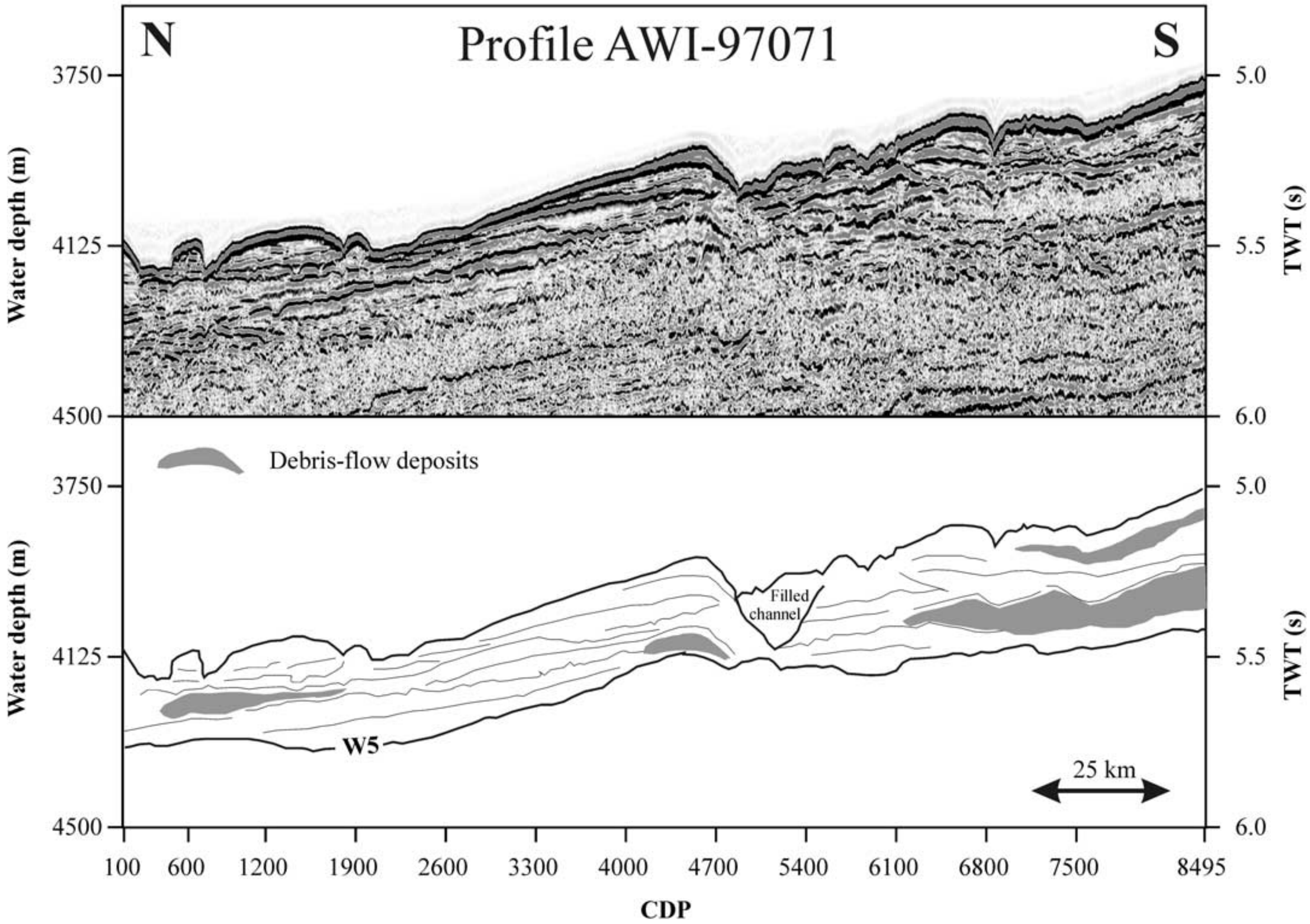

Figure 8. (a) Multichannel seismic profile AWI-97071 along the continental rise in the southwestern Weddell Sea and its interpretation (for location of the profile see Figure 2), (b) Parasound profile AWI-97071(same location).

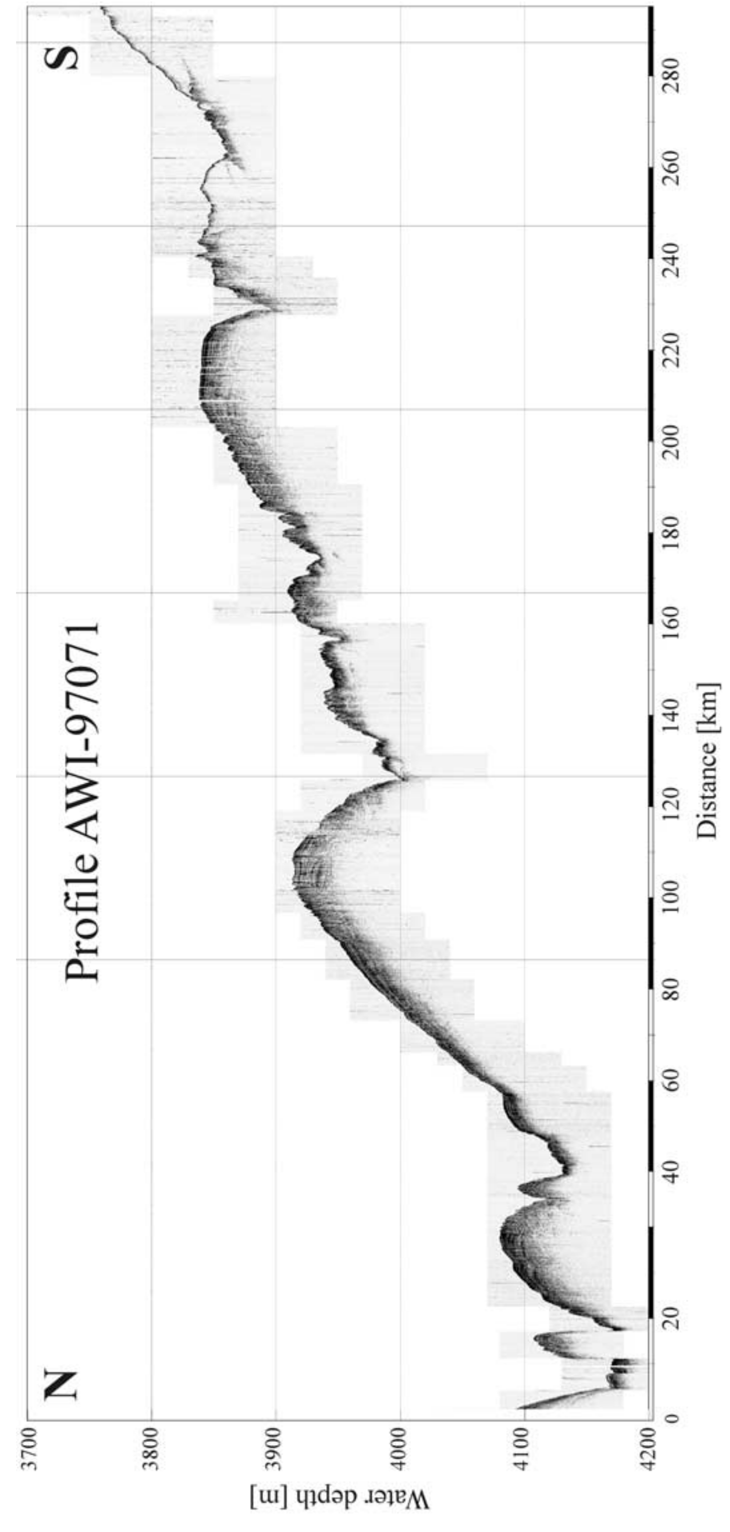

Figure 8. Continued..

A further profile, AWI-97070 (Seismic profile Figure 7a, Parasound profile Figure 7b), has been obtained further southeast off the Ronne Ice Shelf area (for location of the profile see Figure 2). On a 230-km long track the profile crosses several channels separated by ridges/levees that show a strongly asymmetric shape with steep slopes to the southeast and gentle slopes to the northwest. The southeasternmost channel is about 100 m deep and of clearly erosive shape. It probably still has or at least has had turbidite events during the Holocene. The other channels are less deep (up to 60 m) and show continuous parallel reflectors even at their base. On top of the highest levees, flanking the deepest channels, irregular sediment waves developed (Figure 7b details) showing a tendency of upslope migration. From their shape and setting, however, it cannot be deduced whether they are generated and/or maintained by turbidity current spill-over or by contour currents.

The sediments of the levees are characterised by low-amplitude, continuous and parallel reflectors and have a maximum thickness of 0.3 to 0.4 s TWT, thus being much thinner compared to those in seismic profiles AWI-97050 and AWI-97051 (Figures 3b and 6a). This indicates a much lower sedimentation rate at this site. The levees sit on top of an unconformity, which has a very rough and undulating shape, probably being the surface of a slump. This unconformity is thought to correspond to reflector ‘W5’ in the other profiles. A much lower sedimentation rate at this site may be the reason that a transition from a more turbidite-influenced to a more contourite-influenced sedimentation is difficult to identify in the profile. However, an infilling of smaller erosive channels in the northwestern part of the profile is probably related to this change.

The southward extension of this profile is seismic line AWI-97071 (Figure 8a). It shows a rough and irregular surface; only in the middle a thin levee-like sediment body can be seen, bounded in the south by a filled channel. The sediment thickness above reflector ‘W5’ is just 0.2 to 0.4 s TWT and the sediment is characterised by strong, mainly discontinuous, non-parallel reflectors with interspersed slumps. Irregular small sediment bodies north and south of the levee-like sediment body indicate a sediment-starved, current-influenced environment. The groups of small channels and gullies are typical for areas characterised by sediment-bypassing of turbidity currents. Also the Parasound profile (Figure 8b) shows a rough and very strong prolonged surface reflector in the northern parts and a strong surface reflector with low penetration in the south. The profile completes the impression gained from the multichannel seismic data and corroborates the interpretation of a current-swept, sediment starved environment, locally dissected by turbidity channels.

Discussion

The Weddell Sea continental margin

The image of sedimentary processes and structures in the western Weddell Sea, which shows up from the presented data, fits relatively well into the general picture of sedimentary processes along the southeastern (off Coats and Dronning Maud Land), southern (off the Filchner-Ronne Ice Shelf), and northwestern (Powell and Jane Basin area) Weddell Sea known from the studies by Fütterer et al. (1988), Pudsey et al. (1988), Grobe and Mackensen (1992), Kuhn and Weber (1993), Melles and Kuhn (1993), Weber et al. (1994), Melles et al. (1995), Pudsey and King (1997), Gilbert et al. (1998), and Howe et al. (1998). A comparison of the western Weddell Sea with other areas illustrates some systematic changes along the margin, especially regarding the factors controlling sediment transport and drift formation.

In the southeastern Weddell Sea with its narrow continental shelves, the sediment is delivered directly to the slope even during interglacials (Grobe and Mackensen, 1992). During glacials, when the ice sheet was grounded to the shelf edge, the canyons served as a sediment conduit directly to the abyssal plain. Combined with the Weddell Gyre circulation being strongest on the shelf and upper continental slope (Fahrbach et al., 1992), low sediment input led to the formation of small-scale current features on the mid-slope terrace (see e.g. Figure 4e in Michels et al., in press).

In the southern Weddell Sea the dominant elements of the glacial-marine sedimentation system are the Filchner-Ronne ice shelves and the Crary trough-mouth fan (Kuvaas and Kristoffersen, 1991). During glacials the ice sheets advanced to the shelf edge, delivering enormous amounts of glacial debris to the fan. A vivid turbidity current activity within three major channel systems lead to the formation of huge levees along the left-hand side of the channels with sedimentation rates of more than 200 cm/ka on the proximal fan (Weber et al., 1994). In their distal courses the channels bend to an eastward direction, the turbidity current direction thus almost opposing the contour current direction of the Weddell Gyre.

The most significant differences for drift deposit formation in the southern Weddell Sea, compared to the Larsen Shelf area, are a much higher sedimentation rate during glacials, a less strong and less focussed contour current and, at least in its distal part, opposing directions of turbidites and contour currents. Nevertheless these two areas come close to each other in their sedimentary conditions.

The northwestern Weddell Sea continental slope and rise also show channelled sedimentation processes indicating turbidite activity, but current-related sediment features like mudwaves and residual coarse sediments are more dominant in the sedimentary environment (Gilbert et al., 1998; Howe et al., 1998). Compared to the area seaward of the Larsen Ice Shelf current-related features are more pronounced in the northwestern Weddell Sea, whereas channel-levee/ridge-related features are of minor importance. This may have two reasons: First, the western boundary current of the Weddell Gyre is better developed, additionally driven by the deep water formed on the Larsen Shelf; Second, the Quaternary sedimentation rate is significantly lower in the northwestern Weddell Sea, as there is no glaciated shelf bounding the continental slope, thus providing a lower potential for turbidity current activity.

The continental rise west of the Antarctic Peninsula

The drifts on the continental rise west of the Antarctic Peninsula have about the same alongslope extent as the channel-levee/drift bodies on the Larsen continental rise. Their height, however, is significantly greater. Another important difference lies in their shape. Whereas the Larsen channel-levee/drift bodies have a steeper upstream (S) and gentle downstream (N) side, a shape which is regarded as typical for levees, the drifts on the western side of the Antarctic Peninsula mostly have a gentle upstream (NE) and steep downstream (SW) side or are symmetric. Their shape orthogonal to the margin is characterised by a seafloor-trough on the landward side and a gently dipping slope seaward, which merges with the lower continental rise and abyssal plain.

Due to limited availability of seismic profiles and bathymetric data normal to the slope the Larsen channel-levee/drift bodies cannot be described sufficiently well in their basinward shape and extent. By analysis of profiles AWI-97050 and AWI-97051 a landward trough or moat and a gently seaward-dipping slope can be identified for the sediment body on this profile, whereas a ridge-like lateral extent along the channels can be assumed for the channel-levee/drift bodies on profile AWI-97070. This suggests that there generally is a greater variability in the sedimentary structures on the continental rise east of the Antarctic Peninsula than west of it.

Other Antarctic continental rise drifts

Bottom-current related sediment bodies have been described from additional areas around Antarctica (e.g., Kuvaas and Leitchenkov, 1992; Escutia et al., 1997). Sedimentary conditions around Antarctica seem to favour the development of drifts. But the variability of structures and settings arises the question, which factors control the development of drifts. Besides the basic condition of the presence of bottom currents, the development of bottom-current related sediment bodies usually involves the preceding or simultaneous activity of turbidity currents.

The variety of different settings suggests that it is not the mechanism of turbiditic sediment transport but more its effectiveness, which is important for the development of bottom-current related sediment bodies around Antarctica. Especially the examples from the area off the Larsen Ice Shelf presented here illustrate that availability of sediment is an important control. Right seaward of the Larsen Ice Shelf, where sedimentation rate is expected to be highest, particularly at times when grounded ice masses advance onto the shelf, current-related sediment structures are best developed.

The details of the interaction of turbidites with contour currents is a further point of uncertainty. The problem of separating contour- and turbidity-current influence originates basically in their mechanism of sediment supply. On one hand turbidity-current occurrence at the continental slope is positively correlated with the quantity of sediment supply at the shelf edge, and so the sedimentological expression of turbidites increase with sediment supply. On the other hand the process of contour-current development has no immanent sediment source unless the currents are able to erode. Thus even a permanent and well-developed contour current does not automatically generate its sedimentological expression. In a mutual occurrence of both, the contour current is likely to amplify the sedimentological mechanisms of turbidity-current deposition (i.e., levee formation along the channel), especially when Coriolis force on the turbidity current and suspension transport by the contour current act in the same direction, as is the case in the western Weddell Sea. To identify the influence of the contour currents in the resulting sediment sequence is a difficult task since there are no distinctive sedimentological criteria which discriminate the contour current effects from turbidity current ones.

The basic factors, which control whether the sediment bodies show the shape of a levee or a drift are hence inferred to be the interaction of sedimentation rate with bottom-current speed. Judging from modern data for current strength and sedimentation rates for the last glacial cycles, contour currents are stronger and sedimentation rates are higher in the southern Weddell Sea (Weber et al., 1994), whereas currents are stronger during interglacials in the northwestern Weddell Sea (Pudsey et al., 1988; Fütterer et al., 1988). Weber et al. (1994) reported on sedimentation rates of more than 200 cm/ka for the Last Glacial Maximum on the Crary Fan (water depth 2,500 m). Sedimentation rates on the channel levees/drift bodies in the western Weddell Sea (water depth 3,500 m) are 0.7 to 2.8 cm/ka for interglacial conditions and 1.6 to 5.5 cm/ka for glacial conditions down to oxygen isotope stage 9 (C. Holz, personal communication, 2001). The sedimentation rates of the drift bodies on the continental rise of the Pacific margin west of the Antarctic Peninsula (water depth 3,000 m) down to oxygen isotope stage 5e are 3.0 to 5.5 cm/ka (Pudsey and Camerlenghi, 1998). Pudsey (2000) reported late Quaternary interglacial sedimentation rates of 1.1 to 4.3 cm/ka and glacial sedimentation rates of 1.8 to 13.5 cm/ka for these drifts.

Current measurements 8 m above seabed in the drift area on the western side of the Antarctic Peninsula showed average speeds of 6 cm/s, with speed rarely exceeding 14 cm/s (Camerlenghi et al., 1997).

For the northwestern Weddell Sea and Jane Basin Pudsey and King (1997) reported on four current meter moorings, where during a period of 760 days the maximum current speed was 30 cm/s and mean current speed was 9.7 and 10.8 cm/s in 3,800 m and 4,500 m of water depths, respectively.

These data do not allow us, however, to reconstruct the exact interaction of turbidites with contour currents or to estimate their influence on sedimentary processes. We assume that combined drift and turbidity-current deposition also creates channel-levee structures, which lead to an underestimation of the drift component especially for older deposits. Only when drift deposition clearly dominates the turbidity current influence, typical drift-related structures develop.

Summary and Conclusions

We present sediment acoustic and multichannel seismic data from the continental rise of a previously unstudied area in the western Weddell Sea off the Larsen Ice Shelf. The following list summarises the main topographic elements and sedimentary features and gives an interpretation of the data regarding sediment transport processes and stratigraphic coverage. (1) The upper continental rise off the Larsen Ice Shelf is covered by a network of gullies and channels, separated by ridges with steeper southern and flatter northern slopes.

(2) Presently the larger channels are erosive, indicating that they are active turbidity current channels. Smaller channels are, like the ridges, draped by parallel bedded sediment sheets with lower sedimentation rates on the steeper than on the flatter side. Minima in sediment thickness (as revealed by reflectors in Parasound profiles) midway on the steeper slope of some channels suggest the presence of a contourite current.

(3) Some of the levees/drift bodies developed mudwaves on their crests. These cannot, however, be definitely attributed to either turbidity or contour current influence.

(4) Three different phases can be distinguished in the development of the channel-levee/drift system: (a) an initial phase of channelled growth (corresponding to the 'Drift growth' stage of Rebesco et al. (1997)), at the top delimited by an erosional unconformity. This phase is characterised by strong turbidity current activity, combined with contour currents. Early in this phase slumps and debris flows can occur; (b) a drift phase with decreased turbidity-current activity and a subsequently decreased sedimentation rate, which led to an infilling of minor channels and a preferential development of drift features by contourite-current activity; and (c) a phase of sheeted-sequence formation. Phases (b) and (c) correspond to the 'Drift maintenance' stage of Rebesco et al. (1997).

(5) The comparison of this sequence with the drift sequences on the western side of the Antarctic Peninsula allows an analogous dating of the stages. This may be justified because the causes of contour-current action and sediment control, the onset and strengthening of the Weddell Gyre circulation, and the onset

of grounded ice-sheet advances to the shelf edge, are basically the same. Accordingly, the age for the initial phase of channelled growth is late Miocene, the drift phase lasted the Pliocene, and the sheeted sequence phase is Pleistocene in age.

(6) With distance south from the Larsen continental slope and rise area the channel-levee/drift bodies are less well developed or absent. This suggests that turbidity-current input of sediment is critical for the development of these structures on the continental rise. It stresses the importance of a local sediment source.

(7) The development of drift characteristics was only observed where a sharp change in slope inclination favoured the growth of a drift body. This indicates that contour currents are only able to modify existing turbidite channel levees without being able to develop characteristic drift features. Only a change in topography gives the opportunity to build up characteristic drift features. This may be also true for settings in the southern Weddell Sea.

Acknowledgements

Numerous comments and suggestions, which helped to improved the quality of the manuscript considerably, were given in reviews by C. Pudsey, M. Rebesco, and G. Leitchenkov.

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