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Miocene to Recent contourite drifts development in the northern Weddell Sea (Antarctica)

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Abstract

Multichannel and high-resolution seismic profiles complemented with swath bathymetry show a variety of contourite deposits in the northern Weddell Sea resulting from the interaction between bottom currents and the seafloor physiography. Seven types of contourite drifts are identified based on the seismic signature, reflector configuration and geometry of the depositional bodies. Giant elongated–mounded drifts are widespread in the area and associated with major channelized contour currents that flow at the base of large ridges. Thick basement/tectonic drifts result from the seafloor disruptions of the currents caused by the irregularities of the near-surface basement morphology. Sheeted drifts occur under the main core of the Weddell Gyre and also in areas of the abyssal plain away from the main flows. Various types of drifts in-fill depressions or are plastered against steep bathymetric ridges that intersect contour currents. The regional distribution of the drifts is mainly controlled by the physiography of the basin and the confined or unconfined nature of the bottom-current flows.

The northern Weddell Sea is a region dominated by contourite processes and thus provides an area to compare contourite drifts with turbidite systems. The giant elongated–mounded drifts have a net asymmetry of the body, in contrast to turbidite channel–levee complexes that develop levees on each side of an axial turbidite channel. The basement/tectonic drifts prograde parallel to the main flow and are plastered following the irregularities of the basement unlike turbidite deposits. Other drifts, in contrast, show internal reflector characteristics similar to turbidite systems, such as the sheeted drifts. In these cases, however, the associations of turbidite and drift deposits are different. The giant elongate-mounded drifts are stacked along the margins and elongate or transverse drift sequences are observed in the basin centre of confined basins. In the unconfined setting, the

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drifts are normally asymmetric in relation to the marginal channel moats and sheeted drifts develop laterally from the ridges. In turbidite systems of confined or unconfined settings, generally symmetrical proximal channel–levee complexes evolve downstream to sheetlike basin plain sequences.

Five main seismic units separated by regional unconformities are recognized above the oceanic basement. The age of the deposits is based on the magnetic anomalies of the oceanic crust and the overlying seismic sequences. The external geometry and acoustic character of the seismic units indicate strong bottom-current processes, except for the basal deposits attributed to the Early Miocene. The development of extensive drifts in the deposits of Unit 4 (~Middle Miocene) shows the initial influence of the Weddell Sea Bottom Water (WSBW). The opening of the connection of Jane Basin with the Scotia Sea also is marked by a regional unconformity that records a reorganization of bottom flows. The two uppermost Units 1 and 2 (Late Miocene to Recent) indicate intensified bottom currents, which may reflect the increased production of WSBW. The evolution through time of the contourite deposits and the distribution of regional unconformities reflect the ice sheet dynamics that controlled the production of Antarctic Bottom Water (AABW).

Keywords: Contourite drifts; Antarctic paleoceanography; Weddell Gyre; glaciations

1. Introduction

The Weddell Sea is an oceanic basin about 1100 km long located south of the southwest Atlantic Ocean, between the Antarctic Peninsula to the west and the coasts of the East Antarctica to the south (Figs. 1 and 2). The magnetic anomalies of the oceanic crust show a Cenozoic age for the eastern part of the northern Weddell Sea (Tectonic Map of the Scotia Sea, herein BAS, 1985; Livermore and Woollett, 1993; Maldonado et al., 1998; Ghidella et al., 2002). The Scotia Sea, together with the Drake Passage, Powell and Jane Basins were created as a consequence of the spreading between South America and the northern Antarctic Peninsula, which was started during the Oligocene (Thomas et al., 2003). The development of these basins influenced the evolution of the continuous, deepwater circulation of the Antarctic Circumpolar Current (ACC). The ACC is proposed to have profound effects on the changes of the Antarctic climate and the north–

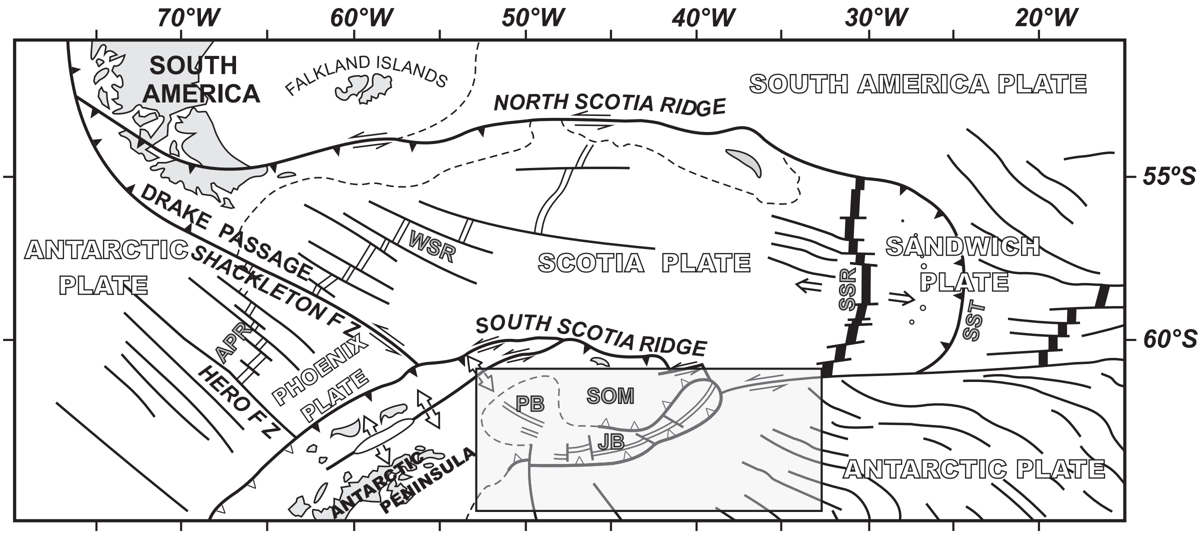


Fig. 1. Geological setting of the northern Weddell Sea. The rectangle indicates the study area. Legend: APR, Antarctic–Phoenix Ridge; F.Z., fracture zone; JB, Jane Basin; PB, Powell Basin; SOM, South Orkney Microcontinent; SSR, Scotia–Sandwich Ridge; SST, South Sandwich Trench; WSR, West Scotia Ridge. Description in the text.

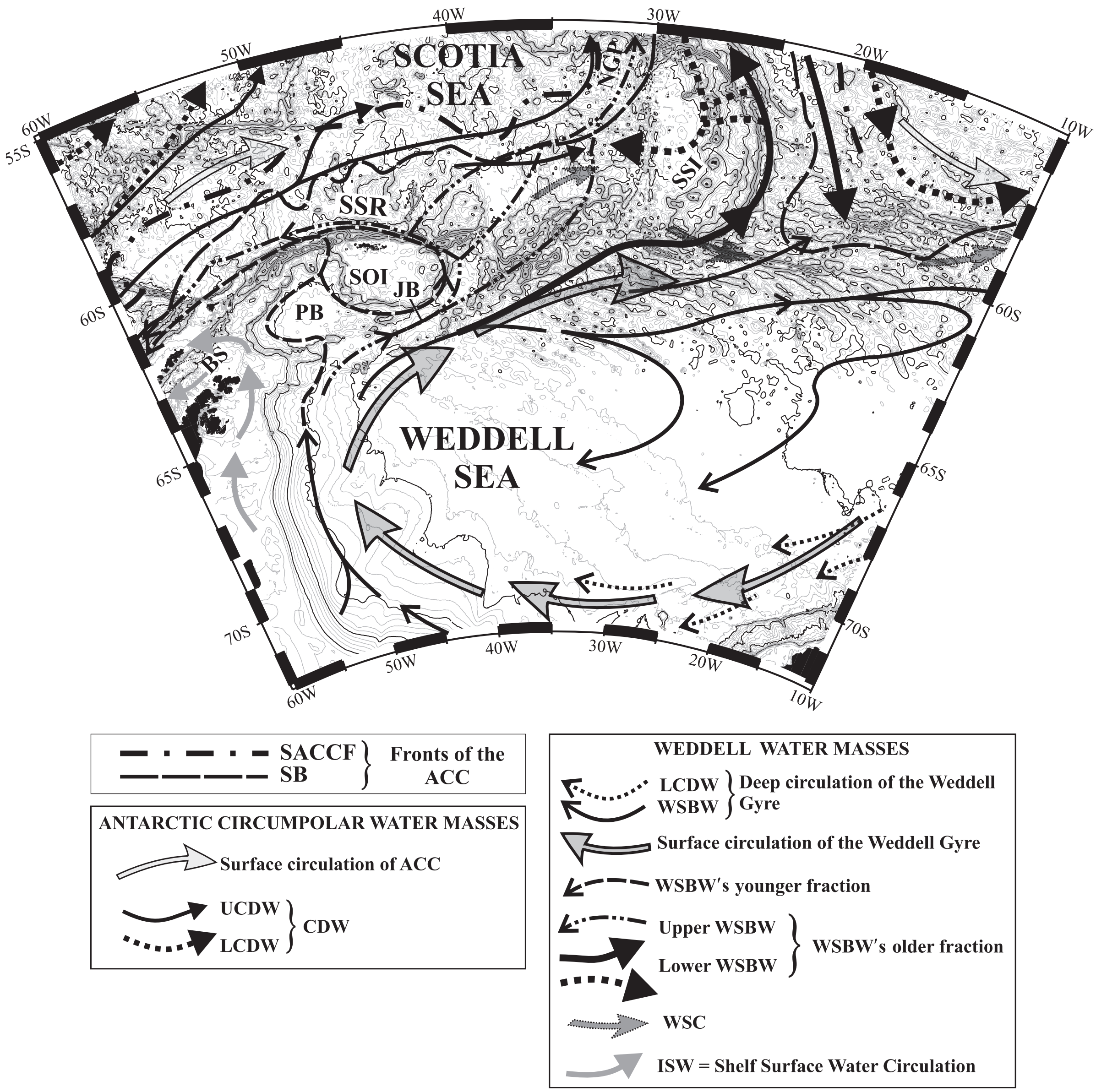


Fig. 2. Main bathymetric and oceanographic features of the Scotia Arc and the northern Weddell Sea region. The regional oceanographic setting of water masses in the Weddell Sea and the southern part of the Scotia Sea shows the Antarctic Circumpolar Current (ACC) fronts and the Weddell Gyre water masses. Legend. (1) Fronts of the ACC: SACCF=Southern ACC front; SB=Southern Boundary of the ACC; (2) Antarctic Circumpolar deepwater masses: CDW=Circumpolar Deep Water; LCDW=Lower Circumpolar Deep Water; UCDW=Upper Circumpolar Deep Water. (3) Weddell Water masses: LCDW=eastern branch in the Weddell Sea of the LCDW; WSBW=Weddell Sea Bottom Water; WSC=Weddell Scotia Confluence; ISW=Shelf Surface Water Circulation;. Geographic locations: BS=Bransfield Strait; JB=Jane Basin; PB=Powell Basin; SOI=South Orkney Island; SSI=South Sandwich Islands; SSR=South Scotia Ridge. (Modified from: Hollister and Elder, 1969; Nowlin and Zenk, 1988; Locarnini et al., 1993; Orsi et al., 1993, 1995, 1999; Whitworh et al., 1994; Barber and Crame, 1995; Pudsey and Howe, 1998; Arhan et al., 1999; Meredith et al., 2001). Discussion in the text.

south ocean circulation patterns (Kennett, 1977; Barrett, 1996; Lawver and Gahagan, 1998).

Paleoceanographic studies of the northern Weddell Sea are important because this area of seafloor is influenced by the Weddell Gyre, which is a main component of the global thermohaline circulation and is the source for a majority of the cold bottom water of the oceans (Fahrbach et al., 1995; Orsi et al., 1999). Previous studies have shown the importance of combined contourite–turbidite sedimentation in the margins of the western Weddell Sea (Michels et al., 2002) and of fine-grained contourites and hemipelagites over the basin plain (Pudsey, 1992, 2002). The sedimentary processes in the Weddell Sea are influenced by ice-shelf dynamics and the Weddell Gyre (Jokat et al., 1996; Rogenhagen and Jokat, 2000). The sediments overlying layers 2 and 3 of the oceanic crust have documented a continuous record of deposition that seems to date the inception of the deep Weddell Sea Bottom Water (WSBW) into Powell Basin back to the Early Miocene (Coren et al., 1997; Rodríguez-Fernández et al., 1997; Howe et al., 1998). The sediments of Pliocene to Quaternary age recovered from ODP Site 967 in Jane Basin also reveal long-term downcore changes of bottom-current processes and glacial influences (Pudsey, 1990). All these deposits have a potential for high-resolution palaeoclimate studies. At present, however, there has not been a regional analysis of the sediment distribution or of the stratigraphic evolution related to bottom-current patterns.

The objectives of this study are to analyze the influence of the WSBW flows on sea-bottom processes and related depositional patterns in the northern Weddell Sea and define its paleoceanographic evolution since the Early Miocene. We describe and analyze an extensive field of contourite deposits that resulted from the interplay between the bottom currents and the complex physiography of basins, ridges and banks. The history of the deepwater flows is recorded in the area by the extensive distribution of contourite deposits above the igneous basement. The spatial distribution of the different type of deposits and their temporal evolution is described. From this, we show the importance of cold deepwater production and discuss its impact in global paleoceanography and the onset of glaciations. The large variety of contourite deposits and their characteristic depositional features observed in the seismic records also allow us to identify some criteria to distinguish between contourite and turbidite deposits in the stratigraphic record, one key issue for paleoceanographic and environmental interpretations.

2. Oceanographic framework and regional tectonic

2.1. Regional oceanography

The two most important deep current systems in the Southern Ocean are the circumpolar eastward flow of the Antarctic Circumpolar Current (ACC), which interacts with the seafloor in many places, and the northward flow of the Antarctic Bottom Water (AABW). The ACC controls the transport of heat, salt and nutrients around the Southern Ocean (Figs. 1 and 2). The ACC has a flow of some $100–140\times10^6$ m^3/s of water from the sea bed (7–12 cm/s) to the sea surface (20–60 cm/s) and is the principal contributor to the boundary currents of the South Atlantic, South Pacific and Indian Oceans (Nowlin and Klinck, 1986; Foldvik and Gammelsrød, 1988; Naveira-Garabato et al., 2002). The Circumpolar Deep Water (CDW) flows continuously to the east, together with the ACC. The CDW is internally structured into the Upper Circumpolar Deep Water (UCDW) and Lower Circumpolar Deep Water (LCDW). Orsi et al. (1999) reserve the generic term of AABW to embody the total volume of southern bottom waters without a circumpolar distribution and that are denser than CDW (Fig. 2). About 80% of the AABW is generated by supercooling and brine rejection of different water masses under the floating ice shelves, mainly from the Weddell Sea (Gordon and Tchernia, 1972; Foldvik and Gammelsrød, 1988). The influence of the production of AABW on ocean circulation and climate through the northward flow of deep water are well recognized (Nowlin and Klinck, 1986; Duplessy et al., 1988).

The Weddell Scotia Confluence (WSC) is found south of the Southern Boundary of the ACC (Fig. 2). The cyclonic Weddell Gyre is influenced by the eastward flow of the circumpolar water masses (Sievers and Nowlin, 1984; Whitworh et al., 1994; Meredith et al., 2001). A branch of the LCDW flows into the eastern and southern Weddell Sea (Fig. 2). In the northwestern Weddell Sea, the Ice Shelf Water (ISW) flows northwestward below the ice shelf, getting colder (Sievers and Nowlin, 1984; Whitworh et al., 1994; Orsi et al., 1995; Meredith et al., 2001). This water mass also sinks and mixes at around 2000 m water depth with the LCDW, leading to the formation of the Weddell Sea Bottom Water (WSBW), which is considered to be supercooled CDW in the southwestern and western Weddell Sea (Foldvik and Gammelsrød, 1988; Orsi et al., 1993, 1999). The WSBW is bathymetrically constrained by Coriolis force to circulate northward and eastward within the Weddell Gyre. The WSBW has an internal structure composed of two different fractions. The younger WSBW fraction mainly moves across the Powell Basin in a clockwise direction, and it partially escapes northwards to the Scotia Sea (Howe et al., 1998). The older WSBW fraction flows below and it is divided into two different main cores. The shallower Weddell Sea Deep Water (WSDW) core is channelized through Jane Basin and flows into the Scotia Sea though gaps of the South Scotia Ridge (Naveira-Garabato et al., 2002; Maldonado et al., 2003). Another important deeper core moves around the South Sandwich Trench toward the north (Fahrbach et al., 1995; Gordon et al., 2001; Naveira-Garabato et al., 2002). A branch of the WSDW spreads westward along the northern slopes of the South Scotia Ridge and it reaches the Antarctic Pacific Margin (Orsi et al., 1999; Naveira-Garabato et al., 2002; Camerlenghi et al., 1997; Rebesco et al., 1997).

2.2. Tectonic setting and paleoceanography

Two main lithosphere plates are recognized in the western South Atlantic: the South American and the Antarctic plates; both of them contain continental and oceanic crust (Fig. 1). The Scotia Sea is located in the boundary between these two major plates, resulting from the fragmentation of the continental connection between South America and the Antarctic Peninsula (Barker et al., 1991). The Scotia plate began to develop at least by 28.5 Ma (BAS, 1985). The most important seismic activity of the region is located mainly in the South Sandwich Island arc and extends along the North and South Scotia Ridges, which determine, respectively, the northern and southern boundaries of the Scotia and Sandwich plates (Pelayo and Wiens, 1989; Thomas et al., 2003). Located along the South Scotia Ridge are deep basins between large blocks of continental crust (Galindo-Zaldívar et al., 1994, 2002).

The main bathymetric features of the oceanic crust of the northern Weddell Sea are recognized from satellite free-air gravity anomalies (Livermore et al., 1994; Sandwell and Smith, 1997). The oceanic seafloor west of 47°W is of Mesozoic age and is mostly uniform, with no magnetic anomalies and only regular gravimetric gradients (LaBrecque et al., 1986, 1989; Kavoun and Vinnikovskaya, 1994; Livermore and Hunter, 1996). The abyssal plain of the eastern province, in contrast, is disrupted by linear, slightly arched fracture zones with a WNW–ESE orientation (Figs. 1 and 3). The fracture zones have a morphological expression by ridges several tens to hundreds meters high above the surrounding seafloor, that is rather flat and with an average depth of 4.2–4.7 km. These ridges have an asymmetric profile, with a subdued western flank and steep slopes in the eastern flank. The boundary between the two provinces is depicted by a NNW–SSE-trending major tectonic fracture observed in multichannel seismic profiles (Maldonado et al., 1998). The oceanic crust also shows linear magnetic anomalies almost orthogonal to the fracture zones (Livermore and Woollett, 1993; Ghidella et al., 2002; Golynsky et al., 2002). The youngest crust in the study area has an age of about 20 Ma (C6An).

Jane Basin is 350 km long, with an average width of 100 km and 3 km depth (Figs. 1 and 3). The basin was developed within a backarc setting, related to the subduction of the Weddell Sea oceanic crust below Jane Bank (Lawver et al., 1991; Bohoyo et al., 2002). The active spreading ridge of the Weddell Sea collided with the trench and was subducted below Jane Bank at 15–20 Ma (Bohoyo et al., 2002). Spreading in Jane Basin and subduction below Jane Bank ended shortly thereafter, in the middle Miocene, and the boundary between the Antarctic–Scotia plates migrated north of the South Orkney Microcontinent, along the South Scotia Ridge. Present tectonic inactivity of Jane arc and backarc system is demonstrated by the absence of seismicity in the region (Pelayo and Wiens, 1989; Galindo-Zaldívar et al., 1996; Maldonado et al., 1998).

The Drake Passage, together with the opening of a strait between the South Tasman Rise and East Antarctica were the final seaways for a complete circum-Antarctic deepwater flow (Lawver et al., 1992; Lawver and Gahagan, 2003). The development of a strong current over the South Tasman rise is

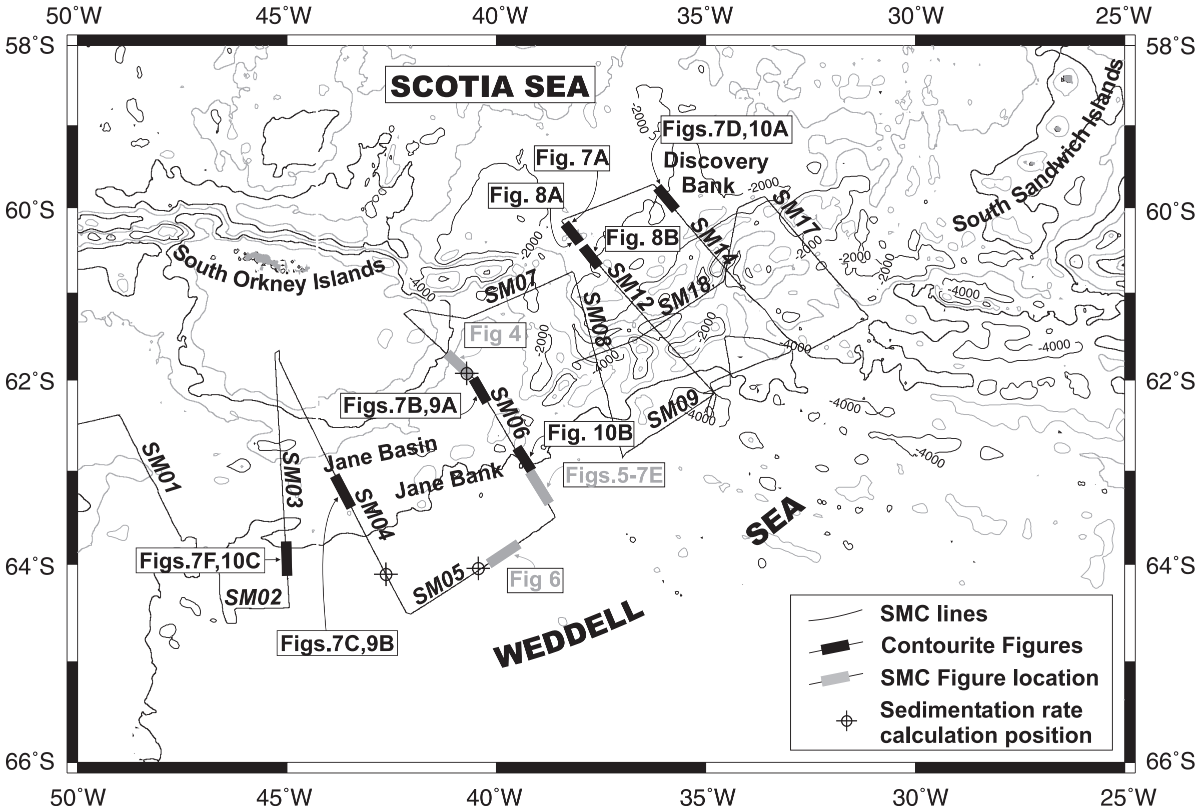


Fig. 3. Bathymetry derived from satellite gravimetry, and location chart of the SCAN 97 cruise with BIO HESPERIDES track lines. Thick lines represent the location of the seismic profiles illustrated in Figs. 4–6, 9–11. The locations of the sites selected for the calculation of sedimentation rates are also shown. Depth in meters. Simplified map from the GEOSAT gravimetric anomaly map recently released by the U.S. Navy.

estimated at 32 Ma, whereas the timing of the opening of Drake Passage is less constrained. The identification of magnetic anomalies suggests that Drake Passage was open to deepwater flow by 29 Ma, although it was probably created earlier, by 31±2 Ma (Maldonado et al., 2000; Lawver and Gahagan, 2003). The seaways located in the Scotia Sea region controlled the evolution of the ACC and the circum-polar deep water flows because of a changing scenario of ridges and basins that were active during the early stages in the development of the region (Barker and Hill, 1981; Barker, 2001; Maldonado et al., 2003). The fall of high latitudes water temperature from high of 15 °C to below 5 °C that occurred during the earliest Oligocene in the southern oceans (Zachos et al., 1994) seems to coincide with the opening of the Antarctic deepwater seaways (Kennett and Stott, 1990; Mead et al., 1993).

3. Methods

During the January–February 1997 austral season, the SCAN97 cruise was conducted aboard the BIO HESPERIDES and, because of the favourable ice conditions, provided an excellent opportunity to collect geophysical data along several profiles in the northern Weddell Sea (Figs. 1 and 3). Most of the profiles are orthogonal to the trend of the main tectonic features of the region, which include the margin of the South Orkney Microcontinent, Jane Basin and Jane Bank (SM01, SM03, SM04, SM06, SM07, SM08, SM12, SM14 and SM17). We also collected several profiles orthogonal to the main tectonic trends of the northern Weddell Sea (SM02, SM05, SM09 and SM18). Gravity, magnetic, swath bathymetry and multichannel seismic data were acquired along these profiles. In addition, high-resolution subbottom profiles were obtained in areas without high relief using a Topographic Parametric Source (TOPAS, BENTECH Subsea PS018) operated at 1.5–4.0 kHz and digitally processed in real time. The swath bathymetric data were collected with a SIMRAD EM12 System and postprocessed with the NEPTUNE software. Visualization was achieved with the FLEDERMAUS program.

The multichannel reflection seismic profiles were obtained with a tuned array of 5 BOLT air guns with a total volume of 22.14 l and a 96-channel streamer with a length of 2.4 km. The shot interval was 50 m. Data in a frequency range of 8 to 128 Hz were recorded with a DFS V digital system and a sampling record interval of 2 ms and 10 s record lengths. The data were processed with a standard sequence, including migration using a DISCO/FOCUS system. A near-field trace of the MCS profiles was also processed with the high resolution DELPH system.

Total intensity magnetic field data were recorded using a Geometrics G-876 proton precession magnetometer. Magnetic profiles SM03, SM04 and SM06 were modelled in order to asses the age of the crust (for details see Bohoyo et al., 2002).

4. Seismic stratigraphy

The MCS profiles show a sequence of depositional units above the basement represented by Layer 2 of the

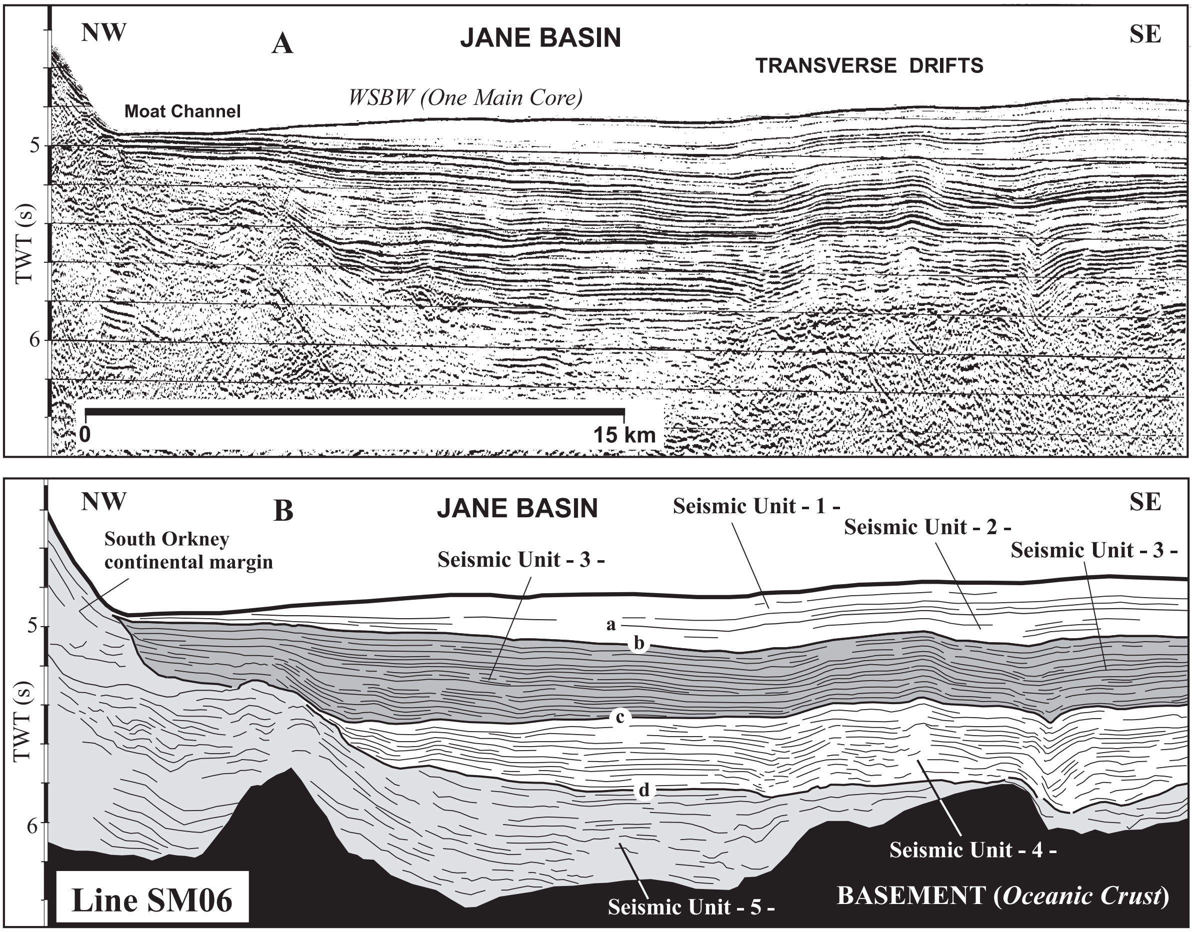


Fig. 4. Selected section of a MCS profile and a line drawing interpretation, illustrating the structure and seismic units of Jane Basin. MCS profile SM06 perpendicular across the northern Jane Basin and the South Orkney margin. See Fig. 3 for location.

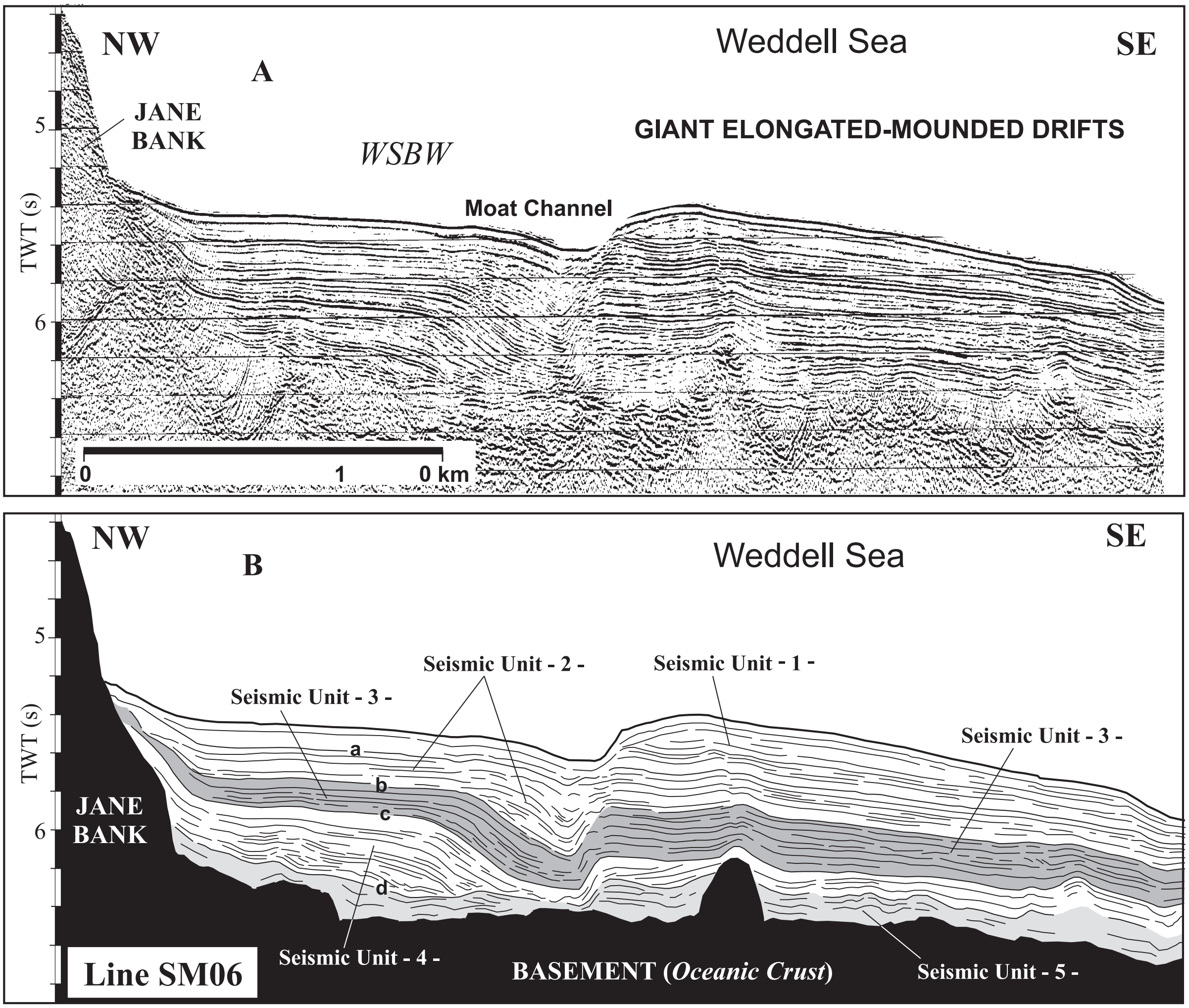


Fig. 5. Selected section of MCS profile SM06 and a line drawing interpretation illustrating the structure and seismic units across the northern sector of the Weddell Sea and the southern margin of Jane Bank. Profile is perpendicular to the main depositional trends of the drifts. See Fig. 3 for location.

oceanic crust (Figs. 4–6). The basement, characterized by high amplitude reflections, is located at depths of 0.8 to 1.6 s (twt) below the seafloor, although locally, the sedimentary cover above the igneous crust is absent. The seismic profiles show a variety of depositional and erosional morphologies and an irregular distribution of the depositional sequences. Four discontinuities characterized by high amplitude continuous reflectors (named a to d from top to bottom) separate five seismic units (named 1 to 5 from top to bottom) that are regionally identified across the area (Table 1). The unit boundaries are conformable or show small-scale erosional features above the underlying deposits and are overlain by reflectors that are either conformable or exhibit downlap terminations.

4.1. Seismic units

4.1.1. Unit 5

This unit lies directly above the igneous basement, filling depressions and onlapping the margins of the spreading ridge of Jane Basin (Figs. 4–6). Unit 5 consists of parallel and discontinuous internal reflectors that evolve laterally into chaotic reflections. The

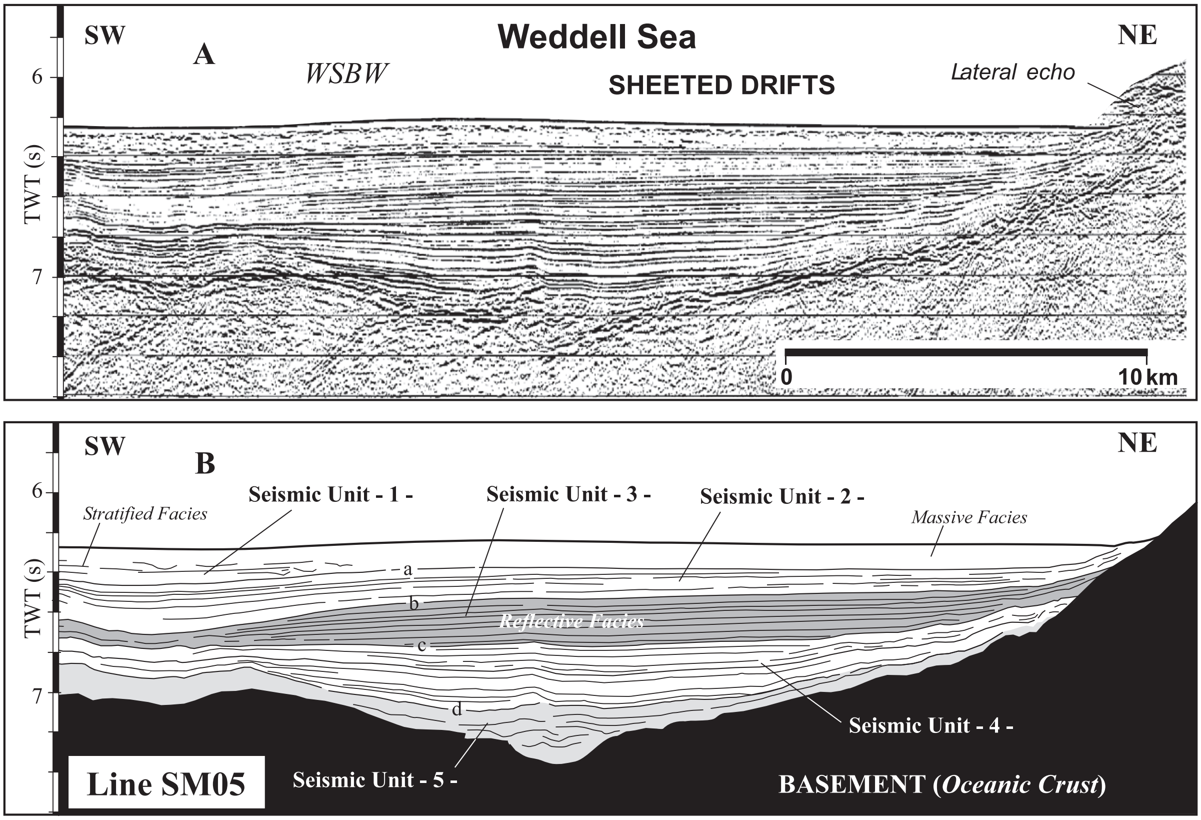


Fig. 6. Selected section of a MCS SM05 profile and a line drawing interpretation illustrating the structure and seismic units of the northern Weddell Sea. Profile is parallel to the main depositional trends of the drifts. See Fig. 3 for location.

thickness varies between 0.7 s (twt) in the depressions of the basement and absent over the structural highs. The unit is tectonically deformed by faults. Unit 5 is bounded at the top by an irregular erosional surface (Reflector d). The reflector amplitude varies laterally. It is laterally discontinuous in Jane Basin, although regionally present in the Weddell Sea, where it represents the most important discontinuity of the abyssal plain.

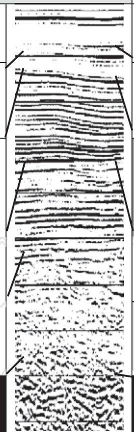
4.1.2. Unit 4

This unit is deposited above Unit 5 or directly on top of the basement. The reflectors onlap the margins of Jane Basin and the structural highs of the basement, whereas they downlap Reflector d or become concordant basinwards with the underlying deposits. Unit 4 is well stratified, with an aggradational configuration. The internal reflectors are continuous, with low to high amplitude that becomes weaker towards the basement highs (Figs. 4–6). The geometry of the unit is lenticular in the Weddell Sea, bounded between structural highs of the basement. The thickness ranges between 0.6 s (twt) and absent in the proximity of the margins and banks (Fig. 6). The top boundary (Reflector c) is a high-amplitude reflector over the region, with a clear erosional character and irregular relief, that is the most important regional unconformity in Jane Basin (Fig. 4).

4.1.3. Unit 3

The basal reflectors of this unit show downlap terminations over Reflector c (Fig. 4). The internal configuration is formed by high amplitude and laterally continuous reflectors. Unit 3 is composed of two well-developed subunits that show progradational geometries and similar internal reflector configuration in Jane Basin (Table 1). The thickness of Unit 3 ranges between 0.1 and 0.6 s (twt). Significant thickness variations are observed in Jane Basin, from

Table 1
Summary of the depositional sequences above the oceanic basement Layer 2 based on the MCS profiles (see Figs. 4–6)

JANE BASIN SEISMIC FACIES				SEISMIC UNITS		WEDDELL TENTATIVE AGE	WEDDEL SEA SEISMIC FACIES			
Paleoceanographic events		Seismic characteristics						Seismic characteristics	Paleoceanographic events	
Contourite processes by the **WSBW**	Increased bottom energy. Extensive development of contourite deposits	Transparent seismic configuration. Sediment waves.		1		Late Pliocene to Recent		Transparent seismic configuration. Laterally stratified discontinuos weak reflectors and chaotic reflectors.	Contourite processes by the **WSBW**	Increased bottom energy. Extensive development of contourite deposits.
					a	**~3.5 Ma**				
		Well stratified internal reflectors, aggradational with weak reflectivity. Tabular shape. Sediment waves.		2		Late Miocene to Early Pliocene		Well stratified internal reflectors, aggradational, weak reflectivity. Tabular shape. Continuous reflectors and chaotic facies.		
					b	**~6.8 Ma**				
	Northeastern exit of Jane Basin into the Scotia Sea.	Unit with very high acoustic response. Well stratified with high amplitude reflectors. Internally composed of 2 subunits with progradational configurations. Sediment waves.		3		Late Miocene		Well stratified with high amplitude reflectors. Very homogeneous facies. Very high acoustic response. Important changes in thickness.		Reorganization of bottom flows.
					c	**~12.1 Ma**				
	Bottom currents	Well stratified internal reflectors, aggradational with moderate amplitude reflectors.		4		Early to Middle Miocene		Aggradational pattern with high amplitude reflectors.		Bottom currents.
					d	**~18.7 Ma**				
Not evidences of contourite deposits		Not well organized. Continuos to discontinuos reflectors		5		Early Miocene		Not well organized. Discontinuos to chaotic reflectors.	Not evidences of contourite deposits	
Basement. High amplitude reflections. Frequent diffractions. Irregular morphology				**BASEMENT IGNEOUS CRUST**				**Basement. High amplitude reflections. Frequent diffractions. Irregular morphology**		

The main characteristic and tentative age of the five seismic units and reflectors identified in the area are summarized. Discussion in the text.

0.2 s in the southern flank to 0.5 s in the northern flank, and in the Weddell Sea, with less than 0.1 s (twt) near basement highs and in related channels. The top boundary (Reflector b) is a laterally continuous, irregular and undulated reflector of low amplitude that is conformable or erosional over the underlying deposits.

4.1.4. Unit 2

This unit is largely conformable over the underlying deposits in the center of the basins, whereas onlap terminations are common towards the margins. The unit is mostly transparent, with some low amplitude internal reflectors that increase reflectivity towards the top (Table 1). The reflectors display an aggradational configuration and they show variable continuity. The geometry is sheeted, but thins out towards the marginal channels of the drifts, such in the northern flank of Jane Basin (Fig. 4). The average thickness is about 0.2 s (twt). The top boundary (Reflector a) is a laterally continuous, high-amplitude reflector that locally changes in character to low amplitude. It is normally conformable or erosional over the underlying deposits.

4.1.5. Unit 1

This unit is characterized by the dominance of transparent and chaotic seismic facies (Figs. 4–6). The unit is more reflective at the base, becoming more transparent towards the top. The maximum thickness is 0.2 s (twt) along the axis of Jane Basin, but it thins towards the margins, where it is absent in the northern marginal contourite channel (Fig. 4). The thickness may reach 0.3 s (twt) in the Weddell Sea, but it also thins laterally over structural highs and contourite channels (Figs. 5 and 6).

4.2. Age of the oceanic crust and regional reflectors

The age of regional reflectors were tentatively estimated for three representative stratigraphic sections selected on the MCS profiles from the northern Weddell Sea (see Maldonado et al., 2003, for the detailed description of the methodology). These profiles were chosen according to the seismic characteristics of the deposits in areas of continuous, predominant hemipelagic deposition and without major erosional features (Fig. 3). The basic parameters used for the calculation are: (1) the age of the basement provided by the magnetic anomalies and (2) the total thickness of the depositional sequence for each section. The travel time depth (twt) of the reflectors was converted into depth in meters using the stacking velocity derived from the MCS profile velocity analysis and complemented with the results of refraction experiments in the nearby Powell Basin (King et al., 1997) for the total depositional sequence. Profiles SM04 and SM06 in the northern Weddell Sea, close to Jane Bank, provided an age of 19.5 Ma (Chron C6n, Early Burdigalian). The oceanic crust becomes younger northeastward, where Chron C5 (Early Tortonian, 9.6 Ma) is the youngest anomaly identified in the area (Livermore and Woollett, 1993). Our analysis of the magnetic anomalies (Bohoyo et al., 2002) also indicate that Jane Basin developed between Chron C5Dn (Late Burdigalian, 17.4 Ma.) and Chron C5ADn (Early Serravallian, 14.4 Ma).

The age of each reflector was also constrained by the sedimentation rate of surface sediment cores and the results of ODP boreholes. The precise sedimentation rates of the Quaternary deposits in the northern Weddell Sea are difficult to calculate because of the lack of biogenic carbonate and the presence of reworked organic material. These sediments, however, show cyclicity and the magnetostratigraphy, trace elements and isotope geochemistry suggest a fairly consistent Late Quaternary sedimentation rate of 3–4 cm/ky for the last 300 ky (Pudsey, 2002 and references therein). The sediments of the ODP Site 697 in Jane Basin provided a sedimentation rate of 4.4 cm/ky for the upper 200 m, that increased down core to about 10 cm/year for the interval of 250–300 m (Barker et al., 1988; Gersonde et al., 1990; Ramsay and Baldauf, 1990). All these results show low sedimentation rates for the Quaternary and the Late Pliocene (less than 3–4 cm/ky), which increase downcore and may reach about 10 cm/ky in the Late Miocene.

With these assumptions, we calculate the following ages for the regional reflectors identified in the northern Weddell Sea (Table 1, Fig. 3): Reflector a, 3.5 Ma (3.3 to 3.7 Ma), early Late Pliocene; Reflector b, 6.8 Ma (6.5 to 7.2 Ma), early Messinian; Reflector c, 12.1 Ma (12 to 12.2 Ma), Serravallian; Reflector d, 18.7 Ma (17.6 to 19.8 Ma), Burdigalian.

5. Drift deposits

Nearly all the sedimentary features in the northern Weddell Sea and Jane Basin are current-related depositional bodies or erosional scour from the strong bottom-current regime and its interplay with the topographic disruptions of current flows (Figs. 2, 7). Most of the wide variety of large- and medium-scale contourite drifts observed in the northern Weddell Sea have been described in other worldwide and nearby areas (e.g., Faugères et al., 1999; Michels et al., 2001; Rebesco and Stow, 2001; Pudsey, 2002; Stow et al., 2002; Maldonado et al., 2003). We have mainly used the summary seismic profile criteria and terminology of Rebesco and Stow (2001, see their Fig. 2) to help define the types of northern Weddell Sea contourite drifts. Swath bathymetric data have allowed us to make some modifications to their terminology and make it more specific to describe seven main types of drifts identified in northern Weddell Sea.

5.1. Giant elongated–mounded drifts

We can distinguish both giant and medium-scale elongated contourite drifts. The giant elongated–mounded drifts exhibit high relief from 200 to 400 meters above the abyssal seafloor (Figs. 8B, 9A and 10B). The width of the giant elongated drifts is 5 to 20 km. Although the length of the drift bodies can only be observed continuously for 10 km in our bathymetric swaths (Fig. 7E), their length probably extends for tens of kilometers to 200 km along the same ridge assuming they continue between our widely spaced seismic lines (Fig. 3).

The entire giant drift bodies onlap onto steep slopes of bedrock ridges in some locations or they downlap onto preexisting older drift deposits (Fig. 8B). The giant elongated–mounded drift deposits are characterized by convex up lenticular seismic reflectors and also exhibit local scour and fill and occasional through-going unconformities.

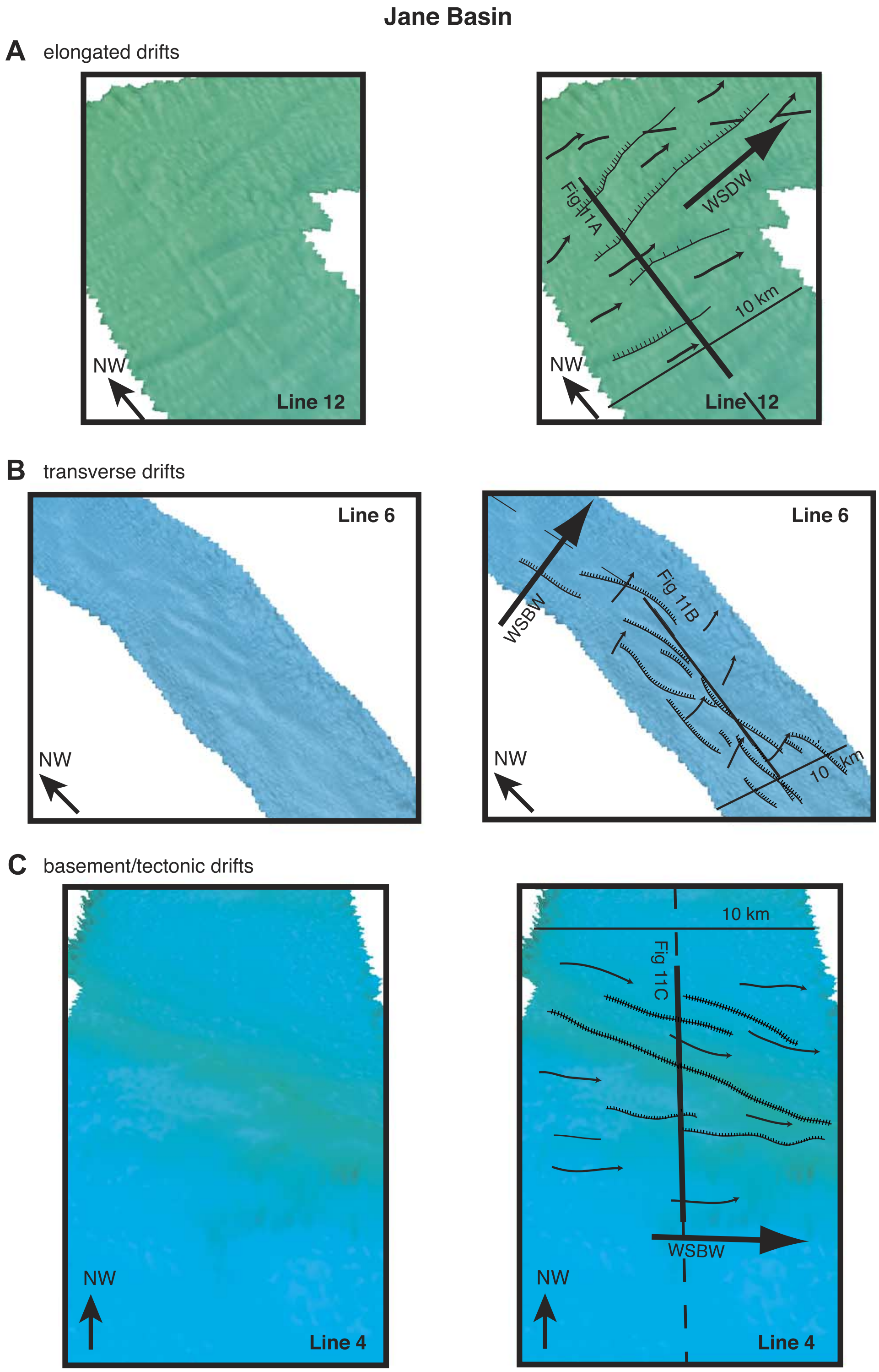
5.2. Elongated drifts

An area with multiple, smaller-scale elongated drifts, that trend southwest to northeast, is found in the constricted passage from Jane Basin into Scotia Sea. The seafloor expression of the drift ridges shows an irregular spacing of 1–4 km between crests with crest lengths of 5–10 km, widths of 1.5–2 km and heights of 15 to 45 m (Figs. 7A and 8A). The present seafloor has some truncation of reflectors along both lateral margins of elongate drifts (Fig. 8A). Truncation is more common, however, on the steeper side of the drifts, whereas reflector continuity is better on the gentler margins. The large-scale association of single drift bodies with ridges, sediment erosion and formation of moat channels along the ridges, and lenticular mounds within drifts are criteria that distinguish the giant elongated–mounded drifts as a separate category from smaller-scale elongated drifts.

5.3. Transverse drifts

In the southern part of Jane Basin, unlike the more constricted northern part, transverse drifts are found (Fig. 7B). Their relief varies from 25 to 75 m, the wavelengths range from 5 to 8 km and the crest lengths extend from 13 to 28 km (Fig. 9A). In seismic profiles, the transverse drifts exhibit wavy and continuous reflectors, and are mainly developed in the youngest seismic unit (Fig. 9A), where distinct sediment waves are observed on the seafloor (Fig. 7B).

Fig. 7. Three-dimensional imagery from multibeam bathymetry showing the main contourite deposits of the area. Nomenclature is the same as in Figs. 8–10. (A) South to north detailed view of the multiple elongate sedimentary drifts associated with the WSDW current at the entrance to the Scotia Sea. The detailed subsurface geometry of these elongate drifts is shown in Fig. 8A. (B) South to north detailed view of transverse drifts or sediment waves developed by the WSBW flow in the centre of Jane Basin. The detailed subsurface geometry of these transverse drift deposits is shown in Fig. 9A. (C) South to north view across the southern Jane Basin area showing the relationship between basement ridges and parallel drift deposits. See Fig. 9B for the subsurface characteristics. (D) South to north view of levee drift contourite deposits between Discovery Bank ridges. See Fig. 10A for subsurface characteristics. Key: M=moat, C=channel, LD=levee drift. (E) South to north view of northern Weddell Sea showing current-scoured Jane Bank on the north and multiple giant elongated and mounded drifts to the south. See Fig. 10B for subsurface characteristics. Key: JB=Jane Bank, M=moat, GED=giant elongated drift, C=channels, SD=sheeted drifts, ED=elongated drifts. (F) South to north view of northern Weddell Sea showing current-scoured Jane Bank on the north, with slope-plastered drifts and sheeted drifts (SD) deposits developed along the bank. See Fig. 10C for subbottom features. For locations see Fig. 3.


Jane Basin
A elongated drifts
NW
Line 12
Fig 11A
WSDW
10 km
NW
Line 12
B transverse drifts
Line 6
NW
Line 6
WSBW
Fig 11B
10 km
NW
C basement/tectonic drifts
NW
Line 4
10 km
Fig 11C
WSBW
NW
Line 4

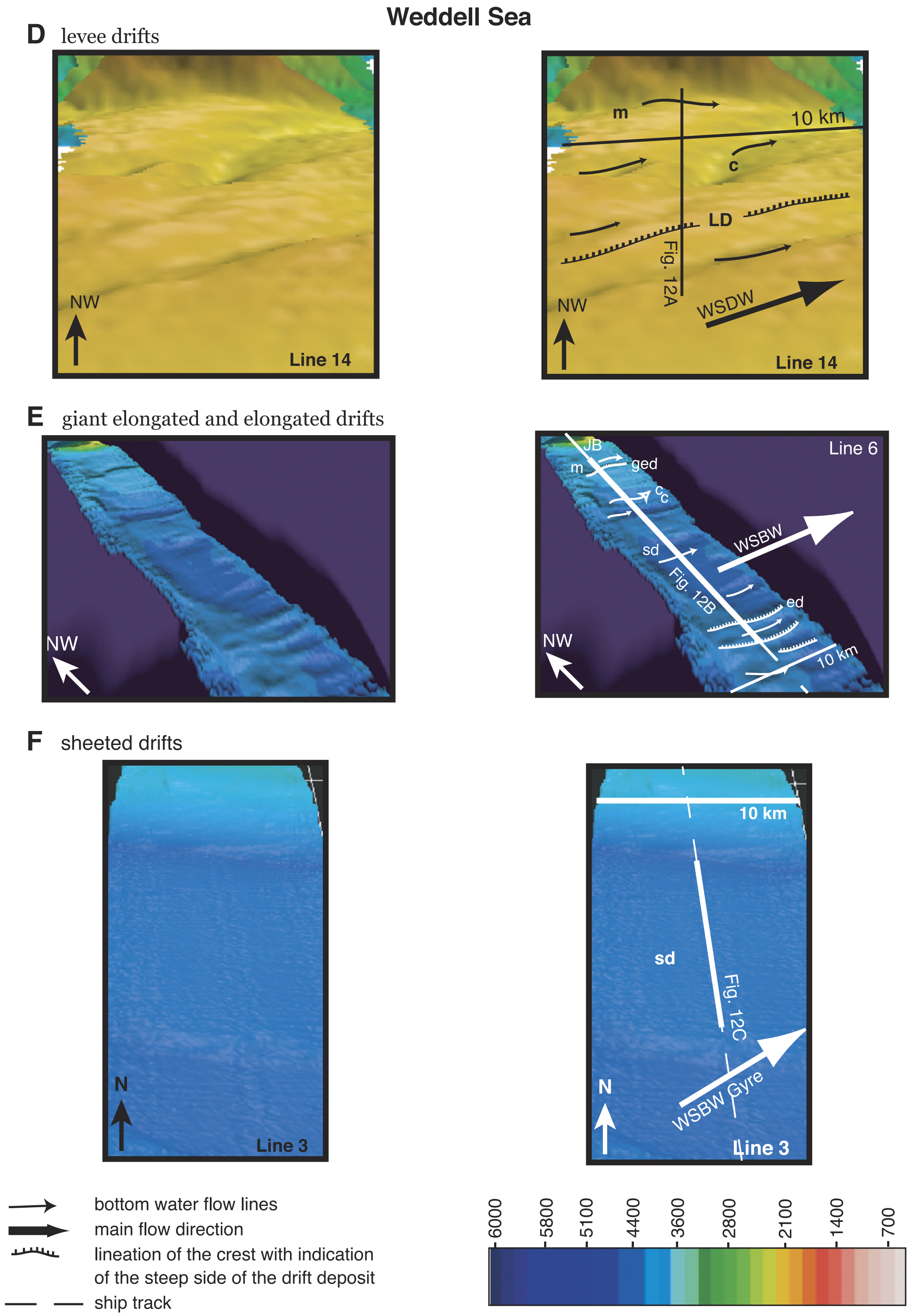


Fig. 7 (*continued*).

5.4. Basement/tectonic drifts

In the Weddell Sea, basement/tectonic drifts result from many types of irregularities of the basement surface, including faults, syn-depositional fault reactivation and diapirs. Typically, the east- to west-trending basement ridges develop drifts paralleling the ridge trends (Fig. 7C). These basement/tectonic drifts have a relief of 75 to 300 m above the surrounding seafloor and the distance between crests have a wide variation from 3 to 18 km that reflects the spacing of the basement ridges (Fig. 9B).

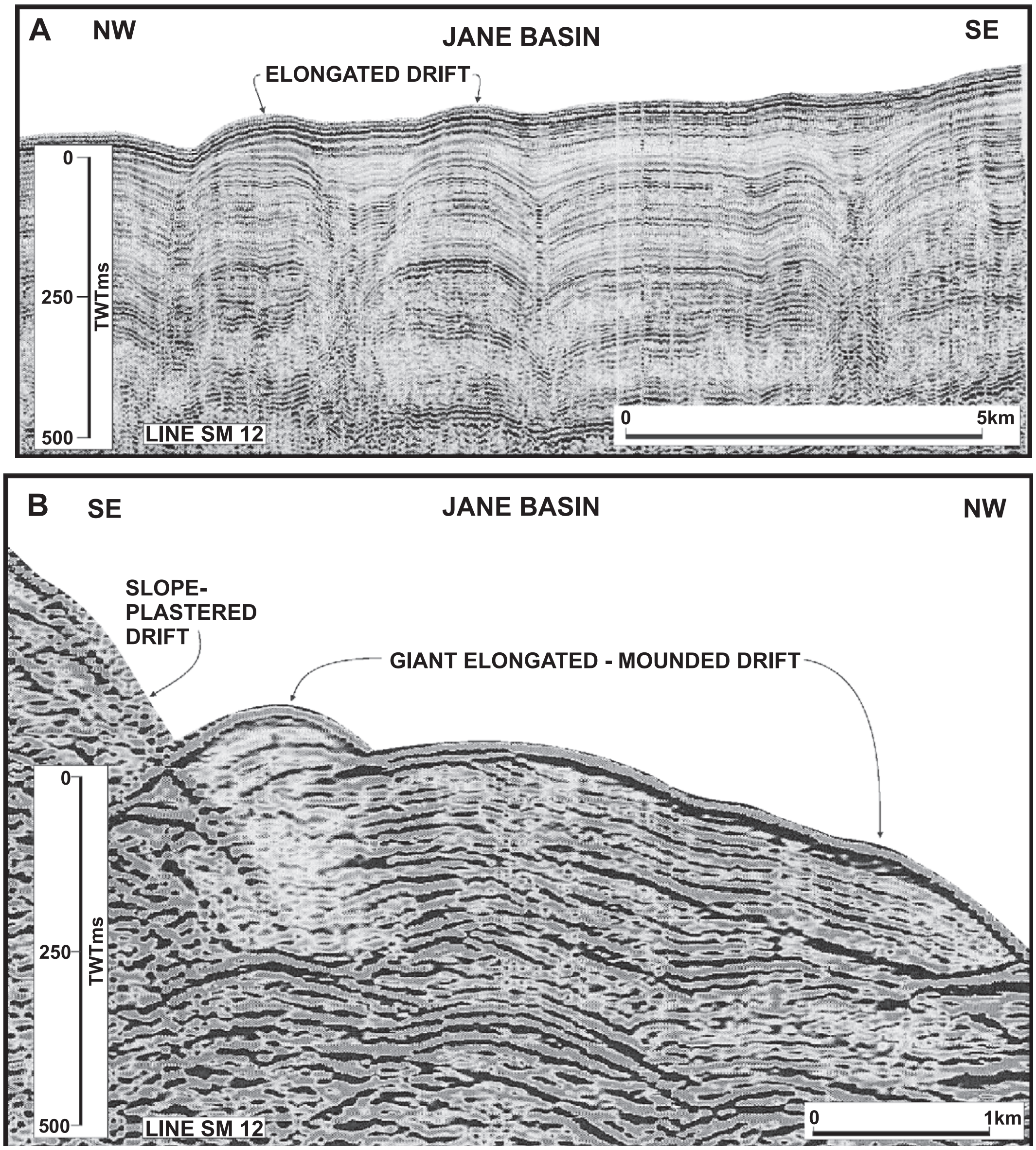


Fig. 8. Selected segments of high-resolution profiles. (A) Elongate contourite drift. (B). Sediment body of giant elongated/mounded countourite drift. See also Fig. 11A for the line drawing interpretation of the entire profile that contains the detailed profile examples of panels A and B. The segments of the multichannel profiles have had Delph processing of a single channel to produce the higher resolution of seismic reflectors shown in this figure. See Fig. 3 for seismic profile locations.

The seafloor surface morphology of the basement/tectonic drifts follows the trend of the near-surface basement morphology, but does not replicate it. Gradually throughout the sedimentary section above the basement, the drift crests are offset from the basement ridge crests and tend to migrate closer together (Fig. 9B; Table 1). The deeper reflectors are more rounded and draped over the basement protrusions. Increasingly up-section, the reflectors become more tepee-like toward the seafloor surface.

5.5. Levee drifts

Levee drifts have significant seafloor expression with a relief of 225 m and width of 12 km adjacent to moat channels (Figs. 7D and 10A). The levee drifts are characterized by aggrading continuous convex upward seismic reflections, in contrast to the lenticular-mounded, oblique to sigmoidal and truncated reflections that characterize the giant elongated–mounded drifts. The levee drifts are distinguished from the elongated drifts because of their larger scale, association with large ridges and moat channels, and reflector continuity without truncations or thickness changes (Fig. 10A).

5.6. In-filling and slope-plastered drifts

Drifts in-filling and plastered along steep basement ridges are common throughout the Weddell Sea region where many high-relief ridges protrude above the seafloor (Figs. 2 and 3). These drifts may in-fill small

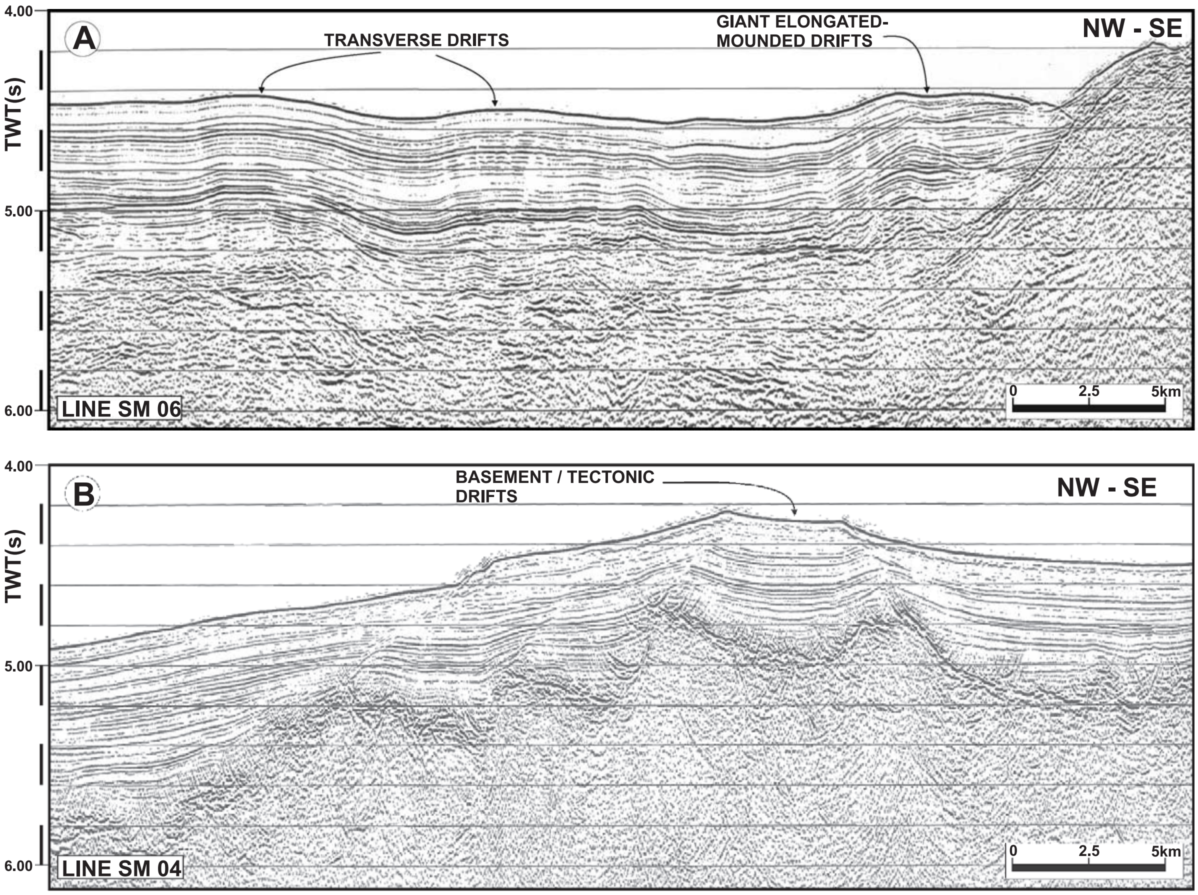


Fig. 9. (A) Transverse drifts developed in Jane Basin shown in MCS profile SM06. On far right of the profile, giant elongated–mounded drifts and a contourite channel are adjacent to Jane Bank. See also Fig. 11B for line drawing interpretation of this profile. (B) Basement/tectonic controlled drifts. See also Fig. 11C for a line drawing interpretation of this profile. See Fig. 3 for seismic profile locations.

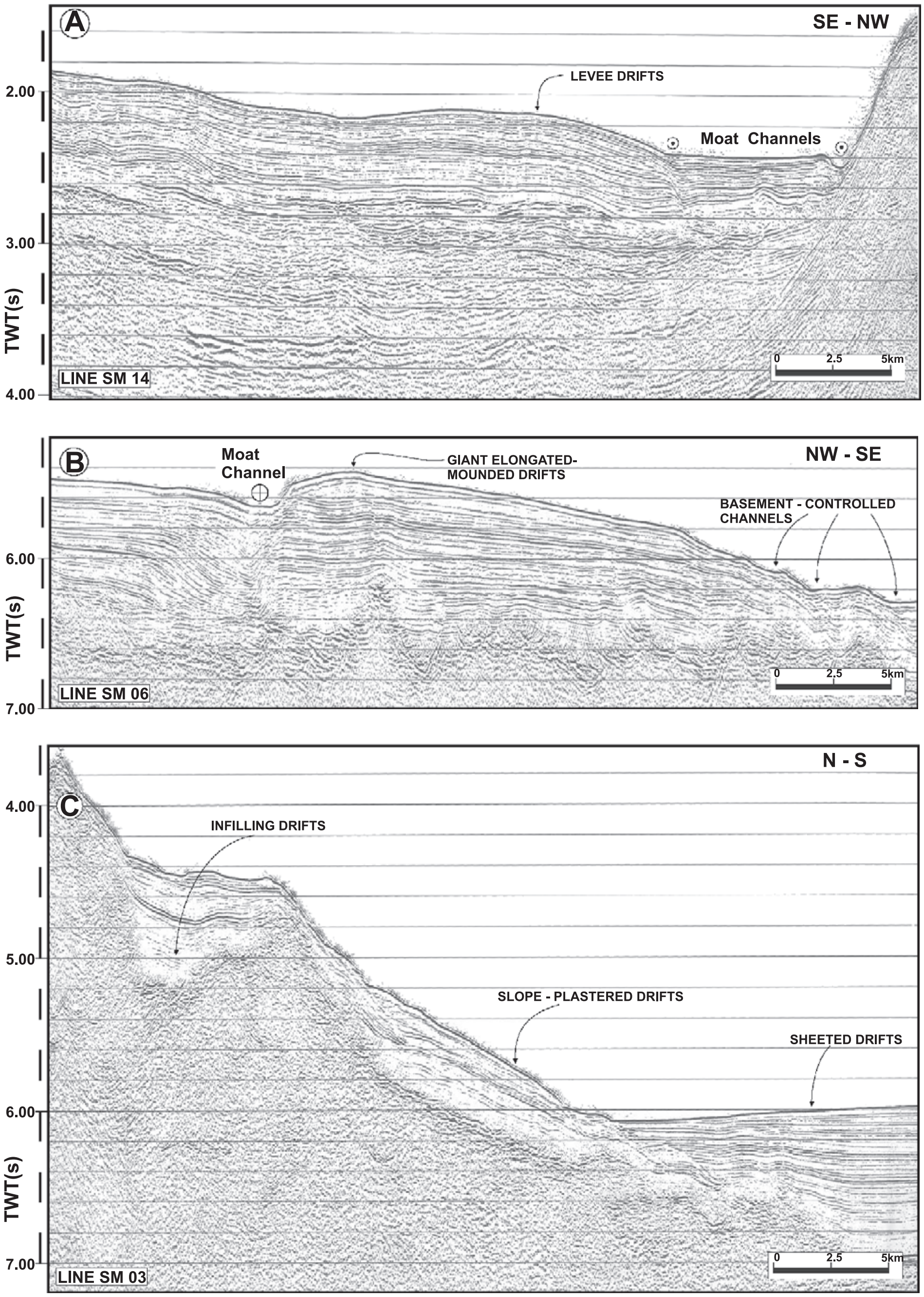


Fig. 10. (A) Levee drifts shown in MCS profile SM14. See also Fig. 12A for a line drawing interpretation of this profile. (B) Large moat channel with giant elongated/mounded drift in the northern part of the MCS profile SM06 and the multiple basement-controlled channels in the southern part. See also Figs. 5 and 12B for a line drawing interpretation of the northern Weddell Sea where this profile is located. (C) Slope plastered and in-filling drift (northern side) and abyssal sheeted drift (southern side) shown in MCS profile SM03. See also Fig. 12C for a line drawing interpretation of this profile. See Fig. 3 for seismic profile locations.

sections of basement ridges or be plastered up entire ridges as much as 1500 m (Fig. 10C). In-filled to slope-plastered drifts show seismic reflectors generally paralleling the surface topography of the basement and onlapping upslope against the steep basement topography (Fig. 10C).

5.7. Sheeted drifts

Sheeted drifts are found in many Weddell Sea abyssal plain regions south of Jane Bank where the basement has low relief for extensive distances (Figs. 6, 7F and 10C). The sheeted drift is characterized by flat-lying relief, wide lateral extent and continuous to transparent reflectors (Fig. 7F). Typically, the basement under the sheeted drift has some relief that has been smoothed over (Figs. 6 and 10C, Table 1). In locations where we find a dominance of wavy character in seismic reflectors, the swath bathymetry usually shows that there are surface elongate (Fig. 7A) or transverse (Fig. 7B) drifts.

6. Interpretation of contour current-related depositional and erosional features

6.1. Seismic interpretation

The stratigraphic units are irregularly distributed because of the complex relief of the basement and thickness variations caused by depositional processes. Fracture zones and banks produce a rugged basement and morphological ridges on the seafloor (Figs. 4–7). We interpret that the seismic characteristics of the sedimentary units are related to bottom contour currents. The features include: (a) discontinuities that can be traced across the area; (b) lenticular, convex-upward geometries; (c) progradational and aggradational reflectors that converge towards the marginal zones of the depositional bodies and are truncated by numerous internal discontinuities; and (d) wavy reflectors (Figs. 8–10). The stratigraphic units tend to be best developed over basement depressions and where large deposits are formed due to the interference between basement topography and the bottom-current flows. Similar contourite deposits are extensively developed in the central Scotia Sea because the confluence between the ACC and the WSDW, at the exit of a major gap of the South Scotia Ridge (Maldonado et al., 2003). Evidence of current erosion or nondeposition, recognized as contourite processes, are also documented in Powell Basin (Howe et al., 1998) and in the continental margins of the western Weddell Sea, where they are attributed to the Weddell Gyre (Rogenhagen and Jokat, 2000; Michels et al., 2002).

Unit 5, the oldest unit, represents the syn-drift deposits in Jane Basin (Fig. 4). The equivalent deposits in the Weddell Sea are postrift, more continuous and uniform, but also fill the irregularities of the igneous crust. Unit 4 shows external geometries and internal reflector configurations that can be attributed to contourite deposits, which are not identified in the underlying Unit 5. A major contourite channel is observed near the northern margin of Jane Basin, together with contourite drifts. The contourite deposits of Unit 4 are better developed in the Weddell Sea, indicating the initiation of permanent and well-established thermohaline flows that are persistent throughout the entire sequence from Unit 4 to the Recent (Table 1).

The deposits of Unit 3 are attributed to a giant elongated–mounded drift in the central Jane Basin (Fig. 4). The marginal channel related to this drift is located along the southern margin of the body, in contrast to the underlying channel in Unit 4 that was located on the northern margin. Several types of drifts are shown by the seismic characteristics of Unit 3 in the Weddell Sea, including elongated and sheeted drifts (Figs. 5 and 6). The deposits of Unit 2 are mainly interpreted as transverse drifts and sheeted drifts, that may locally constitute the bulk of the unit, but other types, such as levee drifts, are also observed (Figs. 4–6). Chaotic seismic facies with sheeted configuration and short, internal high-amplitude reflectors are attributed to sediment waves due to intensified bottom currents (Fig. 6).

Unit 1 exhibits a seismic character similar to the underlying Unit 2. Reflector configurations of sediment waves, drift, channels and chaotic facies are observed throughout the area (Figs. 7 and 8). The increased proportions and the regional distribution of these high-energy deposits in Unit 1, however, indicate intensified bottom-current processes in relation to the underlying deposits (Table 1). The facies of Unit 1 may be laterally correlated with the youngest laminated and stratified contourite facies identified in the margins of the Weddell Sea, which also are attributed to increased current activity (Michels et al., 2002).

6.2. Contourite drift types and relation to bottom-current setting

The giant elongated–mounded drifts are associated with major channelized contourite currents that flow along large ridges and deposit elongated sediment bodies parallel to the ridges and the current flow (Fig. 2–5). Because of current scour, (a) moat channels develop at or near the base of the ridge (Figs. 4, 5 and 7E) and (b) the ridge margin is eroded whether it is located on the right side (Figs. 8B and 9A) or left side (Fig. 5) along the channel. As described by Faugères et al. (1999) and observed in our profiles, the giant drifts generally occur as separated drifts that migrate mainly along-slope with the currents and also upslope toward ridges (Figs. 4 and 8B).

The elongated drifts are not sediment waves because they develop and migrate parallel to the northeast trending currents (Figs. 2 and 7A). Using observations based only on lower-resolution multichannel records, these features may be mistaken as sedimentary sections with multiple faults or erosional furrows like those observed in the Gulf of Mexico (Bean et al., 2002). The high-resolution Delph processing of seismic profiles, however, shows that these are not faults or furrows because of the predominantly continuous reflectors through the multiple elongate drifts (Fig. 8A).

In the southern part of Jane Basin, unlike the more constricted northern part, transverse drifts interpreted as sediment waves are found deposited oblique or transverse to northeastward flowing currents (Fig. 7B). These transverse drifts differ from the elongate drifts because of their orientation perpendicular to currents and larger scale (Fig. 9A and B).

The thick basement/tectonic drifts result from the seafloor disruptions of the current flow caused by the irregularities of the near-surface basement morphology, which generate sediment bodies elongated with the current flow (Fig. 9B). The basement/tectonic drifts that we observe throughout the Weddell Sea region have the same character as fault-controlled drifts defined by Rebesco and Stow (2001).

The levee drifts of northern Weddell sea show similar characteristics as the levee drifts described by Michels et al. (2001) and Rebesco and Stow (2001), and which they indicate are elongated in the downstream contourite flow direction (Fig. 7D). Levee drift development is associated with contourite channels and ridges in Weddell Sea, whereas levee drift formation along the western Antarctic Peninsula is associated with complex contourite/turbidite channels (Rebesco et al., 2002).

As summarized by Faugères et al. (1999), slope-plastered drift has long been recognized, and more recently, others (Rebesco and Stow, 2001; Maldonado et al., 2003) describe various types of contourite drifts that in-fill slump scars or depressions and that ramp up or deposit against steep bathymetric ridges and migrate downstream with the contourite currents. Some descriptions of drift types (Rebesco and Stow, 2001; Stow et al., 2002) have included slope-plastered and slope patch sheets in their category of sheeted drift, whereas in-fill drifts have been a separate category. We prefer to include all of these slope-associated drifts together and separate them from the sheeted drifts category. The reason is illustrated in Fig. 10C where the slope plastered and patch drifts have steep upslope irregular geometry and seismic reflections usually beginning with older in-filling drifts, compared to the flat-lying continuous reflections of sheeted drifts on the abyssal plain.

The seismic features and oceanographic settings of the sheeted drifts indicate that they may develop in different settings. In distal locations, sheeted drifts appear to be associated with slacking of bottom currents (Faugères et al., 1999; Rebesco and Stow, 2001). We also observe sheeted drifts under the main core of the Weddell Gyre currents where the facies of these deposits are wavy or transparent and without continuity of the reflectors (Figs. 2 and 6). We interpret these sheeted drifts, in contrast, as high-energy deposits.

7. Discussion

7.1. Regional bottom-current and bathymetric control of contourite drifts formation

In the northern Weddell Sea, there are two regions with the best development of contourite drift deposits. The first region consists of the basin margins, central floor and exit of Jane Basin into the Scotia Sea (Figs. 3, 11 and 13A). The second region exists along the southern margin of Jane Bank and northern boundary of Weddell Sea (Figs. 3, 12 and 13A). The patterns of drift distribution seem to be basically controlled by basin physiography, which governs the main pathways of WSBW flows (Figs. 11–13). Where ridges constrict currents, we see little influence of Coriolis force. For example, scour always takes place along the ridge margin of moat channels whether it is the right (Fig. 9A) or left (Figs. 5 and 10A) side of the downstream flow. Coriolis force seems to exert little control compared to the current shear along bedrock ridges (Figs. 11B,C and 13). Rebesco and Stow (2001) attribute levee drift development in Antarctica to Coriolis force on the left downstream flow of contourite channels; however, we observe the opposite development on the right levee adjacent to weak channel flow where the left margin is a current-scoured ridge (Figs. 10A, 12A and 13). These observations indicate that the bathymetric constriction of bottom-current flow is a more dominant control than Coriolis force. Consequently, we identify three basic settings in the area based on the bathymetric control: unconfined, confined and transitional (Figs. 11 and 12).

7.1.1. Unconfined setting

The unconfined setting is represented by the northern Weddell Sea south of Jane Bank where the WSBW of the Weddell Gyre flows in a main northeastward pathway with some southward eddies (Figs. 2, 3, 12 and

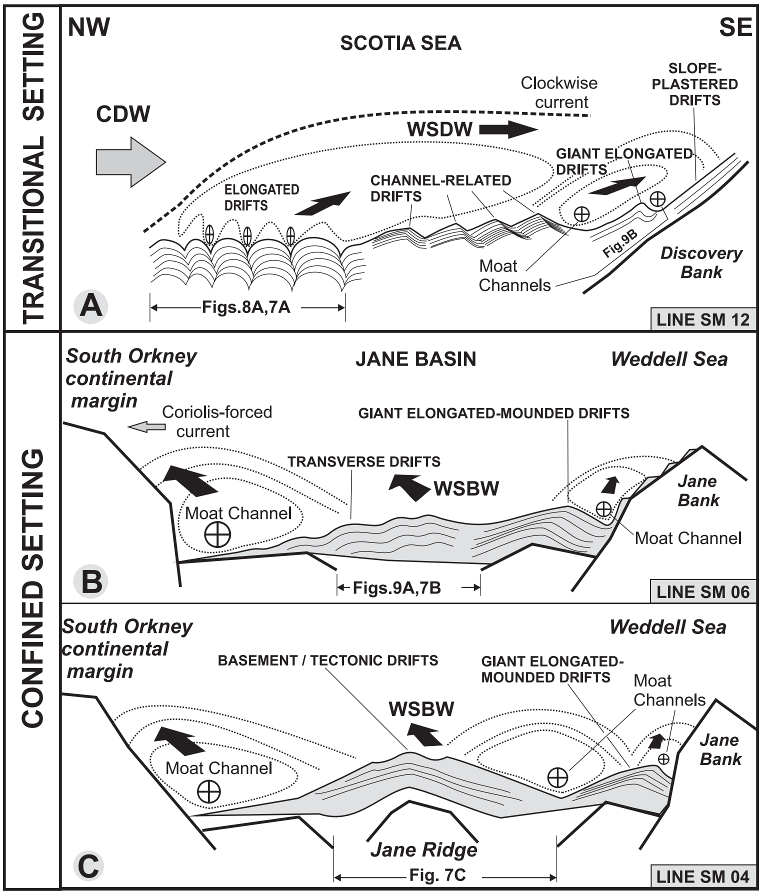


Fig. 11. Generalised schematic drawings (not to scale) based on MCS profile cross sections of Jane Basin and southern Scotia Sea. (A) Section across the transition of Jane Basin into southern Scotia Sea that shows a contourite fan; (B) Section across the centre of Jane Basin that shows several types of confined basin drifts; (C) Section across the southern end of Jane Basin that shows extensive control of basement topography on the development of these confined drifts. See Fig. 3 for location and Figs. 4, 7, 8A and 9A for details.

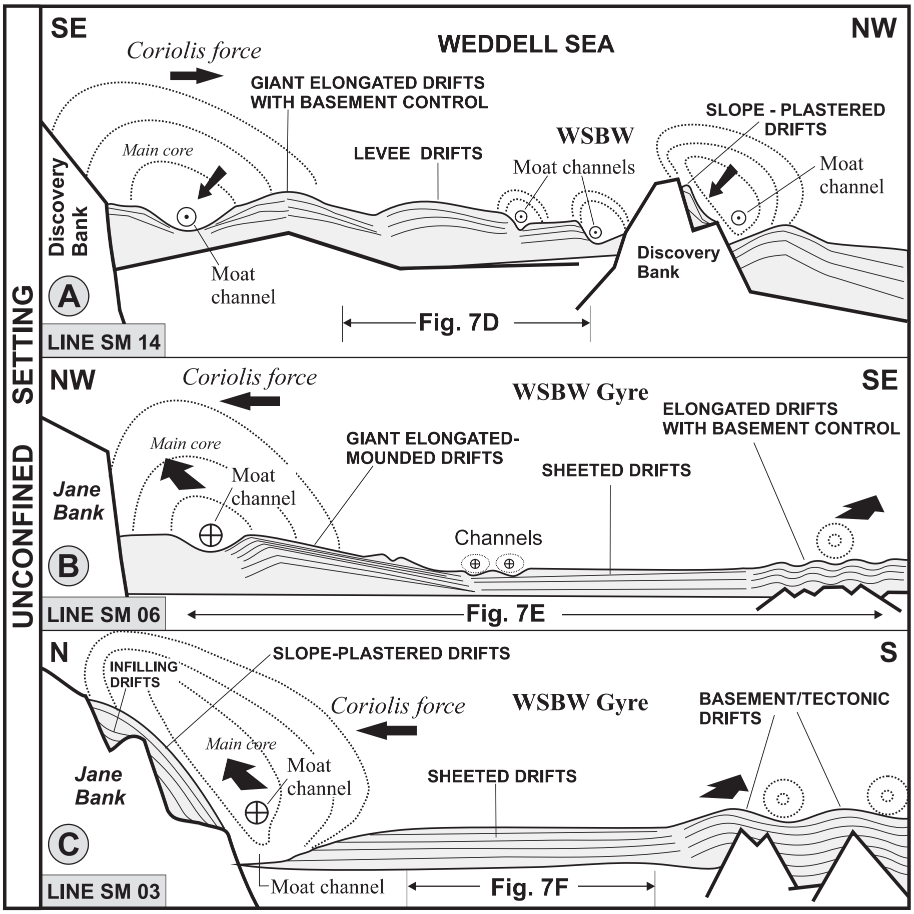


Fig. 12. Generalised schematic drawings (not to scale) based on multichannel seismic profile cross sections in the northern Weddell Sea region. (A) Section across Weddell Sea where it enters into southern Scotia Sea that shows multiple types of contourite drifts confined between basement ridges; (B) Section across Weddell Sea south of Jane Bank that shows gradation of contourite drift types away from the bank margin in an unconfined basin setting. (C) Section across Weddell Sea that shows unconfined drift deposits to the south of Jane Bank. See Fig. 3 for location and Figs 5–7 for details.

13). The types of contourite drifts are determined by the interplay of strong currents shearing along the bank and the increasing basement/tectonic disruptions of the seafloor eastward. The sheeted drifts dominate in the abyssal plain, but along the Jane Bank, slope-plastered and giant elongated–mounded drifts are developed by strong current shear of the gyre (Figs. 12B,C and 13A). The sheeted drifts evolve to the south and eastward from Jane Bank as current energy decreases (Figs. 2 and 13). Further southward and eastward, subsurface basement disruptions have resulted in basement/tectonic drifts intermixed with the sheeted drifts, or in elongated drifts (Figs. 7E, 12B,C and 13A). The dominance of basement/tectonic drifts increases eastward as basement disruption of the seafloor becomes progressively greater (Figs. 3, 12C and 13A).

Against Jane Bank, but predominantly in confined basin settings, wherever the high ridges constrict the flow laterally and the current pathway is straight: (a) the ridge flank has no deposition, (b) moat channels are found at the base of the ridge and (c) giant elongate-mounded contourite drifts form at the base of the ridge (Figs. 4, 5, 11B,C, 12B and 13A). The exception again is where current pathways turn or split and flow apparently slackens. For example, in the westernmost part of northern Weddell Sea, plastered

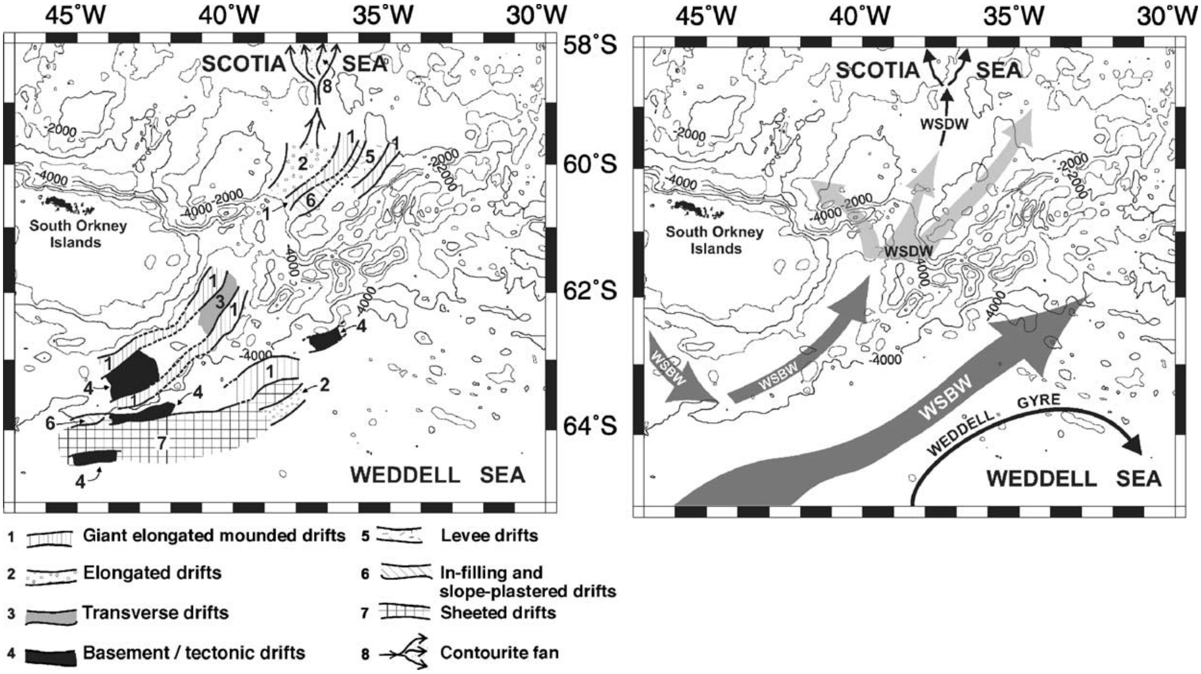


Fig. 13. Sketch of: (A) contourite deposit distribution and (B) bottom water flows in the northern Weddell Sea showing the possible pathways of deep water of the WSBW–WSDW related to the Weddell Gyre. See text for discussion.

drifts, but no giant or elongated drifts are found at the base of the Jane Bank slope (Figs. 12C and 13A), and along southern Discovery Bank, small channels and levee drift rather than giant elongated drifts are found (Figs. 12A and 13A).

7.1.2. Confined setting

The confined setting is represented by Jane Basin, where the deposits can be categorized as confined drifts with limited lateral migration, according to the definitions of Faugères et al. (1999) and Rebesco and Stow (2001). The predominat deposits in this setting are giant elongated–mounded and basement/tectonic drifts (Fig. 11B and C). The WSBW travels northeastward through the basin floor towards the South Scotia Ridge, where it splits into two branches travelling westward and northward into the Scotia Sea (Figs. 2 and 11). As the WSBW current shears along the northwest and southeast margins of Jane Basin, giant elongated–mounded drifts develop (Figs. 4, 11B,C and 13A). In central Jane Basin floor, where there are bathymetric disruptions, basement/tectonic drifts form and migrate downcurrent (Figs. 7C, 11C and 13A). However, where the Jane Basin floor is smooth, transverse contourite drifts form, probably related to the general constriction of flow between ridges (Figs. 7B, 9A, 11B and 13A).

7.1.3. Transitional setting

The transitional setting with contourite fans develops where the exit of the confined Jane Basin opens into the unconfined Scotia Sea (Figs. 11A and 13A). Contourite fans have been previously described by Faugères et al. (1999) and Rebesco and Stow (2001) as types of channel-related drift with more random lateral migration in unconfined settings compared to confined basins. The contourite fan is characterized by elongated drifts on the west side and irregular channel-related drift on the east side (Figs. 11A and 13A). Downstream, a second contourite fan is developed in the central Scotia Sea by the WSDW (Maldonado et al., 2003).

7.2. Comparison of Weddell contourite system with turbidite systems elsewhere

There are a number of locations, particularly in Antarctica, where a complex interplay between contourite and turbidite processes is found. Along a significant area of the continental rise of the Pacific margin of the Antarctic Peninsula, contourite drifts seem to be constructed from the fine-grained components of turbidity currents, which are entrained and transported southwest by bottom currents (Rebesco et al., 1996; 1997, 2002; Camerlenghi et al., 1997). A similar model is proposed for high-relief turbidite system modified with mounded contourite-style deposits developed in the Wilkes Land continental rise (Escutia et al., 2000, 2002). In Powell Basin, many of the contourite deposits seem to result from downslope turbidite flows entrained by nepheloid layers within the ambient, weak bottom currents (Howe et al., 1998). The northern Weddell Sea, without a contribution from downslope gravity flows and where nearly all the basic types of contourite drift are present (see Section 5), provides a basis to compare contourite and turbidite systems based mainly on seismic profile characteristics. Outlining these system-wide differences can help unravel the complex interplay of contourite and turbidite systems that are found elsewhere in the northeastern Atlantic, such as the Gulf of Cadiz (Hernández-Molina et al., 2003), and especially along the margins of Antarctica, such as the Weddell Sea (Michels et al., 2001; 2002), Adelaide Island (Rebesco et al., 2002) and Wilkes Land (Escutia et al., 2000, 2002).

7.2.1. Giant elongated–mounded drifts compared to turbidites

The giant elongated–mounded drifts have a number of characteristics that distinguish them from channel–levee complexes deposited by turbidity currents. Giant-elongated drifts typically develop along high-relief ridges, migrate downstream parallel with the contourite currents that flow along the ridges, have moat channels that are scoured against the ridge and are characterized by extensive unconformities and local lenticular convex-up mounds that cut and in-fill preexisting sections of the drift bodies (Figs. 11B,C and 12B,C). The net result, which is observed in other contourite channels as well as those in Weddell Sea, is asymmetric deposition of an elongate sediment body with mounded sequences along one side of the moat channel and bedrock scour along the other side of the channel (Figs. 7E, 8B, 9A and 10B; Nelson et al., 1993; Faugères et al., 1999; Rebesco and Stow, 2001; Llave et al., 2001).

In contrast, turbidite channel–levee complexes show generally well-developed levees on each side, characterized by a higher right levee in the Northern Hemisphere or opposite in the Southern Hemisphere because of Coriolis force. The reflectors of the turbidite levees prograde mainly laterally away from the channels (not downstream like contourite channels) with seismic reflections that pinch out down the outside flanks of levees and on the levee crests (Nelson and Nilsen, 1984; Nelson et al., 1993). Cut and fill exists in turbidite channel–levee complexes, but it occurs locally along channel walls or systematically with migration of the channel–levee complex (Nelson and Nilsen, 1984; Kolla et al., 2001). Turbidite channels also have a morphologic association with canyon floors or canyon mouths from which there is a systematic change in geometry downstream caused by multiple channel bifurcations (Nelson and Nilsen, 1984; Damuth et al., 1988, Twichell et al., 1992). Contourite channels, in contrast, are found anywhere that bottom-current flow is constricted by ridges and they do not have a systematic development away from continental margin sediment sources (Fig. 13).

7.2.2. Sheeted drifts compared to turbidites

The flat continuous reflectors of sheeted contourite drift have a similar appearance to those of basin plain or abyssal plain deposits of turbidite systems. The main way to distinguish seismic reflections of these types of contourite and turbidite deposits is with their associated depositional bodies. The sheeted contourite deposits are flanked by other contourite drifts, such as elongate-mounded drift or plastered drift (Figs. 10C, 11 and 12). The turbidite basin plain deposits have associated feeder channels (Twichell et al., 1992; Nelson et al., 1992).

7.2.3. Basement/tectonic drifts compared to turbidites

Basement/tectonic-controlled contourite drift appears to be a unique depositional body that is not similar to turbidite depositional bodies. In-filling and slope-plastered contourite drift deposits, also associated with topographic ridges, again seem to be unique to the contourite systems The tepee reflector geometry and irregular spacing of basement/tectonic control (Fig. 9B) as well as the in-filling and ridge parallel reflectors of plastered drift (Fig. 10C) are quite different from any reflections normally observed in turbidite systems. These contourite bodies also prograde elongate to the current following the subsurface or surface basement relief. Basement topography often can influence location of turbidite channel–levee complexes or lobe deposits. However, when turbidite channels follow faulted basement topography, they still develop the classic channel–levee complex with symmetrical geometry and lateral progradation of levees away from the channel (Graham and Bachman, 1983).

7.2.4. Levee and smaller-scale drifts compared to turbidites

Levee drifts of contourite channels (Fig. 10A) have a similar scale to that of turbidite levees along large-scale channels, such as those found in Mississippi or Amazon Fans (Normark and Damuth, 1997). The distinguishing seismic characteristic of contourite levee drift is the convex upward drape of evenly spaced reflectors that are asymmetrically developed on only one side of the channel (Fig. 10A) compared to the classic symmetric "gull-wing" geometry of turbidite reflectors that thin toward the lower levee flanks (Nelson et al., 1993). In some turbidite systems, like Var Fan in the Mediterranenan Sea, one levee has an exaggerated development, but the other levee still has a significant deposit (Piper and Savoye, 1993; Midgeon et al., 2001). There is a similar appearance of draped reflectors on turbidite levees when a hemipelagic drape deposits over an abandoned channel–levee complex, but the core of the complex still exhibits the typical "gull-wing" reflector geometry of turbidite channels (Nelson and Maldonado, 1988).

Smaller-scale elongate and transverse drifts in seismic profile cross-sections (Figs. 8A and 9A) have a similar appearance and scales to sediment waves associated with turbidite deposits (Lee et al., 2002; Normark et al., 2002). The method to distinguish them is with associated seismic facies and depositional environments. Both elongate and transverse contourite drift are found in central basin settings and typically these drifts are flanked by giant elongate-mounded drift deposits on basin edges (Fig. 11A and B). Turbidite sediment waves have been reported from central basin settings where detached outer fan lobes are inferred in outcrops (Mutti, 1992), but this setting has not been well confirmed in modern fan deposits. The elongate contourite drift migrates downstream; however, the transverse drift is similar to the turbidite sediment waves that normally are transverse or oblique to current flow. Turbidite sediment waves are associated with overbank environments (Normark et al., 2002), particularly on outer levee flanks (Midgeon et al., 2001), in crevasse splay deposits (Posamentier and Vail, 1988), and on canyon and channel floors (Malinverno and Ryan, 1988; Piper et al., 1988). Another specific environment where turbidite sediment waves are found is downstream from plunge pools associated with canyon mouths (Nelson et al., 2000).

7.2.5. Confined and unconfined settings of drifts and turbidites

Confined settings show giant elongate-mounded drifts stacked along basin margins with other elongate and transverse drift sequences in the basin centre (Figs. 7C and 11B,C). In contrast, turbidite sequences in confined basins exhibit symmetrical "gull-wing" channel–levee complexes spread throughout the basin in stacked or migrating sequences (Nelson and Nilsen, 1984; Kolla et al., 2001). The turbidite channel sequences typically are not stacked along the basin margins or parallel to ridges as they are in contourite channels (Fig. 11). In the small intraslope mini-basins and slope channel systems, turbidite sequences may be ponded with perched feeder and distributary channels overlying and bypassing channels connecting the mini-basins (Prather et al., 1998). Mini-basins also contain common interbedded units of mass transport deposits with chaotic or transparent seismic reflections (Badalini et al., 2000; Beaubouef and Friedmann, 2000).

In unconfined basin settings, channel-related drifts migrate more widely with a greater variety of contourite channel types and scales than confined contourite basins (Fig. 12). Again, the asymmetric contourite channel reflectors (Fig. 7E) are different than the symmetric and equal-sized channel–levee complexes of turbidites that migrate laterally across the entire basin fill (Damuth et al., 1988; Weimer, 1990). Sheeted drifts are common and intermixed with other types of drifts throughout the unconfined contourite systems. In unconfined turbidite basins, the basin plain deposits, with flat reflectors, are found distal to the channel–levee complexes of the proximal fan sequences (Nelson and Nilsen, 1984).

7.3. Temporal evolution of the contourite deposits: paleoenvironmental implications

The most important paleoceanographic events in the area, represented by major basin-wide unconformities (Table 1), are probably related to the dynamic behaviour of the ice sheets during the Neogene (Miller and Mabin, 1998) and to the establishment of glacial–interglacial fluctuations since the Early Pleistocene (Taviani and Beu, 2003). The deposits of the northern Weddell Sea reveal, in addition, seismic facies indicative of significant bottom-current activity throughout the Miocene to Recent (Figs. 11 and 12). The exception is the older Unit 5 above the igneous basement that shows no evidence of bottom current (Table 1). The deposits of Units 1 to 4 exhibit, in contrast, several seismic characteristics that suggest an evolution in the bottom-current flows, sediment supply and water mass distribution.

7.3.1. The initial incursions of the WSBW and WSDW

Reflector d (tentative age of ~18.7 Ma) represents a prominent erosional discontinuity in the Weddell Sea stratigraphic record and the first incursion of intensified bottom currents to the basin plain. The overlying Unit 4 shows the development of giant elongated–mounded drifts in the proximity of Jane Bank, together with a variety of contourite drift deposits that resulted from the northeastward flow of bottom currents (Fig. 5), and probably associated with multiple intervals of waxing and wanning of ice sheets (Chow and Bart, 2003) led by middle Miocene climatic fluctuations (Florindo et al., 2003). Reflector c (dated at ~12.1 Ma) is the most significant erosional surface over Jane Basin. A major unconformity of similar age is also reported in the Scotia Sea, where it may represent the first incursion of the WSDW into this basin (Maldonado et al., 2003). These authors attribute the inception of WSDW into the Scotia Sea to the opening of gaps in the South Scotia Ridge and subsequent creation of seaways between the Scotia and Weddell seas. Sykes et al. (1998) proposed a major waxing episode of the proto-AABW in the latest Middle Miocene. This allowed the reconnection of southern hemisphere deep basins and also may have favoured the entry of WSDW into the Scotia Sea. The growth stage of giant drifts over the rise of the Antarctic Peninsula may be related to this initial stage of WSDW incursion into the Scotia Sea (Camerlenghi et al., 1997; Rebesco et al., 1997), as well as a second major phase of Antarctic ice sheet expansion (Florindo et al., 2003).

Unit 3 (Late Miocene) recorded a reorganization of bottom flows, probably due to a changing scenario of seaways and banks that resulted from the end of spreading in Jane Basin and of the subduction of the northern Weddell Sea below Jane Bank (Bohoyo et al., 2002). The southward shifting of contourite channels during this time may reflect the strong influence of the sea bottom morphology and new seaways controlling flow paths rather than a pattern of distribution resulting from Coriolis effect. Reflector b (~6.8 Ma) is also an important unconformity over the area, but it is particularly relevant in the northern Weddell Sea, where it marks the beginning of intensified bottom currents and the development over extensive areas of high-energy, chaotic deposits (Fig. 6, Table 1). The Late Miocene is thought to be a time of global cooling. Ice sheets expanded on East Antarctica and the West Antarctic Ice Sheet became grounded below sea level (Ciesielski et al., 1982). However, a Late Miocene increase in global ice volume is still being debated because it is not ubiquitously recorded in Late Miocene benthic foraminiferal δ^{18}O records (Hodell et al., 1986, 2001).

7.3.2. The events leading to the modern conditions

The relative rate of thermohaline overturn reached modern proportions by ~6 Ma and exceeded modern conditions during the Early Pliocene (Billups, 2002). The oxygen isotope values increased during the Late Miocene with a maximum at 6.9 Ma, which was initially explained by an increase in global ice volume. Billups (2002) suggest, moreover, a gradual cooling of the water masses that were sinking in the southern oceans between ~7.4 and 6.9 Ma that may have induced strong thermohaline overturn. What we observe in the northern Weddell Sea Unit 2 is an increase of high-energy, sheeted deposits which we believe reflect a higher production of WSBW under the sea ice and intensified bottom currents. The Early Pliocene climate, in contrast to the Late Miocene, is considered to be a time of relative global warmth (e.g., Billups, 2002 and references therein). There is significant evidence that enhanced oceanic heat transport played an important role in sustaining high-latitude warmth during this period of time (Kwiek and Ravelo, 1999; Ravelo and Andreasen, 2000).

The youngest basin-wide Reflector a (~3.5 Ma) in the Weddell Sea was also identified in the Scotia Sea (Reflector A, ~3.8 Ma) and it marks the Early/Late Pliocene boundary. The deposits of Unit 1 above this reflector are characterized in the Weddell Sea and Jane Basin by the extensive development of chaotic, high-energy sheeted facies, in addition to a variety of contourite deposits (Figs. 4, 5, 6, 9 and 10, Table 1). Units 1 and 2 are also characterized by a distinct cyclic pattern of deposition, more continuous wavy deposits and development of internal unconformities, all of which attest to intensified bottom-current activity (Fig. 8A). The two units record a change in the style of deposition and the environmental parameters over the area. The development of those units was probably related with the invigoration of thermohaline currents in the Antarctic that is supossed to have occurred after the Late Miocene (Michels et al., 2002). The discontinuity between Units 1 and 2 (Reflector a) records an increase in bottom-current activity as indicated by the development of extensive erosional surfaces. The increased current activity may reflect an intensified deepwater production and may predate the onset of the Northern Hemisphere continental glaciations and massive Antarctic ice sheets during the Late Pliocene.

The extensive distribution of contourite deposits in the northern Weddell Sea suggests that, in addition to the development of a strong ACC, the opening of seaways in the Scotia Sea region favoured the production of AABW that later flowed into the south Atlantic. The first evidence for a strong production of WSBW is observed towards the end of the Early Miocene (Reflector d, Unit 4), which may predate the initiation of permanent Antarctic ice sheets and the abrupt climatic threshold that initiated the Mi-4 glaciation (Flower and Kennett, 1994). This flow, in addition, probably was intensified later as result of the creation of deep seaways into the Scotia Sea (Reflector c, Unit 3), which led to significant paleoceanographic changes during the Late Miocene and to the major global cooling that predated the onset of the northern hemisphere ice sheets.

8. Conclusions

The absence of downslope turbidity-current sediment supply, the strong regional bottom currents and the physiographic setting of the basins are the fundamental factors that control the distribution and abundance of contourite drifts in the northern Weddell Sea. In general, we see little influence of Coriolis force on the geometry of the drifts, because the bathymetric constriction of bottom currents seems to be a more dominant control. The confined and unconfined basin settings have a major influence on the bottom-current flows and hence in the type of depositional processes and products (Figs. 11–13). In the unconfined setting of the northern Weddell Sea, slope-plastered drift is developed over the southern margin of Jane Bank (Figs. 12 and 13). Sheeted drifts are more abundant in the abyssal plain of the western area and basement/tectonic drifts become prominent in the eastern abyssal plain where it is disrupted by fracture zones. The deposits of the confined setting of Jane Basin are characterized by the predominance of giant elongated–mounded and basement/tectonic drifts (Fig. 11B and C). The drifts in the confined setting exhibit limited lateral migration, a predominant downcurrent migration and they are mostly elongated. The drifts in the unconfined setting, in contrast, have a more random lateral migration and also a predominant downcurrent migration on the abyssal plain of the northern Weddell Sea. A contourite fan, characterized by elongated and channel-related drifts, is observed in the transitional setting where the confined Jane Basin opens into the Scotia Sea (Figs. 11A and 13).

The development of a pure contourite system in northern Weddell Sea provides a location to compare contourites with turbidites. The main difference that we observe in the giant elongated–mounded drifts is the net asymmetry of the body, with mounded sequences along one side of the moat channel, in contrast to turbidite channel–levee complexes that develop levees on each side of an axial turbidite channel. The basement/tectonic drifts prograde parallel to the main flow and they are plastered along the basement relief unlike turbidite deposits. Other contourites, however, show internal reflector characteristics similar to turbidites, such as the sheeted drifts that are comparable to distal, basin plain turbidites. Different facies associations of turbidites and contourites, nevertheless, may help to differentiate between these types. The giant elongate-mounded drifts are stacked along confined basin margins, whereas elongate or transverse drift sequences are observed in the basin centre. In contrast, the turbidite channel–levee complexes spread throughout the confined basins in stacked or migrating sequences and more sheetlike basin plain turbidites develop at the distal end of more proximal channels. In unconfined basins, turbidites deposit in the same proximal to distal manner, compared to giant elongated–mounded drifts that are associated with basin margins and sheeted drifts that deposit in the unconfined abyssal seafloor.

The MCS profiles of the northern Weddell Sea show an evolution of the contourite drifts throughout the depositional sequence from the Middle Miocene to Recent (Table 1, Figs. 11–13). The opening of Jane Basin into the Scotia Sea is marked by a major regional unconformity near the boundary between the Middle and Late Miocene, which is also recognized in the Pacific margin of the Antarctic Peninsula by the development of giant contourite drifts. The deposits of the upper Miocene recorded intensified bottom currents, particularly in the northern Weddell Sea abyssal plain, which may reflect the increased production of WSBW because of the expansion of the Antarctic ice sheets. The Early/Late Pliocene boundary is also recognized by a major regional unconformity (Reflector a). The deposits above this unconformity are characterized by the extensive development of high-energy contourite facies, which suggest development of intensified deepwater production and may predate the onset of the Northern Hemisphere glaciations and the development of massive Antarctic ice sheets during the Late Pliocene.

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