

Ocean basins near the Scotia–Antarctic plate boundary: Influence of tectonics and paleoceanography on the Cenozoic deposits

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Abstract The distribution of seismic units in deposits of the basins near the Antarctic–Scotia plate boundary is described based on the analysis of multichannel seismic reflection profiles. Five main seismic units are identified. The units are bounded by high-amplitude continuous reflectors, named a to d from top to bottom. The two older units are of different age and seismic facies in each basin and were generally deposited during active rifting and seafloor spreading. The three youngest units (3 to 1) exhibit, in contrast, rather similar seismic facies and can be correlated at a regional scale. The deposits are types of contourite drift that resulted from the interplay between the northeastward flow of Weddell Sea Bottom Water (WSBW) and the complex bathymetry in the northern Weddell Sea, and from the influence of the Antarctic

Circumpolar Current and the WSBW in the Scotia Sea. A major paleoceanographic event was recorded by Reflector c, during the Middle Miocene, which represents the connection between the Scotia Sea and the Weddell Sea after the opening of Jane Basin. Unit 3 (tentatively dated ~Middle to Late Miocene) shows the initial incursions of the WSBW into the Scotia Sea, which influenced a northward progradational pattern, in contrast to the underlying deposits. The age attributed to Reflector b is coincident with the end of spreading at the West Scotia Ridge (~6.4 Ma). Unit 2 (dated ~Late Miocene to Early Pliocene) includes abundant high-energy, sheeted deposits in the northern Weddell Sea, which may reflect a higher production of WSBW as a result of the advance of the West Antarctic ice-sheet onto the continental shelf. Reflector a represents the last major regional paleoceanographic change. The timing of this event (~3.5–3.8 Ma) coincides with the end of spreading at the Phoenix–Antarctic Ridge, but may be also correlated with global events such as initiation of the permanent Northern Hemisphere ice-sheet and a major sea level drop. Unit 1 (dated ~Late Pliocene to Recent) is characterized by abundant chaotic, high-energy sheeted deposits, in addition to a variety of contourites, which suggest intensified deep-water production. Units 1 and 2 show, in addition, a cyclic pattern, more abundant wavy deposits and the development of internal unconformities, all of which attest to alternating periods of increased bottom current energy.

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Introduction

A host of ocean basins and migrating spreading centres, with intervening banks of continental slivers, developed along the Antarctic and the South American plate boundaries between the Oligocene and the present, as shown by the magnetic anomalies of the area (BAS 1985; Lodolo et al. 1997). The results of this tectonic evolution were the opening of Drake Passage and creation of the Scotia Sea, one of the most important Cenozoic features of the Southern Ocean (Barker 2001; Livermore et al. 2004). The Scotia Sea is mainly composed of oceanic crust bounded on three sides by the Scotia Arc, the islands and submarine ridges of the North and South Scotia Ridge and South Sandwich island arc (Figs. 1, 2). The arc is a mixture of old continental fragments, arc volcanoes both active and dead, remnant arcs and accretionary prisms.

Several studies have discussed the tectonic evolution of the region, based mostly on the analysis of magnetic and gravimetric anomalies and the distribution of inferred continental slivers (Barker and Burrell 1977; Livermore et al. 1994; Lawver and Gahagan 1998; Barker 2001). Drake Passage was most probably the final barrier to deep circumpolar ocean currents (Lawver et al. 1992). The opening of this gateway facilitated the formation of the Antarctic Circumpolar Current (ACC), which is proposed to have influenced Cenozoic global cooling and Antarctic glaciation (Kennett 1977; Barker and Thomas 2004; Livermore et al. 2004). There is, however, a debate about the relative importance of Southern Ocean gateways on global cooling. In this respect, the abrupt Eocene–Oligocene (ca. 33 Ma) cooling event may have started earlier than the full opening of Drake Passage (Zachos et al. 2001; Barker 2001). Alternative models propose that closure of low-latitude gateways may bear a greater importance for Cenozoic climate evolution than the opening of the southern gateways (e.g., Lawver and Gahagan 1998). DeConto and Pollard (2003) suggested, on the basis of coupled climate/ice-sheet simulations, that CO₂ decline was the prime cause of abrupt cooling near the Eocene to Oligocene transition and that the opening of Southern Ocean gateways played only a minor role. Sijp and England (2004), using a coupled ocean–atmosphere model of intermediate complexity, concluded that opening at shallow water depths was sufficient to bring about Southern Hemisphere cooling and a significant increase in Antarctic sea-ice, but North Atlantic thermohaline circulation and Northern Hemisphere warming occurred only when Drake Passage opened to full ocean depths.

Regional tectonic studies have focused on the evolution of more restricted areas, where multichannel seismic reflection profiles were acquired (Acosta and Uchupi 1996; Galindo-Zaldívar et al. 1996, 2002; King et al. 1997; Lodolo et al. 1997; Kim et al. 1997; Maldonado et al. 2000, among others). Several studies have also described the deposits of some basins, such as Powell Basin (King and Barker 1988; Coren et al. 1997; King et al. 1997; Rodríguez-Fernández et al. 1997; Howe et al. 1998), Jane Basin (Bohoyo et al. 2002), the central Scotia Sea (Maldonado et al. 2003) and northern Weddell Sea (Kavoun and Vinnikovskaya 1994; Rogenhagen and Jokat 2000; Maldonado et al. 2005). The deposits of the area display a continuous record of sedimentation that dates back to the earlier stages of oceanic basin opening in the Scotia Sea and northeastern Weddell Sea (Maldonado et al. 2006).

The seismic stratigraphy of the basins has been analysed in several papers, but to date there is no documented attempt to correlate the major depositional events among all these basins. In this study we focus primarily on the correlation of the depositional units of the different ocean basins located close to the boundary between the Antarctic and Scotia plates (Fig. 2). The multichannel seismic reflection profiles that we collected over the last decade in the area allow us to propose a preliminary correlation of deposits within all these basins. We here show how the evolution of these deposits was influenced by tectonics, which controlled the opening and closing of seaways, and by global paleoceanographic events.

Methods

We collected geophysical data along several profiles in Drake Passage, the Pacific margin of the Antarctic Peninsula, southern Scotia Sea and northern Weddell Sea during the HESANT 92/93, SCAN 97, ANTPAC 97/98 and SCAN 2001 cruises (Fig. 2B). The multichannel seismic reflection (MCS) profiles were obtained with a tuned array of: (1) six BOLT air guns with a total volume of 15.26 l and a 96 channel streamer with a length of 1.2 km for the HESANT 92/93 cruise, and (2) five BOLT air guns with a total volume of 22.14 l and a 96 channel streamer with a length of 2.4 km for the other cruises. The shot interval was 50 m in all cases. Data were recorded with a DFS V digital system and a sampling record interval of 2 ms and 10 s record lengths, with the exception of the SCAN 2001 cruise, where data were recorded using a GEOMETRIC Strata VisorTM digital system at a

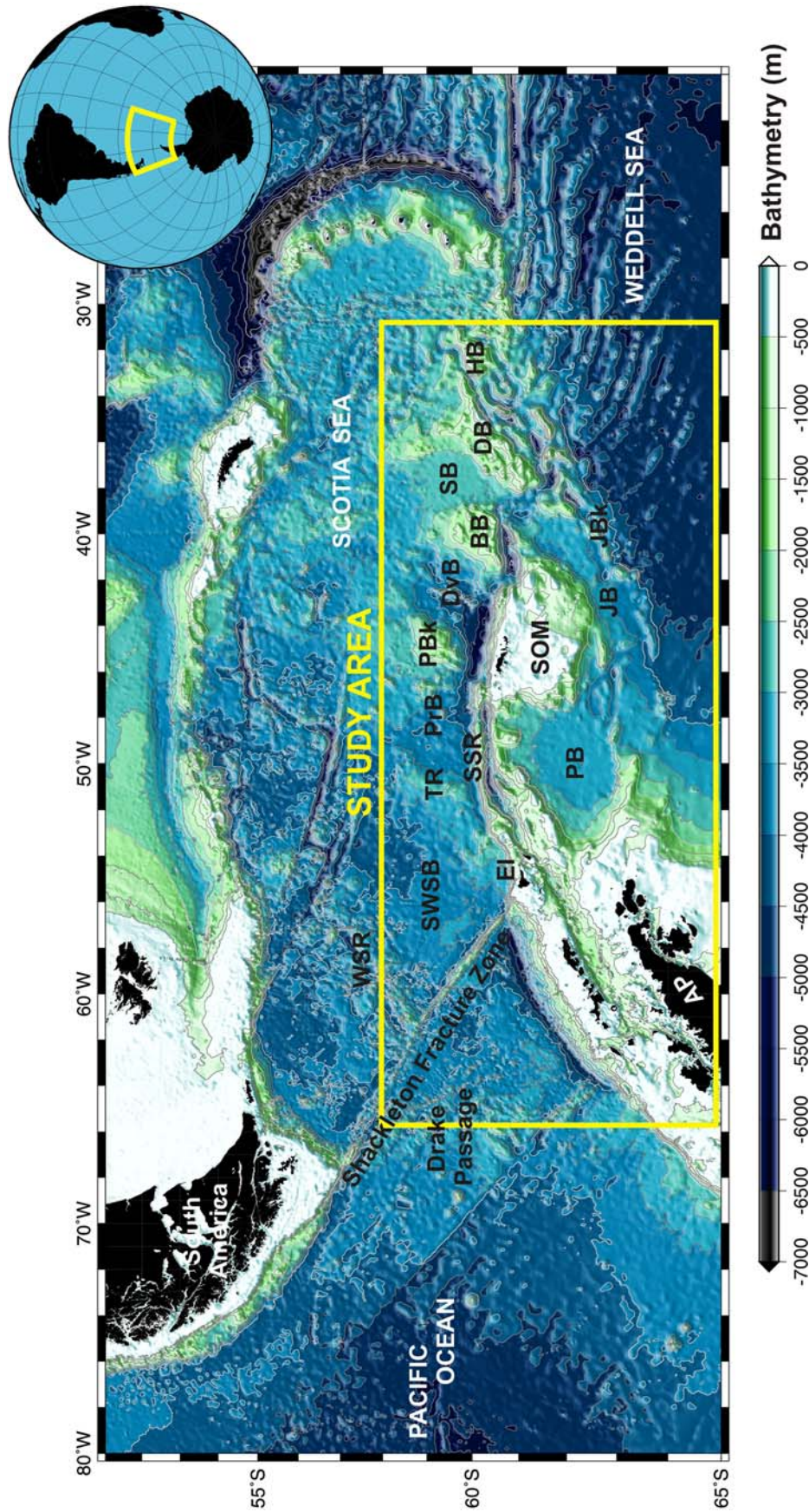


Fig. 1 Simplified bathymetric map from the GEOSAT gravimetric anomaly of the Scotia Sea (Sandwell and Smith 1997). Legend: AP, Antarctic Peninsula; BB, Bruce Bank; DB, Discovery Bank; DvB, Dove Basin; EI, Elephant Island; HB, Herdman Bank; JB, Jane Basin; JBk, Jane Bank; PB, Powell Basin; PBk, Pirie Bank; PrB, Protector Basin; SB, Scan Basin; SOM, South Orkney Microcontinent; SSR, South Scotia Ridge; SWSB, Southwestern Scotia Sea Abyssal Plain; TR, Terror Rise; WSR, West Scotia Ridge (nomenclature of geographical features from BAS 1985; Galindo-Zaldívar et al. 2006 and this study)

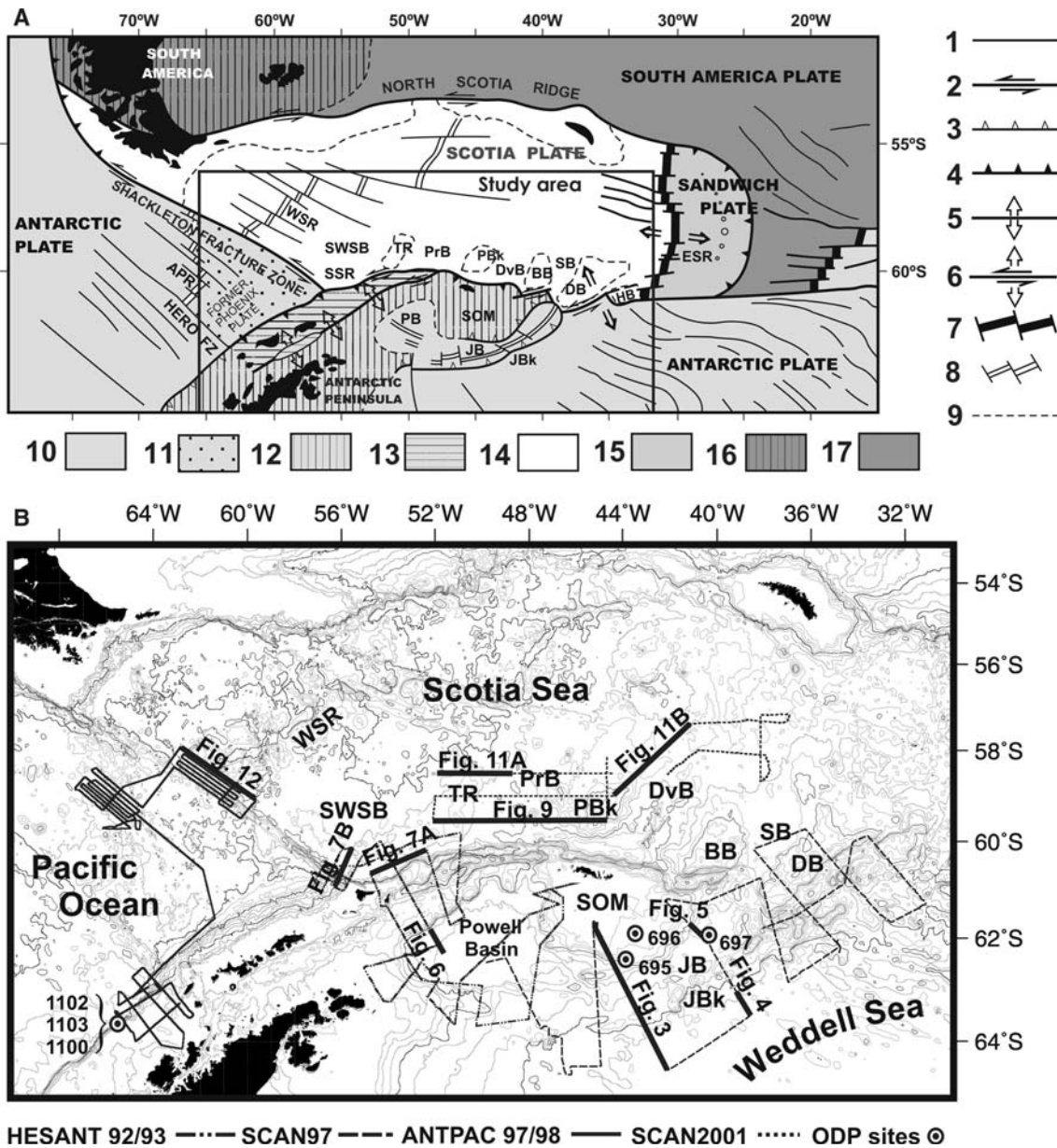


Fig. 2 **A:** Geological setting of the Scotia Sea (modified from: Maldonado et al. 2000; Galindo-Zaldívar et al. 2006). Legend: 1, transform fault; 2, active transcurrent fault; 3, inactive subduction zone; 4, active subduction zone; 5, active extensional zone; 6, active transensional zone; 7, active spreading centre; 8, inactive spreading centre; 9, continental-oceanic crust boundary; 10, Antarctic Plate; 11, Former Phoenix Plate; 12, Antarctic Plate continental crust; 13, South Shetland Islands block; 14, Scotia Plate; 15, Sandwich Plate; 16, South America Plate continental crust; 17, South America Plate. Legend: APR, Antarctic-Phoenix Ridge; BB, Bruce Bank; DB, Discovery Bank; DvB,

Dove Basin; HB, Herdman Bank; JB, Jane Basin; JBk, Jane Bank; PB, Powell Basin; PBk, Pirie Bank; PrB, Protector Basin; SB, Scan Basin; SOM, South Orkney Microcontinent; SSR, South Scotia Ridge; TR, Terror Rise; SWSB, Southwestern Scotia Sea Abyssal Plain; WSR, West Scotia Ridge. **B:** Bathymetry predicted from satellite-derived free air anomaly field of the Scotia Sea (Sandwell and Smith 1997), with the location of cruises mentioned in the text. Thick lines represent the location of the MCS profiles shown in the following figures. See **A** for legend

sampling record of 2 ms interval and 12 s length. The data were processed with a standard protocol, including time migration using a DISCO/FOCUS system. High-resolution sub-bottom profiles were obtained with a Topographic Parametric Sonar (TOPAS)

Konsberg Simrad PS018. A near-field trace of the MCS profiles was processed with the high-resolution DELPH system. Additional data collected during the cruises, but not described in this study, include: swath bathymetry, total intensity magnetic field and gravity

data (see Bohoyo et al. 2002; Galindo-Zaldívar et al. 2000, 2002, 2006; Maldonado et al. 2000, 2003, 2005).

The ship tracks cover the study area reasonably well, although the profiles are widely spaced (Fig. 2B). Stratigraphic analysis and regional distribution of depositional units and discontinuities in the area were supplemented with additional MCS profiles acquired in previous cruises by Italian, Russian and Spanish institutions (Osservatorio Geofisico Sperimentale, OGS: IT90-91, IT95; Sevmorgeologia: 1990, 1992; IACT, cruise ANT 92). For details and additional MCS profile locations see Maldonado et al. (1998, their Fig. 2) and Aldaya and Maldonado (1996, their Fig. 1).

The age of the reflectors and seismic units was tentatively calculated on the basis of: (a) the age of oceanic basement provided by magnetic anomalies, (b) the total thickness of the deposits for selected stratigraphic sections, (c) the results of Ocean Drilling Program borehole sites in the area, and (d) the sedimentation rate of sediment cores (Fig. 2). A detailed explanation of the seismic stratigraphic approach is given in Maldonado et al. (2003). We provide in this work the depth and thickness for the reflectors and stratigraphic units respectively in meters. The conversion from time in the MCS profiles to meters was calculated using the results of wide-angle experiments of Rogenhagen and Jokat (2000) in the northern Weddell Sea (Figs. 3, 4).

Tectonic setting

The internal part of the Scotia Arc is now formed by two minor plates mainly composed of oceanic crust, the Scotia and Sandwich plates, which are separated by an active spreading axis (Figs. 1, 2A). The northern and southern branches of the Scotia Arc constitute the E–W oriented boundaries of these plates, which accommodate the present-day relative sinistral motion between the South American and Antarctic plates (e.g., Pelayo and Wiens 1989; Barker 2001; Livermore et al. 2004). Tectonic deformation of the Scotia–Antarctic plate boundary is concentrated along the South Scotia Ridge. The active tectonic structures are mainly sinistral, transtensional faults that extend westward from Discovery Bank (Acosta and Uchupi 1996; Galindo-Zaldívar et al. 1996). The faults developed E–W to NE–SW oriented half-grabens with wedge-shaped sedimentary infill that has recorded continuous tectonic activity to the present. To the east of these structures, the South Scotia Ridge is formed by a complex array of continental blocks that show evidence of tectonic activity related to the present-day

plate boundary (Maldonado et al. 1998; Galindo-Zaldívar et al. 2002).

The eastern and western boundaries of the arc, however, have different characters. Whereas the eastern boundary is the active trench of the subducting South American plate below the Sandwich plate, the western boundary is the intraoceanic NW–SE oriented ridge of the Shackleton Fracture Zone. The Shackleton Fracture Zone is a major morphologic elevation and structure of the seafloor that crosses Drake Passage between South America and the Antarctic Peninsula (Figs. 1, 2). The Shackleton Fracture Zone is also an active, transpressive fault zone that accommodates relative motion between the Scotia and Antarctic plates in the western Scotia Sea (Aldaya and Maldonado 1996; Klepeis and Lawver 1996; Kim et al. 1997; Maldonado et al. 2000). The depth of the crust–mantle Moho boundary obtained from 3D inversion of the regional gravity anomaly data is greater below the Shackleton Fracture Zone than in the surrounding oceanic crust (Flores-Márquez et al. 2003). These greater depths are coincident with the seafloor elevations, which reflect a crustal thickening along the axis of the Shackleton Fracture Zone according to the gravity models of the crust (Galindo-Zaldívar et al. 2000).

The Shackleton Fracture Zone is probably subducted at present below the northern margin of the South Shetland continental block (Aldaya and Maldonado 1996; Klepeis and Lawver 1996). Eastward of this intersection, the contact between the northern margins of the South Scotia Ridge and the Scotia Sea is generally a reverse fault, which is sealed by the uppermost depositional sequences (Galindo-Zaldívar et al. 1996; Lodolo et al. 1997). A trench, however, is recognized along the northeastern margin of the South Orkney Microcontinent (Kavoun and Vinnikovskaya 1994; Maldonado et al. 1998; Busetti et al. 2000).

The Scotia plate shows in the southwestern area a large oceanic basin, developed from oceanic spreading at the West Scotia Ridge (Figs. 1, 2). Several independent small basins (Protector Basin, Dove Basin and Scan Basin) that are bounded by extended continental blocks (Terror Rise, Pirie Bank, Bruce Bank and Discovery Bank) are also observed in the southern Scotia Sea, near the boundary with the Antarctic Plate (Fig. 1). Two basins floored by oceanic crust are also observed in the northern Weddell Sea, in proximity to the northern boundary of the Antarctic plate (Figs. 1, 2). Powell Basin is a small ocean basin developed from the eastward drifting of the South Orkney Microcontinent, whereas Jane Basin and Jane Bank constitute a relict arc-backarc system related to the subduction of

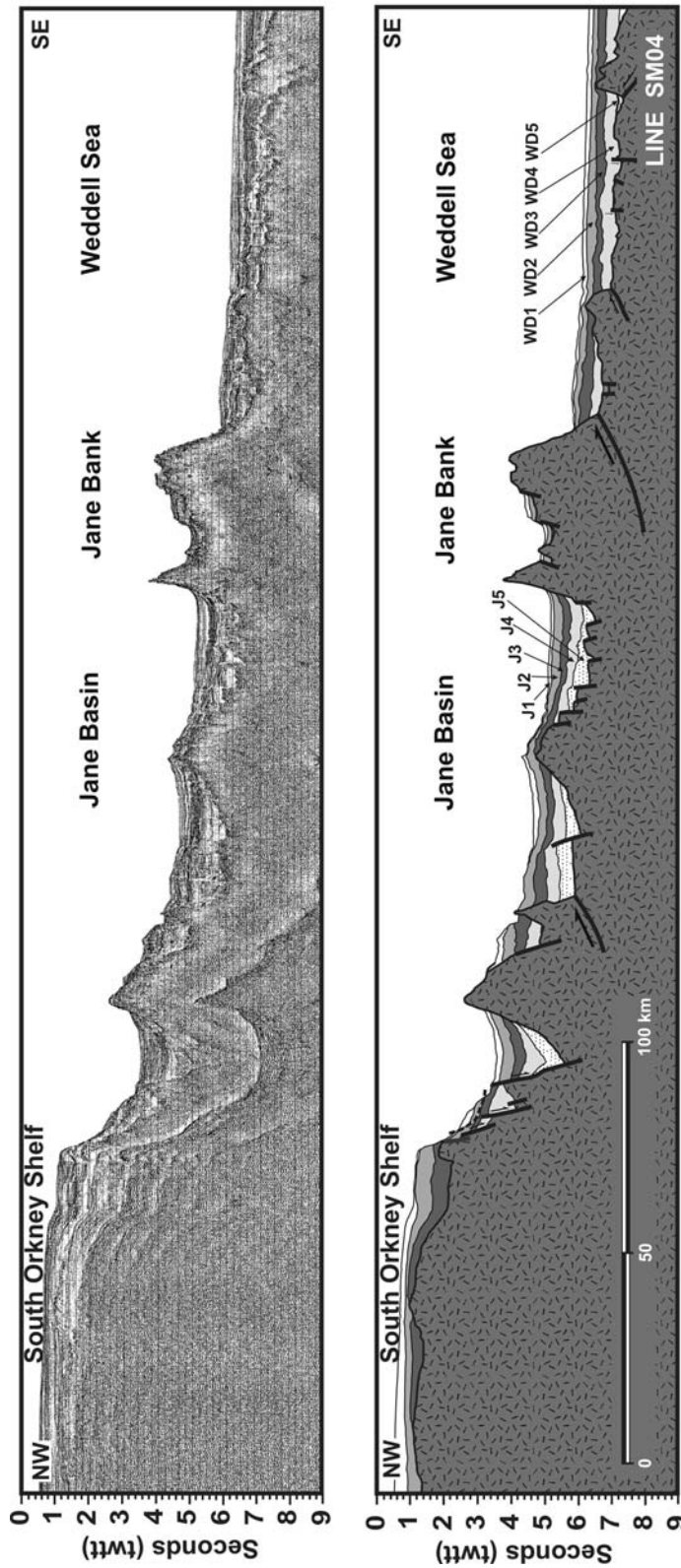


Fig. 3 Multichannel seismic reflection profile SM04 across Jane Basin and Jane Bank and line drawing interpretation of the profile. J1 to J5, seismic units identified in Jane Basin; WD1 to WD5, seismic units identified in the Weddell Sea. Depth in seconds two way travel time (twtt). See text for description of seismic units. See Fig. 2B for location

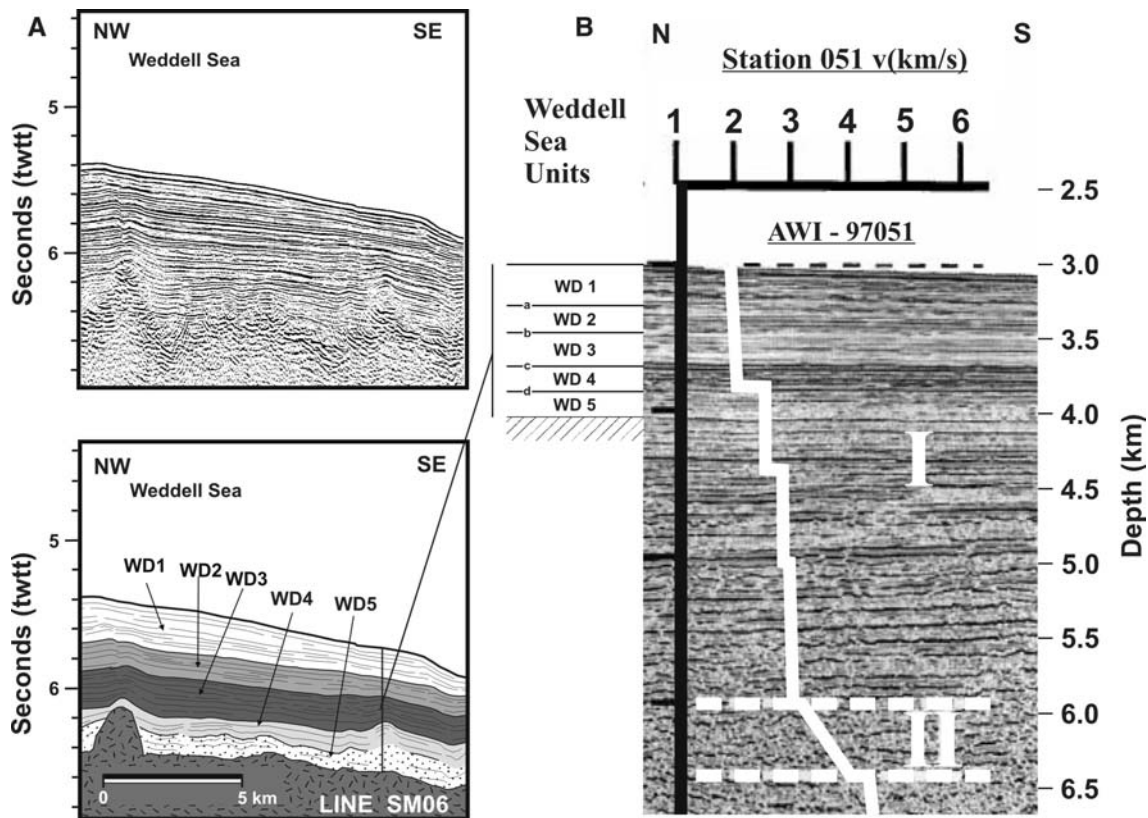


Fig. 4 **A:** Segment of multichannel seismic reflection profile SM06 of the Northern Weddell Sea and line drawing interpretation of the profile showing seismic units WD1 to WD5 identified in this study. Depth in seconds two way travel time (twtt). **B:** Segment of seismic profile AWI-97051 and wide-angle experiment Station 051 in the northern Weddell Sea showing the

units defined by Rogenhagen and Jokat (2000). Depth in kilometres. The correlation with units WD1 to WD5 of this study is depicted. See Fig. 2B for location of profile SM 06. Profile AWI 97051 and Station 051 are located south of the study area ($66^{\circ}11.5' S/51^{\circ}24' W$ to $66^{\circ}10.3' S/51^{\circ}28' W$)

the northern Weddell Sea oceanic crust (King and Barker 1988; King et al. 1997; Maldonado et al. 1998; Eagles and Livermore 2002). All these basins developed as a result of spreading in the Scotia Sea and subduction of the Weddell Sea and Southern Atlantic below several fragments of an eastward and southward migrating trench (Figs. 1, 2).

Basin age and structure

The abyssal plain of the northern Weddell Sea

The oceanic basin floor of the northern Weddell Sea in the province west of $47^{\circ}W$ is mostly uniform, with no magnetic anomalies and only regular gravimetric gradients, suggesting a Mesozoic age (Kavoun and Vinnikovskaya 1994; Livermore and Hunter 1996; LaBrecque and Ghidella 1997; Ghidella et al. 2002; Golinsky et al. 2002). The abyssal plain of the eastern province, in contrast, is disrupted by arched fracture

zones with a WNW–ESE orientation, easily recognized from satellite free-air gravity anomalies (Livermore et al. 1994; Sandwell and Smith 1997; Kovacs et al. 2002; Maldonado et al. 2005). The fracture zones have a morphological expression featuring asymmetric ridges several tens to hundreds meters high above the surrounding seafloor, which is otherwise rather flat and with an average depth of 4.2–4.7 km (Figs. 1, 3).

The boundary between the two provinces is a NNW–SSE trending transform fault (Maldonado et al. 1998). Linear magnetic anomalies almost orthogonal to the fracture zones are also well identified in the oceanic crust (Livermore and Woollett 1993; LaBrecque and Ghidella 1997; Ghidella et al. 2002; Golinsky et al. 2002). The youngest crust recognized in the study area off Jane Bank is represented by chron C6n (19.5 Ma, in the Cande and Kent (1995) geomagnetic timescale), although there is younger oceanic crust to the northeast along the northern boundary of the Weddell Sea (Bohoyo et al. 2002).

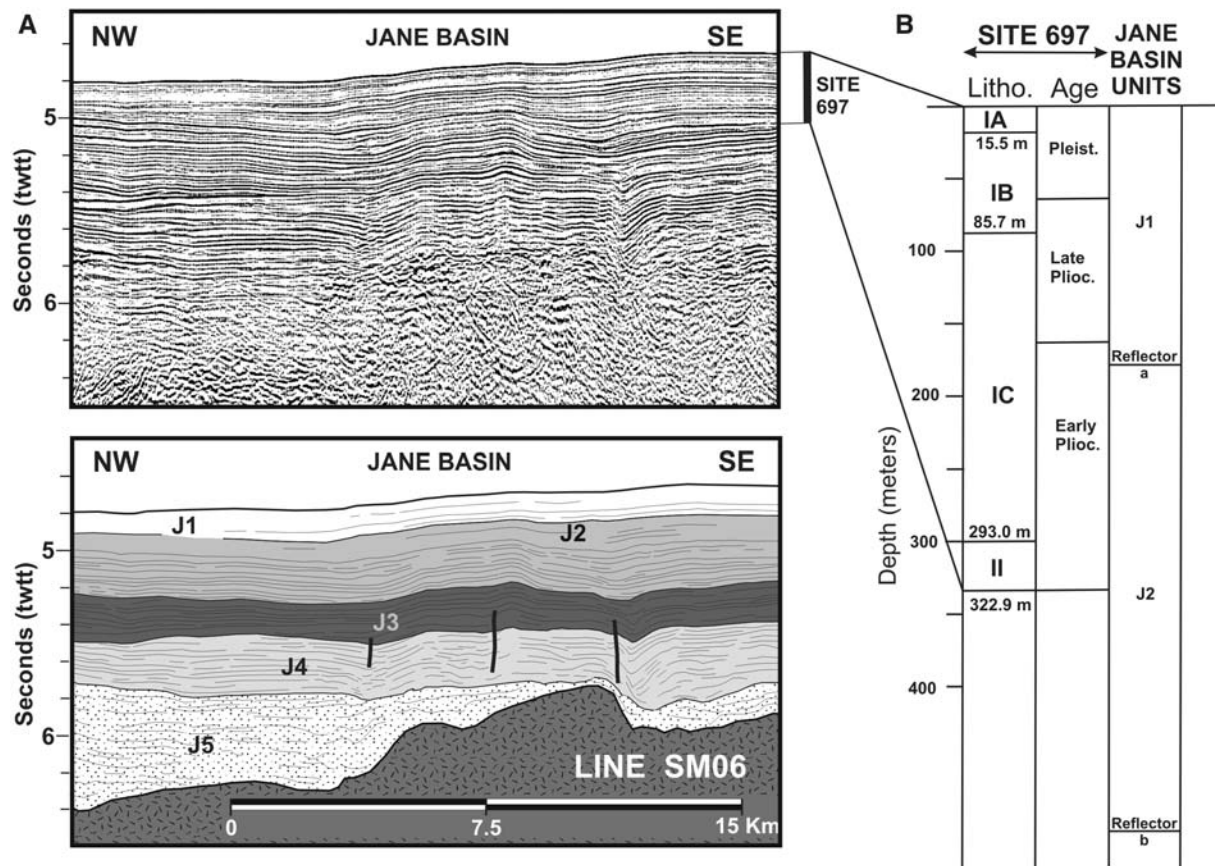


Fig. 5 A: Segment of multichannel seismic reflection profile SM06 across Jane Basin and line drawing interpretations of the profile. Seismic Units J1 to J5 identified in Jane Basin are shown. Depth in seconds two way travel time (twtt). **B:** Summary of lithology and age of the sediments drilled in Jane Basin at Site 697 (Barker et al. 1988). Depth in metres. The correlation

between the two uppermost seismic units J1 and J2 identified in this study and the results of Site 697 is illustrated. For the conversion of the seconds twtt of the seismic profile to the depth below seafloor in metres we have applied the velocities of the wide-angle experiments of Rogenhagen and Jokat (2000). See Fig. 2B for location

The basins of the northern Weddell Sea

Jane Basin is located seaward of the southern and southeastern margins of the South Orkney Microcontinent (Figs. 1–3, 5). The basin is elongated in shape and extends over 350 km, with basin plain depths of up to 3,000 m. It is bounded to the south by a chain of irregular ridges that form Jane Bank (Fig. 1). The basin is connected with the Scotia Sea to the northeast and with Powell Basin and the Weddell Sea to the southwest (Figs. 1, 2).

The spreading in Jane Basin began at chron C5Dn (17.6 Ma) and ended after chron C5ADn (14.4 Ma) (Bohoyo et al. 2002; Bohoyo 2004). The collision of the spreading centre of the northern Weddell Sea with the trench which was probably located at the South Orkney Microcontinent margin occurred after the development of the younger anomaly identified in the northern Weddell Sea. Since anomalies younger than

chron C6n (19.5 Ma) are absent in the Weddell Sea southward of Jane Basin, ridge–crest collision probably took place before spreading ended in Jane Basin at chron C5ADn, assuming that subduction continued to the ridge crest. The final steps of spreading in Jane Basin can be attributed to a mechanism of roll-back, which was probably facilitated by the former subduction of the ridge. The oceanic crust of Jane Basin is deformed by normal faults associated with the spreading processes, and reverse faults related to a final stage of compression in the basin (Fig. 3). Both types of faulting mainly affect the lower depositional sequences of the basin, whereas younger tectonic activity seems to be absent.

Powell Basin is a nearly circular basin with abyssal plain depths between 3,000 m and 3,500 m (Figs. 1, 2). The basin is bounded by the Antarctic Peninsula to the west, the South Orkney Microcontinent to the east and the South Scotia Ridge to the north. A subducted con-

tinental ridge is also located in the southern part, although the basin plain is connected with Jane Basin (Maldonado et al. 1998; Balanyá et al. 1999). The southern and northern margins of the basin are steep and straight with a morphology controlled by faults parallel to the margin without any intermediate crust. In contrast, the eastern and western margins are curved with gentle slopes and develop intermediate crust with thicker deposits (Fig. 6). This structure reflects the evolution of conjugate passive margins derived from the WSW to ENE spreading direction of the basin (King et al. 1997; Rodríguez-Fernández et al. 1997; Howe et al. 1998; Viseras and Maldonado 1999). The spreading centre of the basin has a NNW–SSE orientation, parallel to the passive margins and probably formed by overlapping spreading centres (Rodríguez-Fernández et al. 1997). The opening of Powell Basin is poorly constrained, because the magnetic anomalies are of low amplitude. King and Barker (1988) suggested a spreading timescale of 29–23 Ma, based on the standard age–depth relationship of Parsons and Sclater (1977). Along a magnetic profile across the ridge axis Coren et al. (1997) identified asymmetric spreading magnetic anomalies with a time span between pre-chron C8 (27 Ma) and post-chron C5E (18 Ma).

Lawver and Gahagan (1998) suggested that Powell Basin was opened by 30.5 Ma based on heat flow data correlated with the heat flow versus age relationship of Parsons and Sclater (1977). The analysis of the aerogeophysical data of the area also reveals a pattern of linear magnetic anomalies (LaBrecque and Ghidella 1997; Eagles and Livermore 2002; Kovacs et al. 2002). These magnetic anomalies are too poorly developed and the correlation with magnetic reversal time scale is ambiguous. A sequence of six reversals is tentatively proposed, however, by Eagles and Livermore (2002) with a model of spreading between pre-chron C12 (32.1 Ma) and following chron C6C (23.3 Ma).

The basins of the southern and central Scotia Sea

The oceanic crust in the southwestern Scotia Sea abyssal plain developed from two spreading corridors of the West Scotia Ridge separated by a fracture zone. Magnetic anomaly chron C8r (27.02 Ma) is well identified in the abyssal plain (BAS 1985). More recently Lodolo et al. (1997) proposed, however, an initial period of non-organized emplacement of oceanic-like crust that took place in the area from chron C8r to C10 (27.02–28.7 Ma) based on a study of the character and

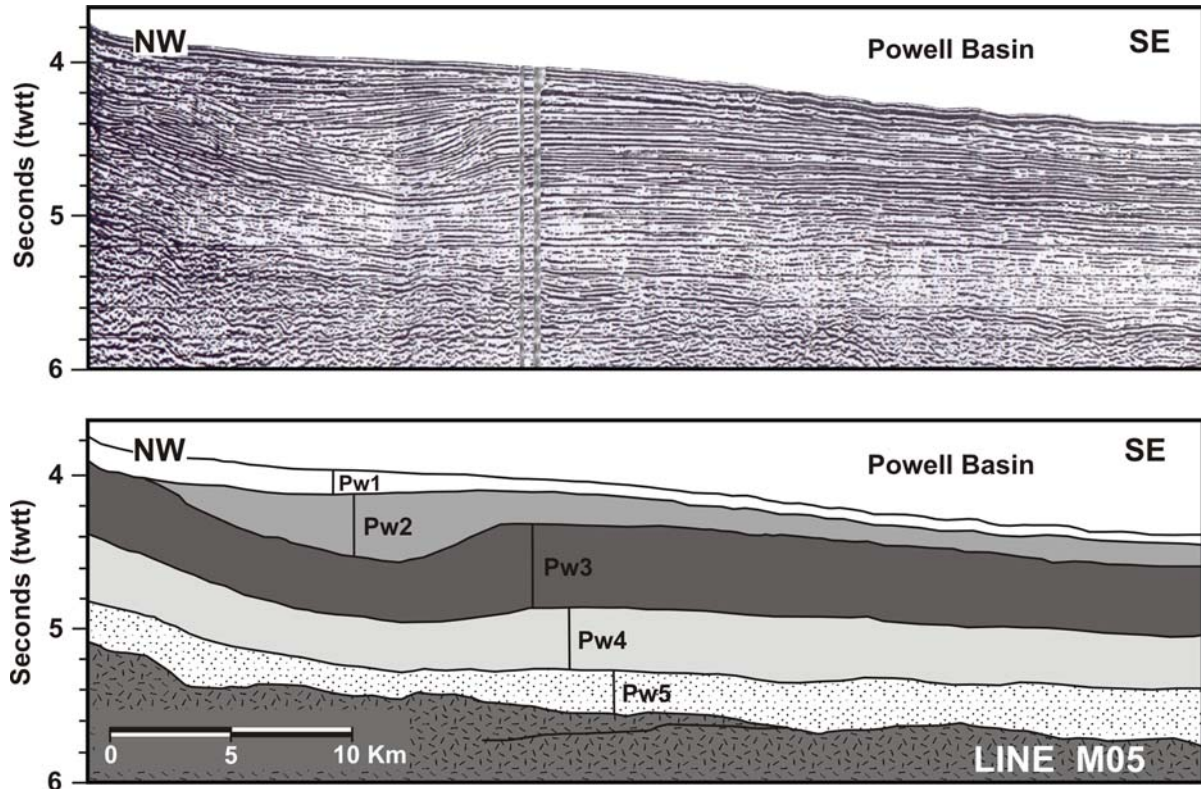


Fig. 6 Segment of multichannel seismic reflection profile SM05 across Powell Basin and line drawing interpretation of the profile. Pw1 to Pw5 seismic units identified in Powell Basin. Depth in seconds two way travel time (twtt). See Fig. 2B for location

shape of the oldest magnetic anomalies. The oceanic crust in this sector is also affected by ancient thrust structures below the margin of the South Scotia Ridge, and a portion of the oldest crust was probably eliminated by subduction (Aldaya and Maldonado 1996; Lodolo et al. 1997). More recent reverse and normal faults disrupt the depositional sequence in the abyssal plain (Figs. 7, 8). The orientation of reverse faults is approximately E–W to WNW–ESE (Galindo-Zaldívar et al. 1996). The southwestern Scotia Abyssal Plain is bounded eastward by Terror Rise, which shows water depths from 2,000 to 3,500 m and a convex relief (Fig. 9).

Protector Basin is located between Terror Rise and Pirie Bank (Figs. 1, 2). This basin has a triangular shape opening towards the south, where it is approximately 250 km wide. The abyssal plain water depth is between 3,000 and 4,000 m, although there is a N–S oriented elevation of the sea floor related to a central spreading centre, covered by sediments towards the south (Figs. 9, 10, 11A). The magnetic anomalies are symmetrical with respect to the N–S oriented spreading centre and they indicate an E–W oriented direction of spreading, and an age range between chron C5Dn (17.6 Ma) and C5ACn (14 Ma) (Galindo-Zaldívar et al. 2006). Pirie Bank forms the eastern boundary of Protector Basin, with water depths between 1,500 and 3,750 m and is formed by thinned continental crust, affected by normal faults that develop half-graben structures and thinning of the crust in the E–W and N–S directions (Figs. 2, 9). Dove Basin, between Pirie Bank and Bruce Bank, is elongated in a NNE–SSW direction, with a central NNE–SSW oriented ridge that may correspond to a spreading centre (Figs. 1, 2).

Another basin lies to the east, between Bruce Bank and Discovery Bank and it is herein named Scan Basin (Figs. 1, 2). The basin has an irregular geometry and it may represent the result of the overprinting of different spreading phases. This basin opens northward into the central Scotia Sea abyssal plain, where magnetic chron 5AD (14.2 Ma) to chron 6A (20.7 Ma) are identified, with an E–W orientation (BAS 1985; Maldonado et al. 2003).

The central sector of Drake Passage

The Shackleton Fracture Zone is intersected by the West Scotia Ridge and the Phoenix–Antarctic Ridge in central Drake Passage. The high relief and uplift of the Shackleton Fracture Zone seem to be rather recent geological features of the ocean floor (Maldonado et al. 2000; Livermore et al. 2004). The swath map of this oceanic transverse ridge and the synthesis of the

previous geophysical studies indicate that the uplift probably occurred as a result of transpression between the adjacent Phoenix and Scotia plates at the fracture zone. The uplift took place during a period of regional compression in the Scotia Sea younger than 17 Ma (Livermore et al. 2004). A small change that occurred in the pole of rotation after ca. 8 Ma probably developed the oblique compression to older fabric and the uplift of the Shackleton Fracture Zone. This compression finally led to the extinction of the West Scotia Ridge after magnetic chron 3A (ca. 6.4 Ma), and of the Phoenix Ridge after chron 2A (ca. 3.3 Ma) (Livermore et al. 2000; Maldonado et al. 2000). Some small depressions were, however, developed as a result of extensional tectonics along the Shackleton Fracture Zone, before compression took place. The convergence between the Antarctic and Scotia plates, moreover, is still active at present which implies that uplift is continuing today.

The sedimentary cover is generally absent over the typical oceanic crust of the area, most probably due to active bottom currents. Thin deposits are observed only in small depressions and basins of the basement. Thick depositional units are observed, in contrast, over the abandoned axis of the western segment of the West Scotia Ridge (Figs. 12, 13).

Seismic stratigraphy

The seismic stratigraphy of depositional units in the basins of the area is discussed on the basis of the analysis of MCS profiles. The basement of each basin is of a different age, but they display similar seismic facies on a regional scale. Oceanic basement is identified by a rough, high-amplitude reflector, with discontinuous high-amplitude reflectors and irregular diffractions, above sparse and weak reflectors (Fig. 14). The top of basement in the basins is attributed to oceanic igneous Layer 2, mainly formed by pillow lavas. Yet in the basin margins and some of the seafloor elevations, basement is characterized by chaotic reflectors that may represent intermediate or continental crust.

The sedimentary cover above the basement is up to 2600 m thick, but it shows significant thickness variations (Figs. 3, 4, 7, 9, 14). Sediments are locally absent, particularly above spreading centres and banks, or in areas of strong bottom current activity (Figs. 3, 9, 12). The seismic units are identified according to seismic facies, relationships with the underlying basement and the age control from Ocean Drilling Program boreholes (Figs. 2B, 4, 5). Five main seismic units are identified in the basins of the area (Fig. 14). According to the age of

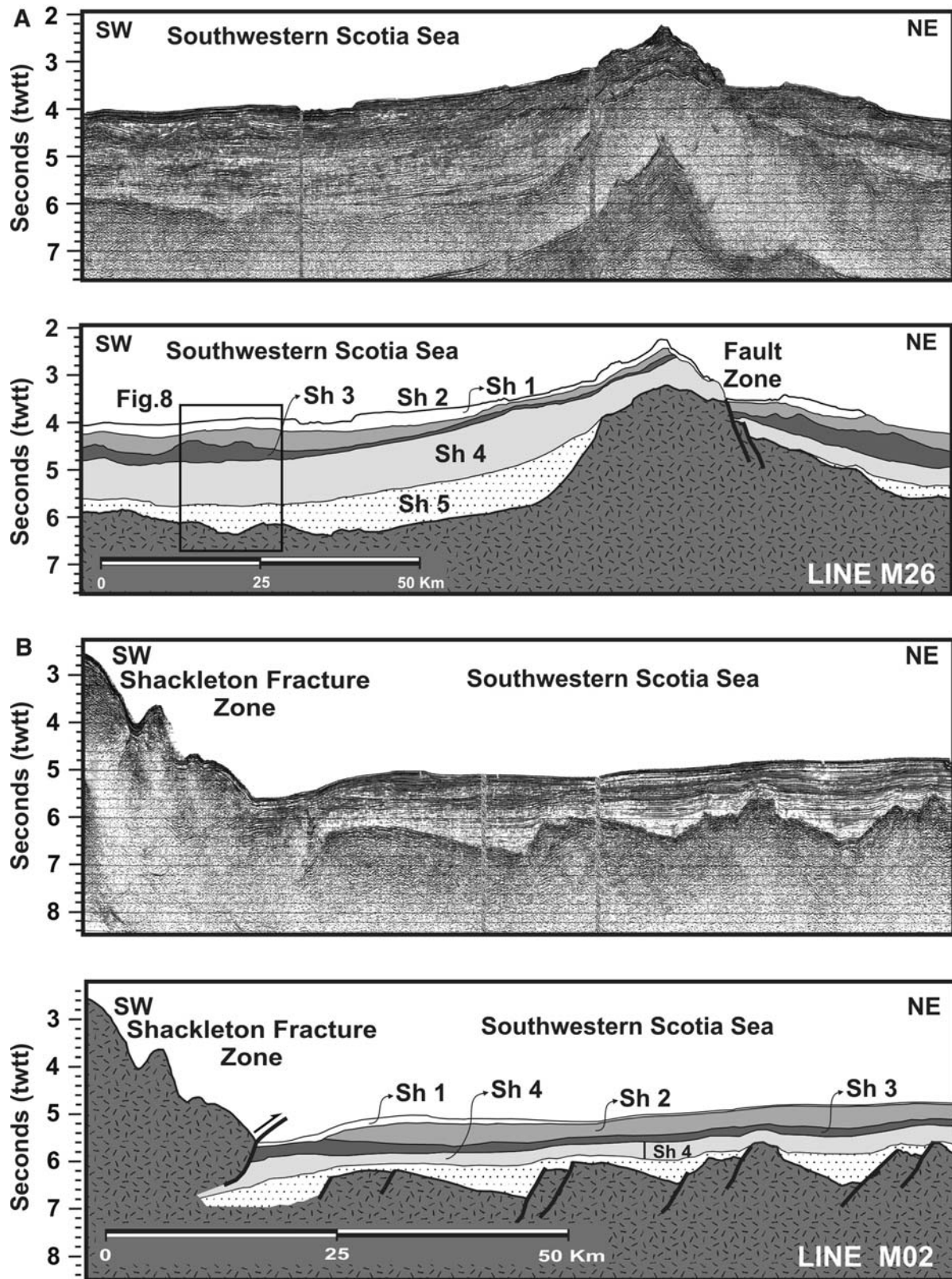


Fig. 7 Representative segments of multichannel seismic reflection profiles M26 (A) and M02 (B) to illustrate the seismic units of the Southwestern Scotia Sea Abyssal Plain and line drawing

interpretations of the profiles. Sh1 to Sh5, seismic units identified in the Southwestern Scotia Sea Abyssal Plain. Depth in seconds two way travel time (twtt). See Fig. 2B for location

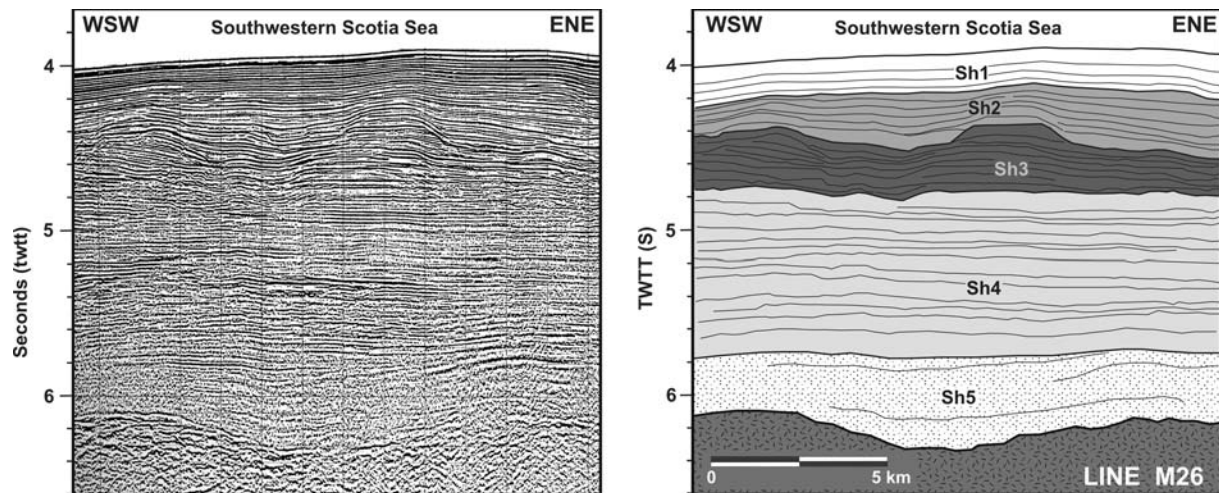


Fig. 8 Fragment of seismic profile M26 across the Southwestern Scotia Sea Abyssal Plain and line drawing interpretations of the profile. Sh1 to Sh5, seismic units identified in the Southwestern

Scotia Sea Abyssal Plain. Depth in seconds two way travel time (twtt). See Fig. 7A for location

basement, the two oldest units are of different ages and show distinct seismic facies. These units were developed in most basins during active rifting and seafloor spreading as syn-rift deposits (Fig. 15).

The seismic units identified in this study are bounded by high-amplitude continuous reflectors (named a to d from top to bottom) that represent major discontinuities in depositional sequences (Fig. 15). The most significant discontinuity is a widespread, very high-amplitude reflector (named Reflector c) that can be traced at a regional scale. This discontinuity locally constitutes a remarkable erosive surface, which may evolve laterally into a non-depositional surface.

The oldest seismic units are described independently because they show different facies and age from basin to basin (Figs. 14, 15). The three youngest units, in contrast, are widespread, rather similar, and can be correlated between basins.

The oldest depositional units

The abyssal plain of the northern Weddell Sea

Maldonado et al. (1998) described the sedimentary record on both sides of a N–S transform fault in the western part of the northern Weddell Sea that separates the Mesozoic and Cenozoic oceanic crusts. These authors identified five seismic units (W1 to W5 from bottom to top) above oceanic crust of Jurassic age, westward of the transform fault. The two lowest units were not observed over oceanic crust of Early Miocene age east of the fault zone. Later, Maldonado et al. (2005) performed a detailed stratigraphic analysis where the Cenozoic deposits were differentiated into

five seismic units named units 5 to 1 (from bottom to top), instead of the previous W3 to W5 (Figs. 14, 15). The correlation between these units and the “Upper Sedimentary Unit I” of Rogenhagen and Jokat (2000) is shown in Fig. 4. The units identified by Maldonado et al. (2005) are the ones used in this study. These units, named here WD5 to WD1 from bottom to top, are well recognized in the northern Weddell Sea, south of Jane Bank (Figs. 2–4, 14, 15).

Seismic Unit WD5 consists of parallel and discontinuous reflectors that evolve laterally into chaotic reflections (Figs. 3, 4). The unit thickness varies from 875 m in basement topographic depressions to absent over structural highs and near the margins of Jane Bank (Fig. 3). This unit is tentatively attributed an age of Early Miocene, based on the magnetic anomalies of igneous basement, and the geometry and distribution of the deposits (Bohoyo 2004; Maldonado et al. 2005).

Seismic Unit WD4 is well stratified, with an aggradational configuration (Figs. 3, 4). Internal reflectors show high lateral continuity and decreasing amplitude towards basement highs. Unit WD4 displays a lenticular shape and its thickness ranges from 750 m to zero over structural highs of the basement (Fig. 3). This unit is tentatively attributed an age of Early to Middle Miocene (Maldonado et al. 2005).

Basins of the northern Weddell Sea

Maldonado et al. (1998) identified two major depositional sequences (J1, J2) in Jane Basin that can be correlated to the two upper (Pw3, Pw4) sequences differentiated in Powell Basin. Recently, more detailed seismic stratigraphic analyses carried out by Bohoyo

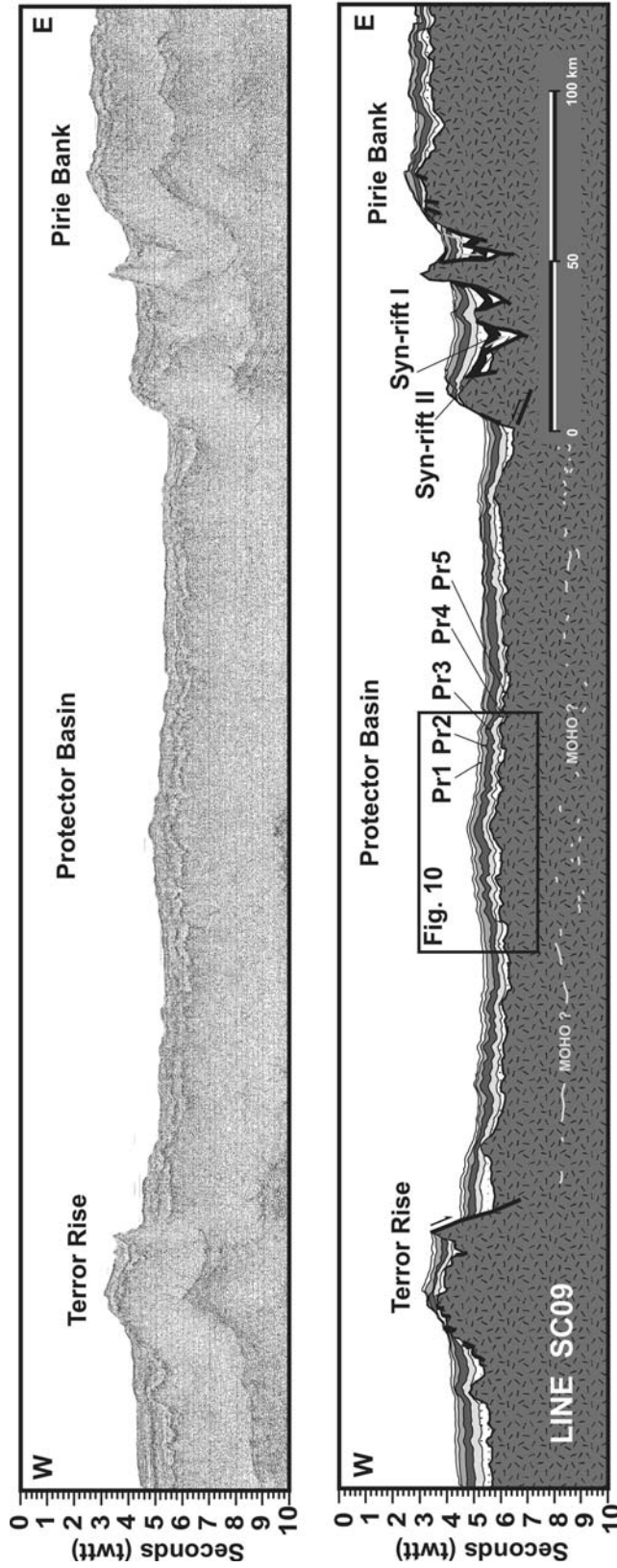


Fig. 9 Multichannel seismic reflection profile SC09 across the Terror Rise, Protector Basin, and Pirie Bank and line drawing interpretation of the profile. Pr1 to Pr5, seismic units identified in the Protector Basin. Depth in seconds two way travel time (twtt). See Fig. 2B for location

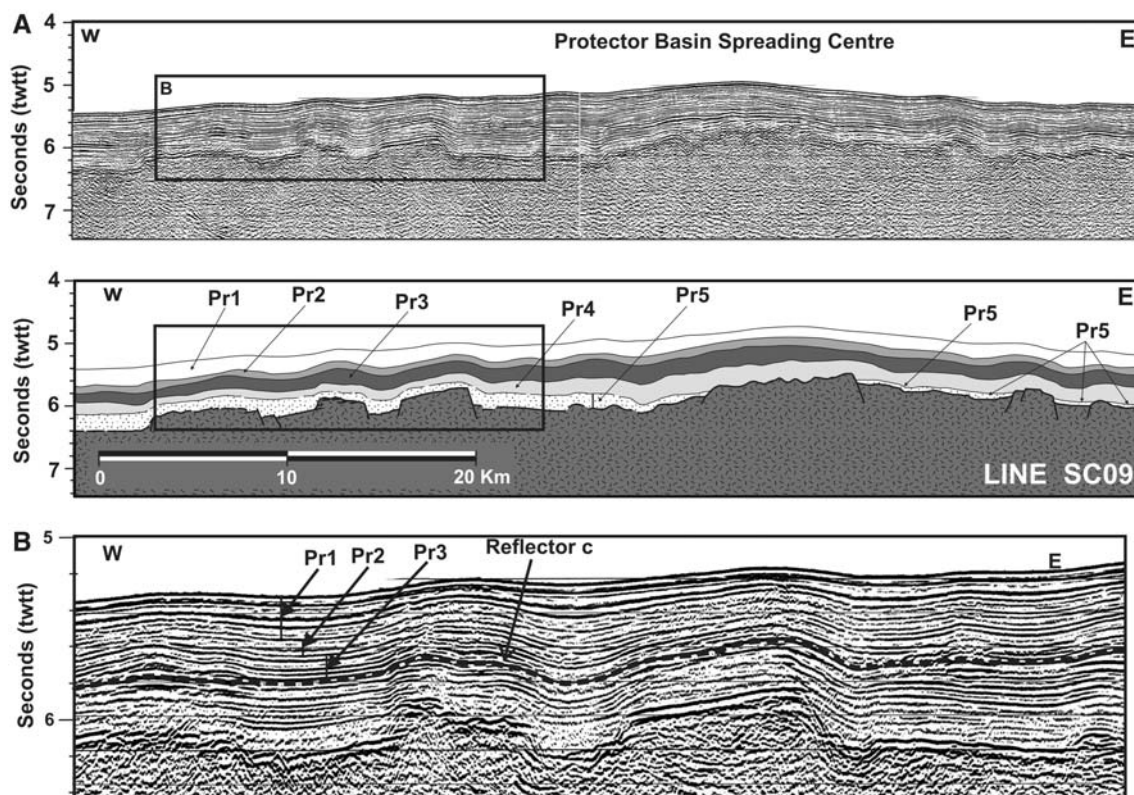


Fig. 10 Fragment of seismic profile SC09 across the Central Protector Basin and line drawing interpretations of the profile. Pr1 to Pr5, seismic units identified in Protector Basin. Depth in seconds two way travel time (twtt). See Fig. 9 for location

(2004) and Maldonado et al. (2005) have suggested a subdivision into five seismic units (J5 to J1 from bottom to top) in Jane Basin (Figs. 3, 5). This recent nomenclature has been adopted in the present study (Figs. 14, 15). The oldest seismic unit (J5 of Jane Basin) onlaps the top of oceanic crust, filling in topographic lows (Fig. 3). This unit exhibits a chaotic configuration with discontinuous reflectors that increase in amplitude towards the top. Total thickness is variable and may reach up to 855 m. The tentative age attributed to this unit is Early Miocene based on oceanic magnetic anomalies and the geometry of the deposits (Bohoyo 2004; Maldonado et al. 2005). Seismic unit J4 may reach 380 m and unconformably overlaps the older deposits or basement directly. It is an aggradational unit with moderate to low-amplitude and usually discontinuous reflectors. Internal reflectors of the unit lap onto the margins of the basin and basement highs. This unit is tentatively attributed to the late-Early to Middle Miocene (Bohoyo 2004; Maldonado et al. 2005).

Coren et al. (1997), Rodríguez-Fernández et al. (1997), and Viseras and Maldonado (1999) identified four seismic units in the sedimentary infill of Powell Basin. The present study reports a more detailed seismic stratigraphic analysis, and we define five seismic units (Pw5 to Pw1 from bottom to top) on the abyssal

plain (Figs. 6, 14, 15). Seismic Unit Pw5 is located in most of the abyssal plain with a thickness that ranges from 250 m to 875 m. Unit Pw5 thins towards the spreading centre along the axis of the basin (Rodríguez-Fernández et al. 1997; King et al. 1997). This unit exhibits an aggradational configuration with discontinuous and low-amplitude reflectors, which onlap both sides of the spreading centre (Fig. 6). The unit represents the syn-rift stage of active seafloor spreading (Figs. 14, 15). According to the different models of spreading proposed for Powell Basin, Unit Pw5 may be attributed an age between Oligocene (chrons C12 to C8) for the lower boundary and Early Miocene (chrons C6C to C5E) for the upper boundary (Fig. 15). Seismic Unit Pw4 onlaps the underlying unit along the basin margins, where it displays discontinuous and low-amplitude reflectors. Unit Pw4 is, however, conformable in the abyssal plain with continuous and high-amplitude reflectors. The thickness of Unit Pw4 ranges between 375 m over basement highs and the spreading centre and a maximum of 1,250 m in depressions of the basin. Unit Pw4 is tentatively attributed an age of early-Middle Miocene, given the geometry and distribution of the deposits and the correlation with deposits of Jane Basin (Rodríguez-Fernández et al. 1997; Maldonado et al. 1998).

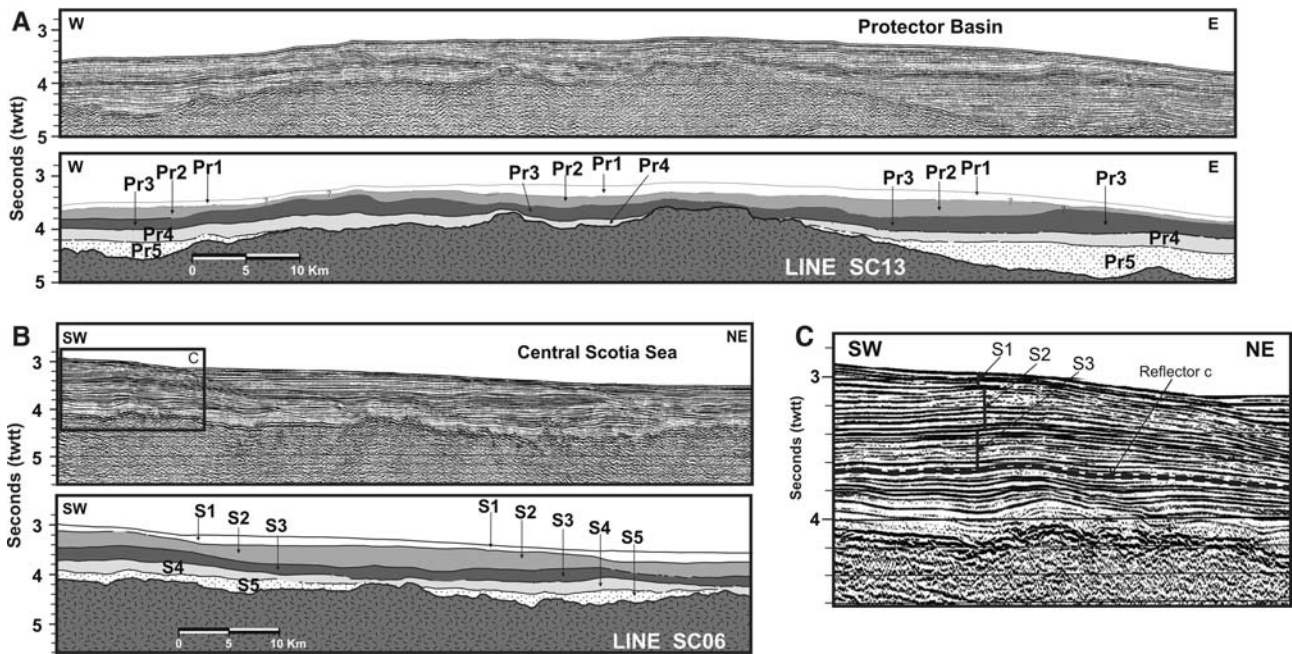


Fig. 11 Representative segments of multichannel seismic reflection profiles SC13 (**A**) and SC06 (**B**) across the Protector Basin and the Central Scotia Sea Abyssal Plain and line drawing interpretations of the profiles. Pr1 to Pr5, seismic units identified

in the Protector Basin; S1 to S5, seismic units identified in the Central Scotia Sea Abyssal Plain. Depth in seconds two way travel time (twtt). See Fig. 2B for location

Basins of the southern and central Scotia Sea

Depositional sequences of the southwestern Scotia Sea Abyssal Plain are between 1,500 m and 3,300 m thick (Figs. 7, 8). Five seismic units have been identified, named Sh5 to Sh1 (Figs. 14, 15). Seismic unit Sh5 fills basement depressions, where it exhibits a lenticular shape with a maximum thickness of 750 m. Unit Sh5 has low-amplitude, discontinuous internal reflectors, except over basement highs where higher amplitude and continuous reflectors are observed (Figs. 7, 8). The unit laps onto basement highs. The upper boundary of Sh5 is a distinct discontinuity (Fig. 8). Oceanic magnetic anomalies and the geometry of the deposits suggest an Oligocene–Early Miocene age for this unit (Fig. 15). Unit Sh4 exhibits a sheet-like shape with a thickness that ranges between 625 m and 1,000 m. Unit Sh4 shows parallel, continuous, high-amplitude reflectors, that evolve laterally into discontinuous, low-amplitude reflectors (Figs. 7, 8). Several secondary discontinuities can be identified within the unit. The estimated age of Sh4 is late-Early to Middle Miocene (Fig. 15).

The deposits of Protector Basin have a rather uniform thickness of 1,200 m to 1,550 m. Five seismic units, named Pr5 to Pr1 from bottom to top are identified (Figs. 9–11A). Additional seismic units not discussed in this work and attributed to the syn-rift deposits are observed over Pirie Bank (Figs. 9, 10).

Unit Pr5 exhibits internal reflectors with moderate lateral continuity over the abyssal plain. Yet some reflectors show higher amplitude and lateral continuity. The distribution of unit Pr5 is controlled by the basement morphology and fills depressions with parallel reflectors. This unit is attributed an age of early-Middle Miocene, according to the age of the oceanic magnetic anomalies and geometry of the deposits (Figs. 14, 15). Unit Pr4 is characterized by sub-horizontal reflectors of high amplitude and lateral continuity and a sheet-like external configuration. Some mounded morphologies with low-angle progradational reflectors occur locally (Figs. 9, 10). This unit is tentatively attributed Middle Miocene age (Fig. 15).

Deposits in the central Scotia Sea Abyssal Plain have thicknesses between 660 m and 770 m, although the average thickness decreases towards the northeast (Fig. 11B). Maldonado et al. (2003, 2005) made a preliminary description of the seismic stratigraphy of this region, where they identified six seismic units VI to I, from bottom to top. In this study we conducted a regional correlation of all the seismic units of the southern and central Scotia Sea, and define five new seismic units (units S5 to S1 from bottom to top) instead of the six previous ones (Figs. 14, 15). The oldest seismic unit, S5, is located east of Pirie Bank (Figs. 2B, 11B). This unit shows an aggradational pattern and a lenticular shape, with well-stratified internal

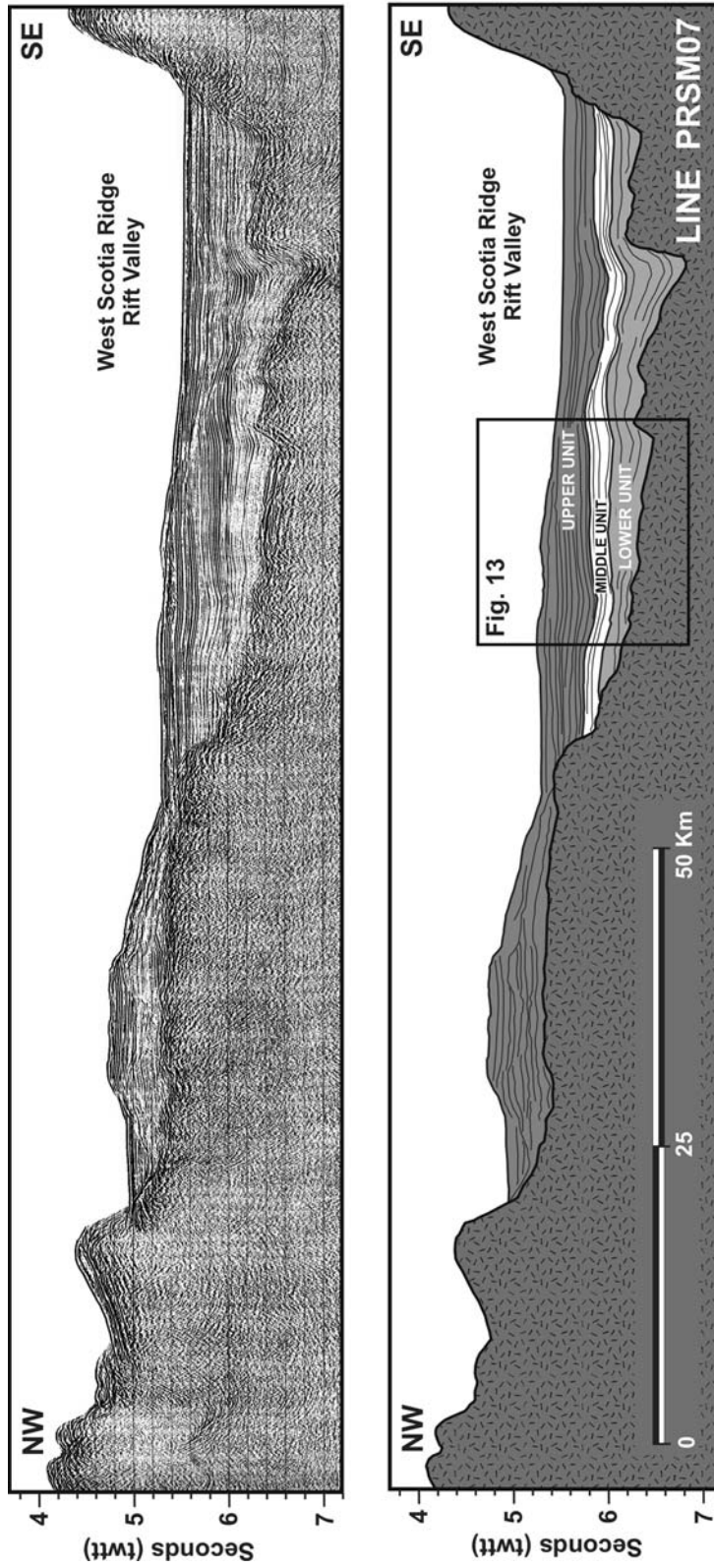


Fig. 12 Representative segment of multichannel seismic reflection profile PRSM07 across the West Scotia Ridge rift valley and line drawing interpretations of the profile showing the three seismic units identified in the central Drake Passage. Depth in seconds two way travel time (twt). See Figure 2B for location

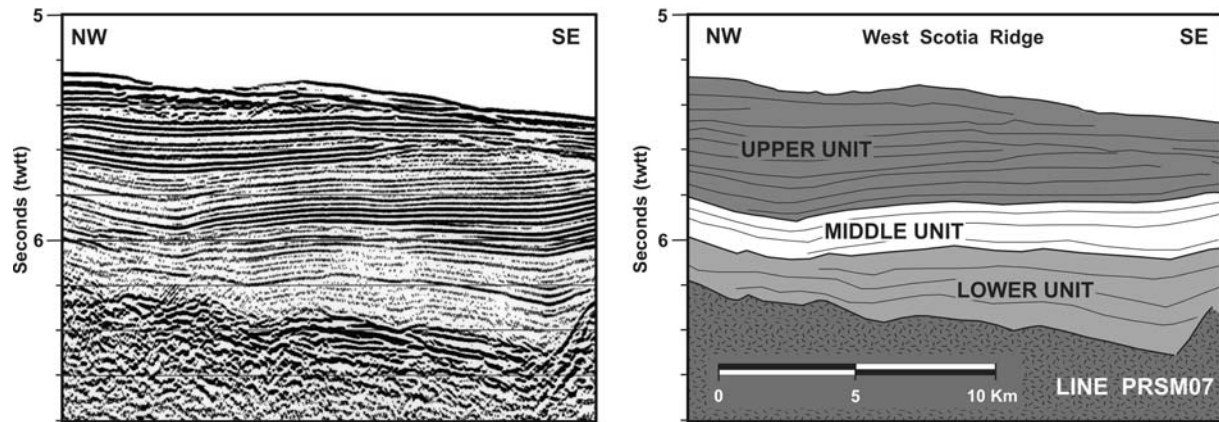


Fig. 13 Fragment of seismic profile PRSM07 across the West Scotia Ridge rift valley and line drawing interpretations of the profile. Depth in seconds two way travel time (twtt). See Figure 12 for location

reflectors. Unit S5 is attributed an age of Early Miocene on the basis of the oceanic magnetic anomaly age and the geometry of deposits (Maldonado et al. 2003). Unit S4 also shows a lenticular geometry, and is internally characterized by progradational to sub-parallel configurations. This unit progrades locally southward, in contrast to the northward progradation observed in overlying units, and is tentatively attributed to the early-Middle Miocene (Maldonado et al. 2003). The distribution patterns of these two units are consistent with ages of oceanic magnetic anomalies (Figs. 11B, 15). Thus, unit S5 thins and disappears to the northeast, where the oceanic crust becomes younger. Seismic unit S4 also reduces thickness in the same direction, although it is recognized in the central Scotia Sea Abyssal Plain.

The three youngest seismic units of the abyssal plains

The three youngest seismic units in the northern Weddell Sea abyssal plain (WD3, WD2, WD1), Powell Basin (Pw3, Pw2, Pw1), Jane Basin (J3, J2, J1), southwestern Scotia Sea Abyssal Plain (Sh3, Sh2, Sh1), Protector Basin (Pr3, Pr2, Pr1) and central Scotia Sea Abyssal Plain (S3, S2, S1) are developed above the regional Reflector c (Fig. 14). They show similar seismic facies and represent depositional units developed after seafloor spreading ended on the Antarctic Plate, although the oldest deposits correspond locally to syn-rift units coeval with seafloor spreading in the Scotia Plate (Figs. 14, 15). These units are grouped herein into seismic Unit 3, Unit 2 and Unit 1, from bottom to top and they are described on a regional basis because of their similarities from basin to basin.

The basal seismic Unit 3 is characterized by a stratified laminar configuration, with very high-amplitude and laterally continuous reflectors (Figs. 3–13). The internal reflectors of Unit 3 frequently show downlap terminations over Reflector c, although they locally onlap the basement highs. The upper boundary (Reflector b) is a continuous reflector that represents an erosive unconformity with low to moderate amplitude. Reflector b is conformable over the underlying deposits in the central part of the basins and erosive over the edges. Unit 3 most frequently shows a mounded geometry, although sheet-like morphologies are also common. Both morphologies have locally superimposed sediment waves. Minor discontinuities are frequently observed within the unit. The thickness of Unit 3 is variable in each basin, ranging from 380 m to 570 m (Fig. 14). The unit is tentatively attributed an age of Middle to Late Miocene (Maldonado et al. 2003, 2005).

Unit 2 is generally conformable over the underlying deposits in the central parts of the basins, whereas it shows onlap terminations towards the basin margins (Figs. 4, 5, 8, 10). The unit displays an aggradational configuration and moderate to low amplitude reflectors with variable lateral continuity, although transparent acoustic responses can be observed in places. Mounded and sheet-like external shapes are dominant within Unit 2, particularly in the basins of the southern Scotia Sea (Fig. 11). Superimposed bedforms and associated wavy facies are locally found. The thickness ranges from 190 m in Powell Basin to 570 m in the southwestern Scotia Sea basin (Fig. 14). The upper boundary (Reflector a) is a high-amplitude reflector. This unit is attributed an age of Late Miocene to Early Pliocene based on the geometry of the deposits, the regional sedimentation rates and correlation with the ODP sites of the area (Fig. 5).

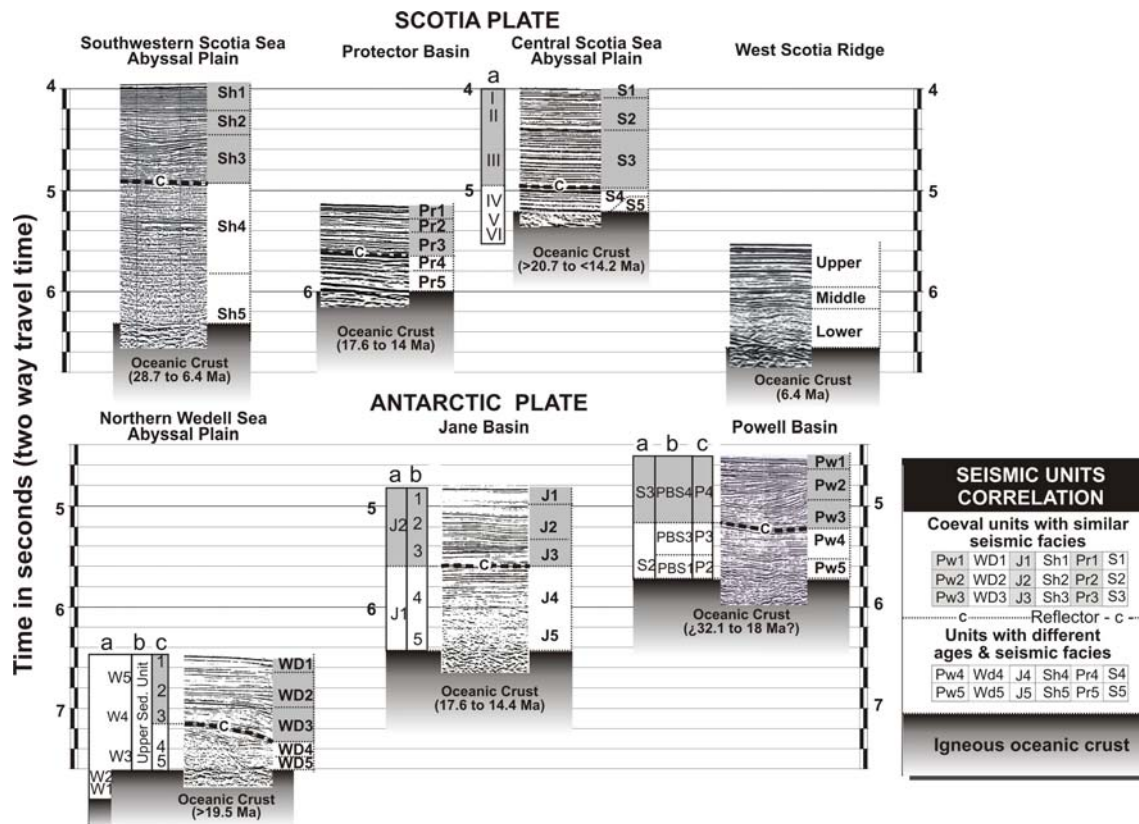


Fig. 14 Correlation of seismic units identified in the basins near the boundary between the Antarctic and Scotia plates. The fragments of multichannel seismic reflection profiles illustrate representative sections of the basins. Depth in seconds two way travel time (twtt). The seismic units identified in this study are shown in the vertical bar to the right of seismic reflection profiles. The seismic units described by previous authors are shown in vertical bars to the left of the seismic reflection profiles. The age of the oceanic basin floor is given according the identified magnetic anomalies. The major discontinuity named Reflector c is illustrated in the seismic records. The basins described in the

Scotia Plate include: Southwestern Scotia Sea Abyssal Plain, Protector Basin; Central Scotia Sea Abyssal Plain: (previous studies: a, Maldonado et al. 2003, 2005), and the West Scotia Ridge. The basins identified in the Antarctic Plate include: Northern Weddell Sea Abyssal Plain: (previous studies: a, Maldonado et al. 2005); Jane Basin: (previous studies: a, Maldonado et al. 1998; b, Rogenhagen and Jokat 2000; c, Maldonado et al. 2005); Powell Basin: (previous studies: a, Rodríguez-Fernández et al. 1997; b, Coren et al. 1997; c, Viseras and Maldonado 1999)

Unit 1 is relatively thin and rather discontinuous (Figs. 3, 7, 9, 11). The unit is dominated by reflective acoustic responses at the base, but becomes more transparent towards the top in the northern Weddell Sea. Upslope migrating giant sediment waves (2.5–3.7 km long and up to 80 m high) are identified in Powell Basin, mainly along the base of the slope of the northwestern margin (Howe et al. 1998). The unit shows sub-parallel, high-amplitude reflectors with high lateral continuity that fill in previous mounded morphology in the basins of the southern Scotia Sea (Fig. 11). The internal reflectors downlap the basal discontinuity. Small amplitude sediment waves are identified locally in the upper deposits, which are also often cut by channels and moats. A cyclic pattern of alternating low- and high-amplitude internal reflectors is generally observed within the unit. The average

thickness of the unit is about 100 m. The tentative age of Unit 1 is late-Early Pliocene to Recent (Fig. 5). Clays and fine silts with subordinate siliceous oozes were recovered from this unit in the northeastern Jane Basin of ODP Site 697 (Barker et al. 1988).

The central sector of the Drake Passage

The thick depositional sequences on the West Scotia Ridge near the intersection with the Shackleton Fracture Zone are younger than chron C3A (Figs. 2, 12, 14, 15). These deposits are described independently because this is a key area for paleoceanographic reconstructions of Drake Passage.

The deposits in the rift valley form a wedge about 32 km wide, with a maximum thickness of 950 m. Three major seismic units (lower, middle, upper) are

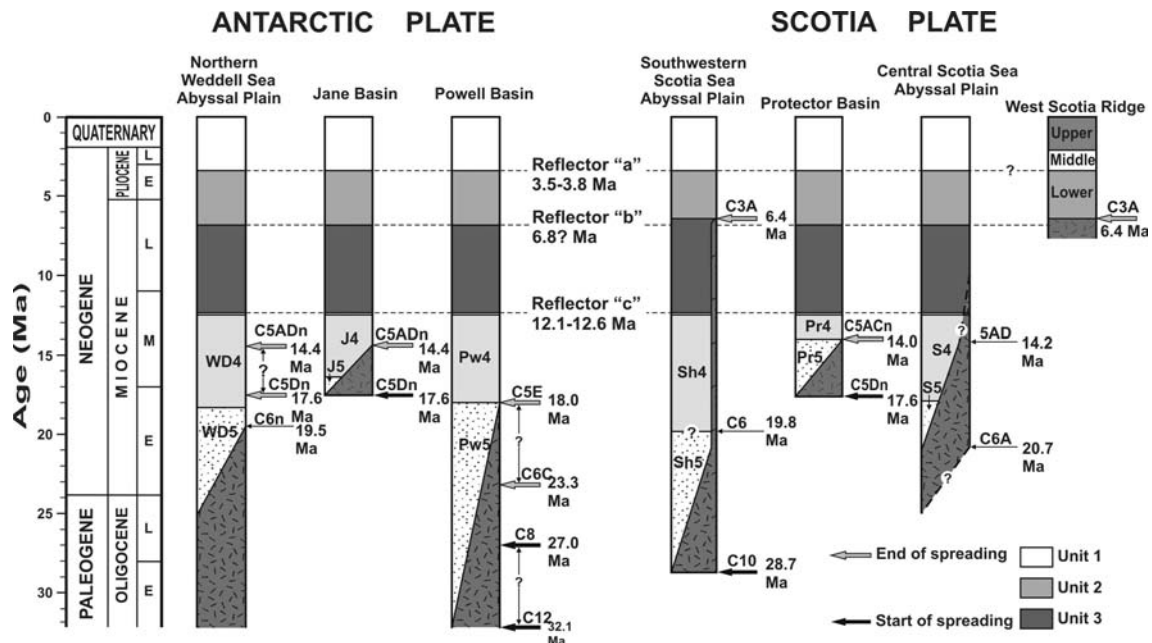


Fig. 15 Stratigraphic correlation of seismic units and key reflectors identified in the basins of the area. The spreading time span of each basin is also shown. Discussion in the text

characterized in the deposits, separated by two main seismic discontinuities (Figs. 12–15). The lower seismic unit is an aggradational sediment drape that fills topographic depressions of the basement (Fig. 12). The internal reflectors show low amplitude and poor lateral continuity, and onlap the lower boundary (Fig. 13). Maximum thickness is about 475 m. The upper boundary is locally erosive but becomes laterally to concordant. The middle seismic unit is formed by internal reflectors of high amplitude and lateral continuity, with variable terminations in relation with the lower boundary (Fig. 12). Internal reflectors are mounded, with a predominant aggradational pattern. Maximum thickness is about 285 m. Erosional truncation of the upper boundary is identified locally. The upper seismic unit has similar seismic facies to the underlying unit. The configuration of internal reflectors, in contrast, is aggradational to progradational. Correlation between these deposits and the youngest seismic units of other basins is ambiguous, because the deposits are isolated inside the rift valley. The strong reflector at the base of the middle unit shows a character and stratigraphic position similar to Reflector a identified elsewhere (Figs. 14, 15). If this tentative correlation is correct, the upper and middle units of the West Scotia Ridge may correspond to the uppermost Unit 1 recognized basinwide. The lower unit most probably represents the bulk of Unit 2, since the spreading centre became extinct at ca. 6.4 Ma (Maldonado et al. 2000).

Seismic interpretation of depositional units

Many of the seismic characteristics observed in the three youngest units indicate that these deposits were developed under the influence of strong bottom currents. These 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. 6, 8, 11, 13). The geometry of the units also indicates that these deposits are distributed parallel or oblique to the main morphologic features of the basins, rather than down-slope and or following the gradients of the margins and abyssal plains. We interpret all these deposits as contourites that were developed under the influence of the two most important flows in the area, the ACC and the Weddell Sea Bottom Water (WSBW).

The older units may have similar characteristics indicative of contourite deposits, but the basins themselves show different features. In the Weddell Sea, Powell Basin and Jane Basin, the seismic facies indicate bottom flows with an eastward or northeastward orientation throughout the entire depositional units, with the exception of the basal deposits attributed to the Oligocene to Early Miocene (Howe et al. 1998; Maldonado et al. 2005). The contourite deposits of

Unit WD4 are better developed in the Weddell Sea, indicating the initiation of permanent and well-established thermohaline flows that persist throughout the deposits from Unit WD4 to the Recent (Figs. 14, 15).

Similar deposits are extensively developed in the central Scotia Sea Abyssal Plain (Maldonado et al. 2003). These deposits also reveal strong flows that have shaped the geometry of the depositional bodies nearly parallel to the main topographic features. The geometries and facies distributions of deposits at the West Scotia Ridge in central Drake Passage indicate strong bottom currents throughout the units (Fig. 12).

The three uppermost units differentiated in the area also show the characteristics of contourite deposits (Fig. 14). The distribution and seismic features of these deposits vary in relation to the bottom topography, which significantly influenced the distribution of bottom currents (Maldonado et al. 2003, 2005, 2006). In the unconfined setting of the abyssal plain, the type of contourite drift is determined by the interplay of strong currents shearing along the margins of submarine banks and tectonic disruptions of the sea floor. Sheeted drifts dominate in the abyssal plain, but along the margins of the banks, plastered and giant elongated-mounded drifts are developed by the currents (Figs. 7, 9, 11). In the more restricted confined setting of the basins, as in Powell Basin, Jane Basin and West Scotia Ridge, 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 predominant deposits in this setting are giant elongated-mounded drifts and drifts influenced by the tectonic disruption of the basement (Figs. 6, 12). Transverse contourite drifts are also observed in this type of setting where the floor is smooth, probably due to the general constriction of flow between ridges (Maldonado et al. 2005).

In the stratigraphic sequence the type of contourites also shows a vertical evolution. The deposits of Unit 3 are frequently characterized by elongated and sheeted drifts. The deposits of Unit 2 are mainly interpreted as transverse drifts and sheeted drifts, which may locally constitute the bulk of the unit, though other types such as levee drifts are also observed. 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. 6, 8, 13). 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 are also attributed to increased current activity (Michels et al. 2002).

Discussion and conclusions

Tectonic evolution

Major plate reconstructions of Lawver and Gahagan (1998, 2003) based on seafloor magnetic anomalies and the distribution of fracture zone lineation show the age of the opening of the seaway between the South Tasman Rise and Antarctica to be around the Eocene–Oligocene boundary, with an unrestricted opening deeper than 2,000 m dating from about 32 Ma. For these authors the timing of opening of Drake Passage is less constrained because the exact motions of several Scotia Sea continental fragments are not well known (Fig. 1). Their tectonic reconstructions indicate that Drake Passage was most likely open to deep-water circulation by $\sim 31 \pm 2$ Ma. Drake Passage was blocked initially by a narrow wall-like sliver of continental fragments extending from the northwestern Antarctic Peninsula towards the Pacific margin of the southwestern tip of South America (Barker 2001). The cusp-shaped junction between South America and the Antarctic Peninsula began to break up during or after the Eocene and the fragments were dispersed eastwards in response to an eastward flow of the Pacific mantle (Pearce et al. 2001). By the time of anomaly C10 it is clear that the tip of the Antarctic Peninsula was sufficiently far from southern South America, regardless of how the continental fragments of the Scotia Sea are arranged.

Barker and Burrell (1977) suggest that deep-water flow was inhibited in Drake Passage by continental slivers along the Shackleton Fracture Zone that overlapped each other until about 23.5 Ma. More recent studies show, in contrast, that the Shackleton Fracture Zone is a rather recent feature that came into existence well after the Middle Miocene (Livermore et al. 2004). True oceanic crust is approximately 2,500 m below sea level or deeper soon after formation (Parsons and Sclater 1977). We propose that probably by the time, or shortly after that South Tasman Rise was well away from East Antarctica (32 Ma), there was probably also a deep seaway in Drake Passage. Supporting evidence for this assumption comes from the age of the oldest oceanic chron C10 (28.7 Ma) in the Scotia Sea and from the fact that some of the early oceanic crust in the area was lost by subduction below the South Scotia Ridge (Aldaya and Maldonado 1996; Lodolo et al. 1997).

Lawver and Gahagan (1998, 2003) alternatively argued for an Early Oligocene age for the opening of a middle to deep-water passage through Powell Basin around the northern tip of the Antarctic Peninsula and

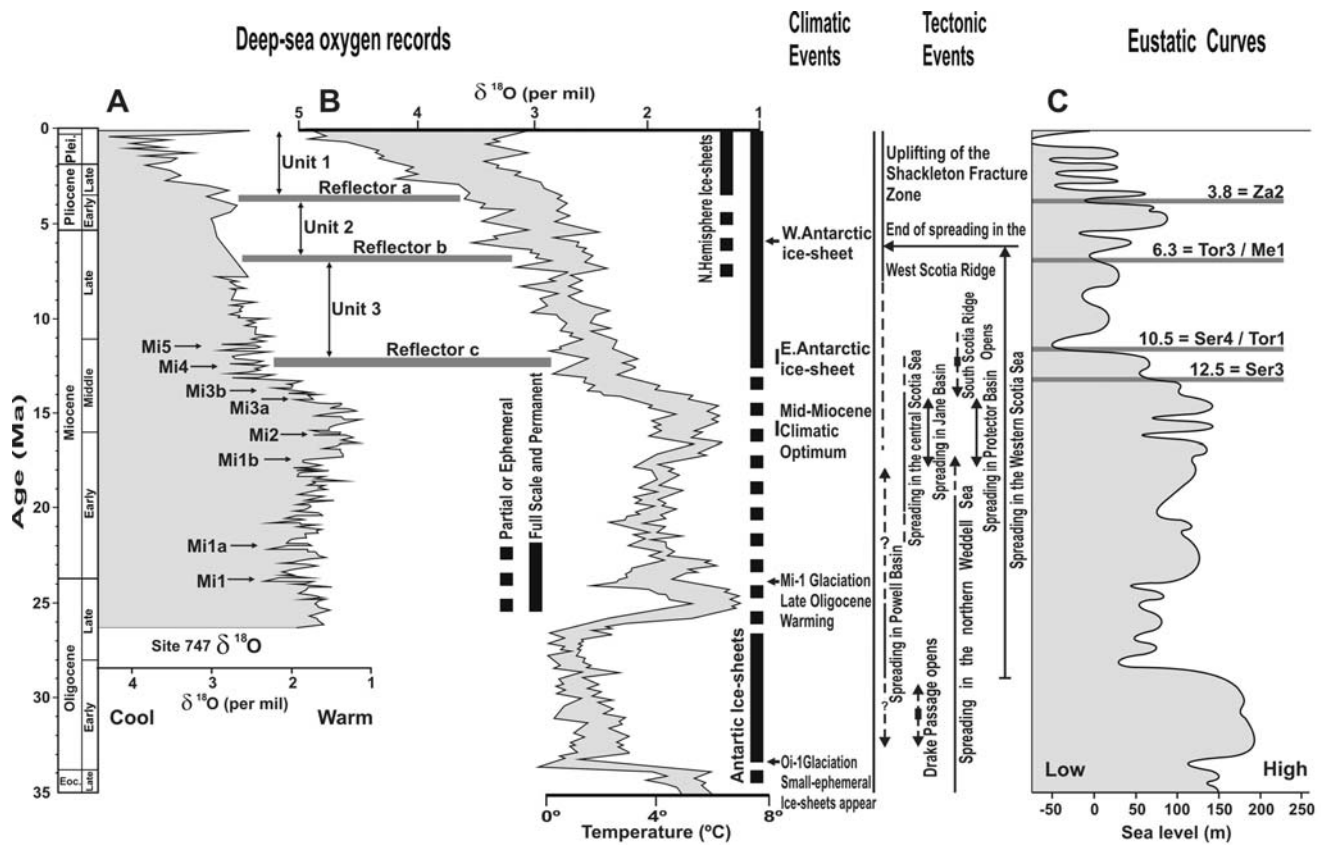


Fig. 16 Deep-sea $\delta^{18}\text{O}$ records, key climatic and tectonic events and eustatic curves. **A:** ODP site 747 $\delta^{18}\text{O}$ record from Wright and Miller (1992). **B:** Global deep-sea $\delta^{18}\text{O}$ record based on data compiled from DSDP and ODP sites by Zachos et al. (2001). Key climatic events and the development of Antarctic ice-sheets are shown by vertical bars that provide a rough qualitative

indication of ice volume (Zachos et al. 2001). The time span of key tectonic events in the study area is represented by vertical bars. **C:** Eustatic curves (curve of Haq et al. 1987, recalibrated by Hardenbol et al. 1998). The stratigraphic location of reflectors and seismic units identified in this study is also shown in the deep-sea oxygen record

west of the South Orkney Islands block, with the basin actively opening in a generally east–west direction from 34 Ma to 30 Ma. This interpretation, however, contradicts not only the ages of all the other models, but also the paleogeography in which the northern boundary of Powell Basin remained blocked by the South Scotia Ridge (King et al. 1997; Rodríguez-Fernández et al. 1997; Eagles and Livermore 2002).

A reconstruction of the western Scotia Sea by Maldonado et al. (2003) at chron C6A (21.3 Ma) shows that continued separation of the northern tip of the Antarctic Peninsula enabled the continental fragments to clear South America and thereby allowed the development of a strong ACC in the Scotia Sea (Fig. 16). The correlation of seismic units and reflectors between Powell Basin and Jane Basin shows a reflector that seals the spreading centre of Powell Basin and can be traced to the base of the depositional units atop the oldest oceanic crust of Jane Basin (Maldonado et al. 1998). This correlation indicates that

the deposits begin to develop in Jane Basin shortly after spreading ended in Powell Basin, although a stratigraphic hiatus may exist between these two events (Figs. 15, 16). The magnetic anomalies of Jane Basin and Protector Basin indicate that spreading in these two basins was almost coeval (Fig. 15). The end of subduction and spreading in the northern Weddell Sea also occurred at the same time as development of Jane Basin. These tectonic events allowed the connection of the Weddell Sea and Scotia Sea through gaps in the South Scotia Ridge (Fig. 16).

The depositional units and major reflectors

The earliest depositional units were primarily influenced by the tectonic evolution of the different basins and the opening and closing of gateways. Once the basins were fully established, however, the strongest control over abyssal plain deposits was the development of bottom current flows (Maldonado et al. 2003,

2005). The majority of the units identified beneath the abyssal plains of the northern Weddell Sea and Scotia Sea, with the exception of the older deposits, are high-energy seismic facies indicative of significant bottom current activity (Fig. 14). These deposits exhibit, in addition, seismic characteristics that suggest an evolution in the bottom current flows, sediment supply and water mass distribution. Unit WD4 (Early to Middle Miocene) in the northern Weddell Sea shows the development of giant elongated mounded drifts close to Jane Bank, together with a variety of contourite drift deposits that resulted from the northeastward flow of bottom currents (Maldonado et al. 2005, 2006). The older deposits of the Scotia Sea, units Sh5 and S5 (Early Miocene) recorded strong bottom current flows and high sediment supply. During these earlier stages, the bottom part of the ACC flow entering into the Scotia Sea was probably forced into a clockwise gyre because of the bottom topography, and developed important southward prograding sediment drifts (Maldonado et al. 2003).

The major regional unconformity represented by Reflector c (tentative age 12.1–12.6 Ma) seems coeval with a major Miocene glaciation (Mi4), a lowering of sea level (Ser3) and with the initiation of the permanent eastern Antarctic ice-sheet (Fig. 16). This reflector suggests a major event in the dynamics of bottom water circulation, which would represent the connection between the Scotia Sea and the Weddell Sea across the South Scotia Ridge). Unit 3 (Middle to Late Miocene) above Reflector c in the northern Weddell Sea recorded a reorganization of bottom flows, probably due to a changing configuration of gateways that resulted from the end of both spreading in Jane Basin and subduction of the northern Weddell Sea below Jane Bank. It also coincides with a major lowering of the global temperature (Fig. 16). The initial incursions of the WSBW into the Scotia Sea are also observed in the deposits of Unit 3, which forced a northward progradational pattern in the central Scotia Sea, similar to the overlying deposits. This evolution in the deposits was controlled by the opening of gaps in the South Scotia Ridge and the connection of the Weddell Sea and Scotia Sea through Jane Basin (Figs. 14–16).

Reflector b is also a regional unconformity (Figs. 14–16). The tentative age of this reflector (6.8 Ma), coincides with a major regression (Tor3/Me1) and is located in the vicinity of the initiation of ephemeral Northern Hemisphere ice sheet, coincident with a global temperature drop (Fig. 16). Unit 2 (Late Miocene to Early Pliocene) in the northern Weddell Sea show an increase of high-energy, sheeted deposits that we believe reflect a higher production of WSBW

and intensified bottom currents as a result of the expansion of the west Antarctic ice sheets (Fig. 16).

Reflector a recorded a major regional unconformity tentatively dated near the Early to Late Pliocene boundary (Figs. 14–16). This reflector coincides with the initiation of the permanent northern Hemisphere ice-sheet and a major sea level drop (Za2). The deposits of Unit 1 (Late Pliocene to Quaternary) are characterized in the Weddell Sea and Scotia Sea by the extensive development of chaotic, high-energy sheeted facies, in addition to a variety of contourite deposits, which suggest development of intensified deep-water production. Units 1 and 2 additionally show a distinct cyclic pattern of deposition, more continuous wavy deposits and the development of internal unconformities, all of which attest to increased bottom current energy.

Climate, tectonics and paleoceanographic evolution

The change in the Cenozoic climate from relatively warm and certainly ice free during the Paleocene to massive ice-sheets in both the southern and northern hemispheres in the Pliocene has been ascribed to a number of causes (Fig. 16). The Earth's climate certainly experienced a major change near the Eocene–Oligocene boundary, but whether the change can be explained strictly as a result of the opening of southern latitude oceanic seaways, or attributed to changes in atmospheric CO₂ concentrations, or is in fact the result of multiple causes, remains a subject of debate (Zachos et al. 2001; Lawver and Gahagan 2003; DeConto and Pollard 2003; Livermore et al. 2004).

The main source of Antarctic Bottom Water is considered to be located in the Weddell Sea, where deep circulation is controlled by the clockwise flow of the Weddell Gyre (Nowlin and Klinck 1986; Foldvik and Gammelsrød 1988; Naveira-Garabato et al. 2002). The circumpolar eastward flow of the ACC is another important deep current system in the Southern Ocean that interacts with the sea-floor in many places. A circumpolar flow could have initiated before sea-floor spreading commenced at the Drake Passage, however, since shallow gateways may existed during the process of rifting of South America and the Antarctic Peninsula. Considering the timing we propose for a deep seaway in Drake Passage, the onset of the ACC date back close to the development of the Oi-1 glaciation, which represents the expansion of the East Antarctic ice-sheet (Fig. 16). The global causes for the climatic change near the Eocene–Oligocene boundary, including changes in atmospheric CO₂ concentrations, could

not be those behind the opening of the southern gateways, but certainly the development of the Antarctic ice-sheet was favoured by the thermal isolation of the continent.

Plate tectonic reconstruction shows that none of the central and eastern Scotia Sea existed before 20.7 Ma, at which time the Shackleton Fracture Zone was under extension and probably had a subdued relief (Maldonado et al. 2003; Livermore et al. 2004). The ridges and basins that were active during the early stages in the evolution of the Scotia Sea controlled the development of the ACC and the circumpolar deep water flows (Barker 2001; Maldonado et al. 2003, 2005). Lawver and Gahagan (1998, 2003) furthermore suggest that collision of the Australia–New Guinea block with Southeast Asia around 15 Ma was an important tectonic event with respect to ocean circulation. Among other global causes, the blocking of substantial equatorial transport of water from the Pacific into the Indian Ocean enhanced the driving forces of the ACC and led to the late-Middle Miocene expansion of the East Antarctic ice-sheet.

Dingle and Lavelle (1998) found the earliest observed glacial event on the Antarctic Peninsula to be 29.8 ± 0.6 Ma. The Oligocene glaciers of Antarctica were isolated and a West Antarctic ice-sheet that advanced onto the continental shelf did not develop until Late Miocene (Anderson and Shipp 2001), which seems to be recorded by Reflector b and may also be coincident with the end of spreading at the West Scotia Ridge (Fig. 16). It is proposed that a major factor for the present global ocean circulation and the Late Pliocene formation of the West Antarctic and Northern Hemisphere ice-sheets was the closure of the Isthmus of Panama, between 3.7 Ma and 3.0 Ma (Keigwin 1982; Lawver and Gahagan 2003) or about 3.5 Ma (Coates et al. 1992). Closure of the Panamanian seaway increased thermohaline circulation and moisture supply to high latitudes where the additional heat may have initially inhibited ice growth (Driscoll and Haug 1998). The coincidence between the ages calculated for Reflector a and the timing of closure of the Panamanian seaway is remarkable (Fig. 16). About this time, however, spreading ended at the Phoenix Ridge (Livermore et al. 2000), which may also had a more significant influence on the paleoceanography of the area by modifying the deep water flows through significant changes in the sea-floor topography of Drake Passage.

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