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# Western Scotia Sea margins: Improved constraints on the opening of the Drake Passage

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[1] We present a revised tectonic interpretation (from ∼28 Ma to 3.2 Ma) of the western sector of the Scotia Sea, incorporating new multichannel seismic reflection profiles and magnetic anomaly identifications for the continental margin off the Tierra del Fuego Island, and available complementary data for the conjugate margin of the northwestern flank of the South Scotia Ridge. Seismic profiles show a remarkable diversity of the pair of conjugate passive margins of the western Scotia Sea in both their morphology and structural framework. The Tierra del Fuego continental margin can be related to a classic rifted passive margin, while the southwestern margin of the Scotia Sea is characterized by steep slopes mostly generated by subvertical faults that abruptly separate the continental crust of the South Scotia Ridge from the oceanic crust of the western Scotia Sea. This structural difference was caused by intense strike-slip tectonism, mostly concentrated along the modern South Scotia Ridge since the early development of the western Scotia Sea. We find evidence for a previously unrecognized magnetic anomaly 10 (∼28 Ma) at the foot of the Tierra del Fuego continental margin; the same anomaly is present at the conjugate northern flank of the South Scotia Ridge. The timing of events leading to the earliest development of the western Scotia Sea, which determined the opening of the Drake Passage is important because this gateway opening had a profound effect on global circulation and climate. The thickness and the distribution of the sedimentary cover overall in the abyssal plain off the two western Scotia Sea margins is different. This is due to the different regimes of the bottom-current flows which affected the western Scotia Sea, both in the past and in the present time.

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## 1. Introduction

[2] The Early Oligocene opening of the Drake Passage gateway between South America and the Antarctic Peninsula, forming the Scotia oceanic plate, represented the last phase of the fragmentation of Gondwana. The final disruption of the barrier between these two landmasses is thought to have been an important event in the history of global oceanic and atmospheric circulation because, for the first time, it allowed the transfer of water masses between the Pacific and Atlantic oceans at mid to high southerly latitudes. This event had profound consequences on global palaeoclimate by generating the Antarctic Circumpolar Current (ACC), a continuous water current both at the surface and at deep levels, whose development has been implicated in the formation of permanent ice sheets on Antarctica [*Kennett*, 1977; *Barker and Burrell*, 1977; *Zachos et al.*, 2001; *Exon et al.*, 2002; *Barker and Thomas*, 2004].

[3] Despite the considerable amount of geophysical data collected in the last years in the Scotia Sea region [*Barker et al.*, 1991; *Maldonado et al.*, 1993; *Livermore et al.*, 1994; *Cunningham et al.*, 1995; *Galindo-Zaldívar et al.*, 1996; *Klepeis and Lawver*, 1996; *Acosta and Uchupi*, 1996; *Coren et al.*, 1997; *Lodolo et al.*, 1997; *Maldonado et al.*, 2000; *Geletti et al.*, 2005], no complementary magnetic and seismic profiles were available to allow a comparative analysis of the conjugate passive margins of the western sector of the Scotia plate, represented by the Tierra del Fuego continental margin to the north, and by the northern flank of the South Scotia Ridge to the south. These data are crucial for reconstructing, through time, the relative positions of the pair of continental margins, and for constraining the events that occurred immediately after break-up and the opening of the Drake Passage.

[4] In this paper, we present results derived from the analysis of the first multichannel seismic and magnetic profiles collected off the Tierra del Fuego continental margin, along with complementary seismic and magnetic profiles across the conjugate northern flank of the South Scotia Ridge (Figure 1). These data are used, together with a

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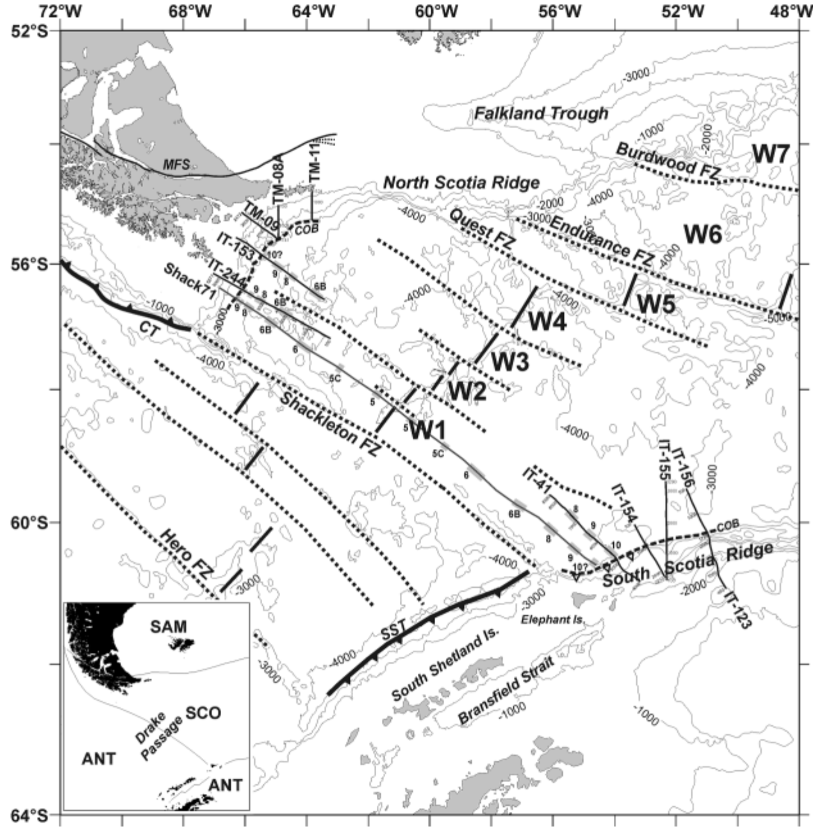

**Figure 1.** General map of the western Scotia Sea and surrounding regions, with the position of the seismic and magnetic profiles presented in this study. The position of the magnetic profile Shack71 is taken from *Barker and Burrell* [1977]. Bathymetric contours are from satellite-derived data [*Sandwell and Smith*, 1997]. Spreading corridors from W1 to W7 have been taken from *Eagles et al.* [2005]. Numbers along the westernmost spreading corridor W1 of the western Scotia Sea, and on the northernmost flank of spreading corridor W2, are obtained from the identified magnetic anomalies along the tracks presented in this study. Box in the bottom-left corner shows a simplified plate tectonic sketch for the region. SAM, South America plate; ANT, Antarctic plate; SCO, Scotia plate; CT, Chile Trench; SST, South Shetland Trench; MFS, Magallanes-Fagnano transform system [*Lodolo et al.*, 2003]; COB, Continent-ocean boundary.

reappraisal of available magnetic data in the region, to: (1) compare the morphological and structural features of the two western Scotia Sea margins; (2) obtain new constraints on the oldest marine magnetic anomalies adjacent to both margins; (3) propose a regional tectonic reconstruction of this sector of the Scotia Sea; and (4) identify the depositional setting related to the activity of the main water bottom currents across the Scotia Sea region.

## 2. Regional Tectonic Setting and Palaeo-Oceanographic Circulation

[5] The tectonic development of the oceanic Scotia plate is the result of the fragmentation and subsequent dispersion of the former Mesozoic continental link connecting southernmost South America and the Antarctic Peninsula (see *Barker et al.* [1991] and *Barker* [2001] for a general review of the tectonic development of the Scotia plate). The blocks that were once part of the continental link are now distributed along the Scotia plate periphery, and their original position has been partially reconstructed on the basis of petrologic affinities, the palaeomagnetic signature, fitting geometries of margins, and magnetic anomaly identifications. The northern and southern boundaries of the western sector of the Scotia plate are defined by the North Scotia Ridge and the South Scotia Ridge, respectively, which morphologically consist of a series of islands and submarine continental crust fragments with bathymetric relief of up to 1000 m. The western end of the North Scotia Ridge corresponds to the continental margin of the Tierra del Fuego Island. The left-lateral Shackleton Fracture Zone is a N-W-trending linear ridge [*Maldonado et al.*, 2000; *Geletti et al.*, 2005] that became the western boundary of the Scotia plate after cessation of seafloor spreading at the Antarctic-Phoenix ridge (~4 Ma [*Barker*, 1982; *Barker and Dalziel*, 1983], or 3.2 Ma [*Livermore et al.*, 2000]), located immediately west of the fracture zone. The active N-S-trending East Scotia Ridge represents the eastern tectonic boundary of the Scotia plate. Present-day relative motions, determined mainly from earthquake data [*Forsyth*, 1975; *Pelayo and Wiens*, 1989; *Giner-Robles et al.*, 2003], and from global plate circuits [*DeMets et al.*, 1990, 1994;

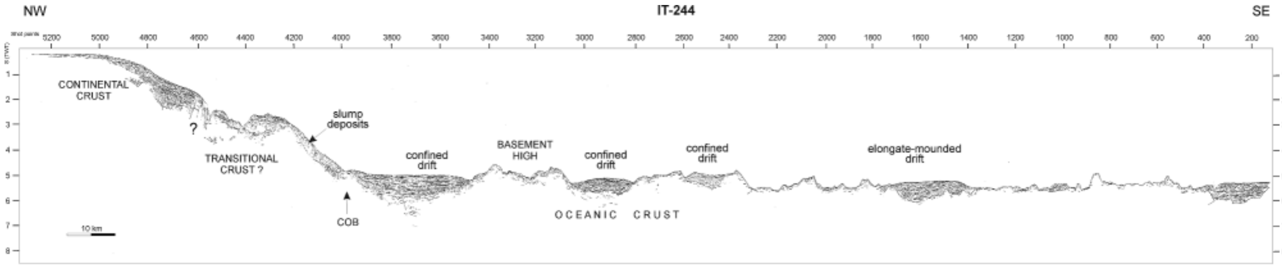

**Figure 2.** Interpreted line drawing of the multichannel seismic profile IT-244 across the Tierra del Fuego margin in the western Scotia Sea. Location of the corresponding profile is shown in Figure 1. COB, Continent-ocean boundary.

*Thomas et al.*, 2003], show that in the Scotia Sea region the Antarctic plate is slowly moving (1.7 to 2.0 cm/yr) easterly relative to the South America plate. The relative motion of these two major plates is presently partitioned along the left-lateral, strike-slip northern and southern boundaries of the Scotia plate [*Pelayo and Wiens*, 1989].

[6] A major consequence for the global climate of the Scotia plate formation was the opening of the Drake Passage oceanic gateway and the onset of the ACC. The ACC is considered to be largely or entirely wind-driven. Despite its origin, there is evidence of the ACC interaction with the seafloor in the Scotia Sea [*Barker and Burrell*, 1977; *Pudsey and Howe*, 2002; *Maldonado et al.*, 2003]. The prominent relief of the Shackleton Fracture Zone would have prevented a deep-water pathway until about 22 Ma [*Barker and Burrell*, 1977]. A possible further delay in the deep ACC development to the east would also have been caused by the presence of continental fragments and subduction-related volcanoes around the Scotia Sea [*Barker and Burrell*, 1982]. Recently, *Livermore et al.* [2004] suggested that during the Miocene, the ACC deep flow in the Drake Passage was much less constricted than today because the morphology of the Shackleton Fracture Zone was more subdued, and it only uplifted by transpression between the Scotia and the Phoenix plates at about 8 Ma [*Geletti et al.*, 2005]. The Weddell Sea Deep Water is the other important wind-driven water circulation present in the southern Scotia Sea. It originates as a consequence of the production of dense, cold and salty bottom waters in the southern Weddell Sea [*Foldvik and Gammelsrod*, 1988]. The Weddell Sea Deep Water escapes from the northwestern Weddell Sea through gaps in the South Scotia Ridge, and flows into the Scotia Sea with a dominant westward component [*Nowlin and Zenk*, 1988; *Camerlenghi et al.*, 1997; *Pudsey*, 2002].

## 3. Seismic and Magnetic Data

[7] Two sets of multichannel seismic reflection profiles crossing the Tierra del Fuego continental margin, and its conjugate to the south, across the northern flank of the South Scotia Ridge, are presented here (Figures 2 to 9). Seismic data TM-08A, TM-09, TM-11, and IT-244 represent the first available information documenting the structure and sedimentary setting off the Tierra del Fuego Island, spanning an area of about 400 km along the continental shelf, slope, and rise. Seismic profiles IT-41, IT-154, IT-155, IT-156, and IT-123 across the southern margin of the western Scotia Sea complement and expand the seismic coverage along the northern flank of the South Scotia Ridge, as published by *Galindo-Zaldívar et al.* [1996], *Acosta and Uchupi* [1996], and *Coren et al.* [1997]. The presented data (see Figure 1 for location) were acquired during several geophysical Antarctic campaigns performed by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) in the frame of the Italian Programma Nazionale di Ricerche in Antartide (PNRA). The main acquisition parameters of the seismic lines are summarized in Table 1.

[8] Processing sequences applied on the seismic data were slightly different among profiles, according to their specific acquisition parameters. Nevertheless, the adopted processing flow may be summarized as follows: (1) spherical divergence and absorption compensation, (2) trace editing and despiking, (3) normal-move out and common-depth-point stacks, using stacking velocities derived from semblance-velocity-analyses, and constant-velocity-stacks (generally every 5–6 km), (4) deconvolution after stack, (5) three adjacent trace mixing, and time-variant filtering, and (6) Kirchhoff time migration.

[9] The magnetic profiles presented in this paper (see Figure 10), collected with a proton magnetometer during different Antarctic campaigns, comprise available data (IT-41 [*Lodolo et al.*, 1997]; IT-153 and IT-244 [*Geletti et al.*, 2005]), and an old magnetic profile (Shack71) originally presented by *Barker and Burrell* [1977], and more recently presented by *Eagles et al.* [2005]. This profile shows the continuous sequence of the magnetic anomalies along the spreading corridor W1 (see Figure 1) of *Eagles et al.* [2005], and is useful to correlate them with the oldest anomalies identified at the base of the two conjugate margins. The obtained anomaly profiles were produced by subtracting the Definitive Geomagnetic Reference Field (DGRF) from the recorded total field measurements for the period of the investigations, according to the method presented by *Langel* [1995]. The identification of the chrons in the magnetic profile is based on the magnetic timescale proposed by *Cande and Kent* [1995]. The parameters adopted for the model are: dip: −68°; declination: 10°; body thickness: 1.0 km; depth of top of the ridge: 2.5 km, according to a detailed bathymetric mapping of the westernmost Scotia ridge segment [*Maldonado et al.*, 2000]; susceptibilities: 0.03 (at 6.0 Ma), 0.066 (at 8.0 Ma), and 0.02 (at 29 Ma); symmetric spreading rates along 300°, at half rates of 2.5 cm/yr from 16 to 29.0 Ma; 2.0 cm/yr from

**Table 1.** Technical Parameters of the Multichannel Seismic Lines Presented in This Paper

| | R/V *OGS-Explora* (1989/1990) | R/V *OGS-Explora* (1991/1992) | R/V *OGS-Explora* (1995) | R/V *OGS-Explora* (1997) | A.R.A. *Puerto Deseado* (1999) |
|---|---|---|---|---|---|
| Seismic lines | IT-41 | IT-123 | IT-154, IT-155, IT-156 | IT-244 | TM-08A, TM-09, TM-11 |
| Source | Two arrays of 15 air-guns each (45.16 L) | Two arrays of 20 air-guns each (71.96 L) | 36 BOLT air-guns (80.4 L) | 36 BOLT air-guns (80.0 L) | 2 G.I. guns (7.0 L) |
| Marine streamer | Analogue 3000 m 120 channels | Analogue 4650 m 180 channels | Analogue 3000 m 120 channels | Analogue 3000 m 120 channels | Solid-state 1200 m 96 channels |
| Shot interval | 50 m | 50 m | 50 m | 50 m | 37.5 m |
| Sampling rate | 4 ms | 4 ms | 4 ms | 4 ms | 2 ms |
| Recording length | 12 s | 14 s | 14 s | 14 s | 10 s |

10.0 to 16.0 Ma; 1.6 cm/yr from 6.4 to 10.0 Ma. The assumption of variable susceptibilities and spreading rates in the model gives the best fitting with the observed anomalies. The full amplitude corresponding to these anomalies generally does not exceed 400 nT.

## 4. Structural and Stratigraphic Analysis

### 4.1. Tierra del Fuego Continental Margin

[10] Among the seismic lines analyzed in this sector (from west to east: IT-244, TM-09, TM-08A, and TM-11), only profile IT-244 (Figure 2) crosses the entire continental margin from the continental shelf to the oceanic domain. The significant distance between these profiles, and the high variability of the morphological and structural features found on seismic records, do not always allow a coherent correlation between them. For these reasons, we describe the structure and the stratigraphic setting of the margin line by line.

[11] In the northernmost part of line IT-244, between shotpoints (SPs) 5277-4800 where the water depth is less than 75 m, strong seafloor multiples prevent a clear identification of both the structural and morphological features. The continental slope gently deepens to SP 4000, where the oceanic domain starts. In the slope area, the acoustic basement is not always easily recognizable and only occasionally is marked by continuous reflectors. Between SP 4850 and SP 4500 approximately at depths of 2.2–2.4 s TWT (two-way travel time), high-amplitude reflectors appear to be widely cut by a series of landward dipping faults. From SP 4500 to SP 4000, the seismic signal is difficult to discern, possibly owing to the presence of a highly faulted crust that we interpret as a transitional-type crust. Two V-shaped incisions up to 150 m in relief cut the sedimentary sequence at SPs 4450 and 4400. From SP 3900 southward, the profile changes to an acoustic character typical of the oceanic crust. It presents a very rough topography, which is particularly impermeable to the penetration of the seismic signal. From a structural and morphological point of view, this margin appears as a rifted passive margin [*White and McKenzie*, 1989; *Buck*, 1991; *Lister*, 1991; *Mutter*, 1993], where the faulted and stretched basement is about 40 km wide. The continental slope sedimentary sequences, about 1.0 s TWT thick, are dominated by aggrading sequences, with reflectors gently dipping toward the rise area. The lower stratigraphic levels are often cut by subvertical faults, propagating upward from the tectonized basement. Between SPs 4400–4200, low relief upward-convex bodies have been detected. The internal configurations of these bodies are characterized by chaotic facies, which we interpret as representing mass flow deposits. From SP 3950 to SP 3500 a well layered, about 800 ms TWT thick sequence, has been deposited. It is constituted of two main units. The lower unit shows medium to high amplitude, more or less continuous, subhorizontal reflectors, deposited above the acoustic basement and onlapping it. A high-amplitude reflector marks the top of this unit and the initial growth of a mound-shaped deposit, separated from the continental slope and from the adjacent basement high by a moated area. This feature has been interpreted as a bottom-current-related deposit; because of its topographic confinement, it can be interpreted as a confined drift [*Stow et al.*, 2002]. South of the basement high, other confined basins up to 500 ms TWT thick were deposited. The lowermost stratigraphic levels, onlapping the acoustic basement, are characterized by subhorizontal, subparallel reflectors. The upper, 200–300 ms TWT thick part of the sedimentary sequence is characterized by the progressive growth of an asymmetric sediment drift, separated from the adjacent basement highs by moated areas. Between SP 1700 and SP 1400, a well-layered sequence about 800 ms TWT thick has been deposited. The seismic stratigraphy is made up of the vertical and lateral stacking of several seismic units bounded by unconformities. Mounded, almost symmetric bodies, where the internal character reveal progressive upward growth, are identifiable. They are overlain by continuous subhorizontal and subparallel reflectors, downlapping toward the moated area located at SP 1400 and constituting a so-called elongate-mounded drift [*Faugeres et al.*, 1999].

[12] Seismic line TM-09 (Figure 3), which runs parallel to the previously described profile IT-244, crosses the Tierra del Fuego continental shelf and slope, but does not reach the oceanic domain. The northern half of the seismic section shows very rough topography. Toward the south, incisions with V-shaped cross sections, two of them more than 1 km deep (centered at SPs 1770, 1350, and 1200) deeply cut the entire sedimentary sequence and the basement. The basement top is clearly identifiable by a high-amplitude reflector, widely disrupted by subvertical faults that also affect the upper sedimentary sequence. In the northern part of the profile, the basement lies at an almost constant depth, between 600 ms and 1.0 s TWT below the seafloor. Then, from SP 700, it abruptly deepens toward the south. The penetration of the seismic signal does not always allow a reliable identification of the basement top. Mounded asymmetric features developed against the flanks of the basement highs (SP 1100). These contain low-amplitude reflectors

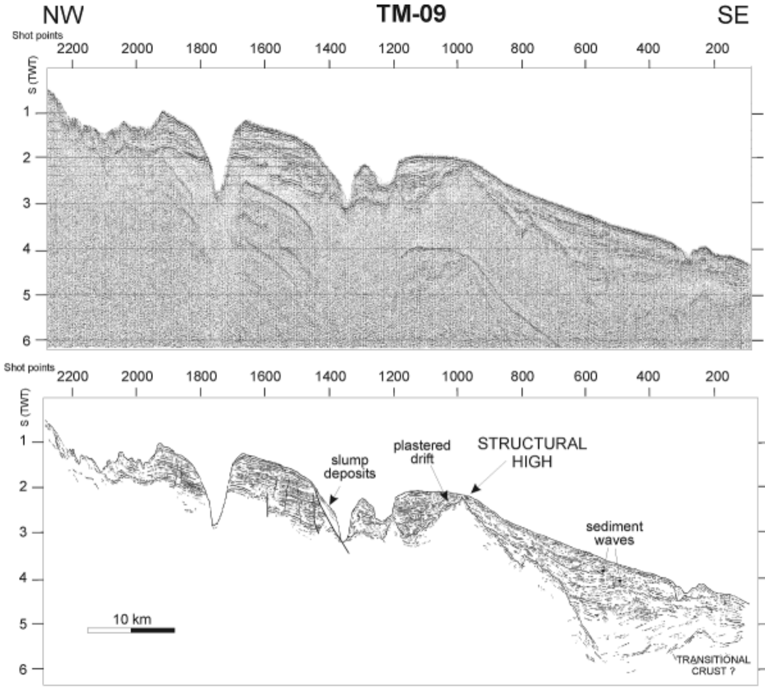

**Figure 3.** (top) Multichannel seismic profile TM-09 and (bottom) interpreted line drawing across the Tierra del Fuego margin in the western Scotia Sea. Location of the corresponding profile is shown in Figure 1.

and are interpreted as plastered sediment drifts [*Faugeres et al.*, 1999]. Two main seismic sequences, both consisting of southeast-dipping reflectors, have been identified. The lower unit is represented by high-amplitude reflectors, displaying low lateral continuity and frequent displacements by subvertical faults that propagate from the lower tectonized basement. The upper sequence is characterized by lower amplitude, more continuous reflectors that are often truncated at the seafloor. In the southernmost part of the profile, wavy reflectors represent sediment waves deposition.

[13] Seismic line TM-08A (Figure 4) was acquired in a N-S direction, and crosses the continental slope down to water depths of about 3400 m. A prominent structural high dominates the central part of the seismic line (SPs 800–1100). It consists of two main asymmetric and tilted blocks, up to 1.0 s TWT in relief (SP 1050), internally cut by subvertical, southward dipping faults. The basement appears also highly faulted from SP 1200 to the end of the line toward the south, and interpreted to be a transitional-type crust. The sedimentary sequence reveals a variable thickness along all the section, ranging from a minimum of about 100 ms TWT on the structural highs (SPs 800–900) and in the northernmost sector, where the basement is very steep, to a maximum of 1.0–1.5 s TWT within the basin located between SP 500 and SP 700. This area is characterized by a highly irregular seafloor topography. Above the basement high, a ~400 ms TWT thick, well-stratified sequence has been deposited. This feature represents a small-scale elongate-mounded drift [*Faugeres et al.*, 1999]. On the southern part of the profile, the stratigraphic sequence consists of two main seismic units. The lower sequence, 1.0 s TWT thick, contains high-amplitude, discontinuous reflectors, displaying wavy to hummocky configurations, and locally representing sediment waves. This sequence is characterized by a progressive upslope crest migration. The upper sequence comprises more continuous, subparallel reflectors.

[14] Profile TM-11 (Figure 5) is the easternmost seismic profile analyzed along the Tierra del Fuego margin and crosses the continental shelf and slope. Most of the margin architecture in the shelf area is obscured by strong seafloor multiples. At SP 1200, a subvertical escarpment separates the continental domain from a deep basin, leading to the deposition of an up to 2.2 s TWT thick sedimentary sequence. This discontinuity represents a major fault trace. To the south, the basement forms a prominent 25-km-wide structural high, with an internally chaotic to semitransparent seismic character, in which local discontinuous reflections are identifiable. Aggrading sequences with reflectors truncated at the seafloor (SP 1200), are seen in correspondence to the steep slope escarpment. South of the escarpment, within the about 14-km-wide basin, the lowermost stratigraphic levels appear strongly deformed by tectonic displacements propagating upward from the basement. The top of these deformed units is marked by a high-amplitude reflector, above which mounded, asymmetric bodies, interpreted as plastered sediment drifts, developed (SPs 1000–800). In the upper 800 ms TWT, the stratigraphic sequence is characterized by widespread erosional unconformities. The emplacement of the structural high south of this basin has strongly affected the sedimentary setting, as demonstrated on the southern flank of the basin by the occurrence

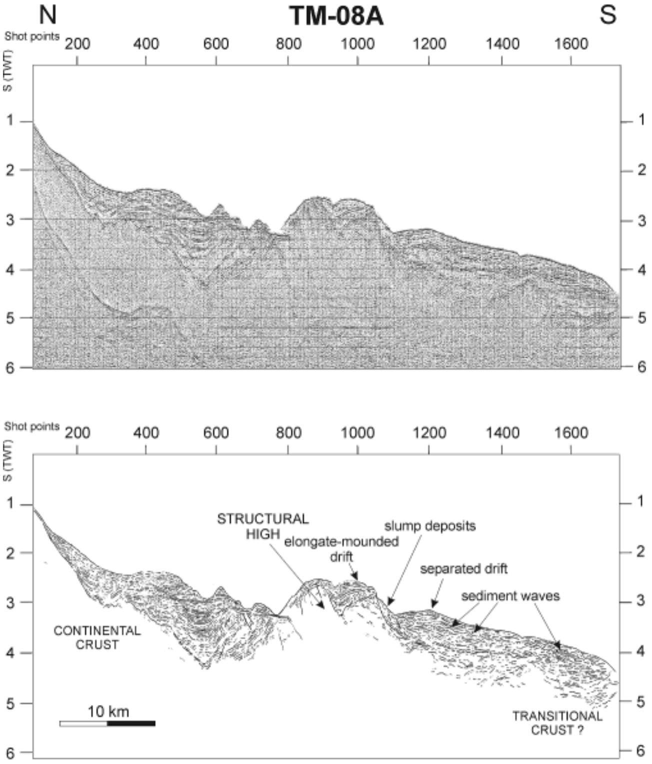

**Figure 4.** (top) Multichannel seismic profile TM-08A and (bottom) interpreted line drawing across the Tierra del Fuego margin in the western Scotia Sea. Location of the corresponding profile is shown in Figure 1.

of low-amplitude reflectors dipping conformably toward the north. Evidence of bottom-current-related deposits come also from the southernmost part of the seismic line (SP 250), where a ~3800-m-wide mounded sediment body interpreted as a separated sediment drift has been deposited.

### 4.2. Northwestern Margin of the South Scotia Ridge

[15] Along the northern flank of the South Scotia Ridge, five seismic profiles have been analyzed in this study (from west to the east: IT-41, IT-154, IT-155, IT-156, and IT-123). The main structure of this segment of the western Scotia Sea margin was already well known from multichannel seismic profiles published by *Galindo-Zaldívar et al.* [1996], *Acosta and Uchupi* [1996], and *Coren et al.* [1997]. The South Scotia Ridge is a complex structure composed of two prominent continental elevated blocks separated by steep scarps and troughs along which the boundary between the Scotia and Antarctic plates runs. The deepest part of those depressions is the Hesperides Deep [*Acosta and Uchupi*, 1996] which is V-shaped in profile and reaches over 5300 m in water depth. Here we provide a general description of the main structural and sedimentary features characterizing the northern flank of the South Scotia Ridge and the oceanic domain of the western Scotia Sea farther to the north.

[16] Figure 6 shows a reprocessed version of line IT-41, part of which has been already published by *Lodolo et al.* [1997]. The line crosses the slope of the northern continental block of the South Scotia Ridge and then extends about 170 km farther to the north. The continental slope is steep and may have been generated by a major subvertical fault. This fault connects the oceanic crust of the Scotia Sea with the continental domain of the South Scotia Ridge, as also suggested by *Galindo-Zaldívar et al.* [1996]. The top of the oceanic basement is characterized by a series of high-amplitude reflectors and shows an irregular topography, with a general landward dipping trend overall in the southernmost (at the base of the slope), and northernmost sectors. It is dissected by several tectonic displacements, which led to the formation of tilted, landward dipping blocks, with vertical displacements ranging from 0.5 s to more than 1.0 s TWT. At SP 6200, a crustal high is interpreted as representing a fracture zone. The sedimentary sequence shows thicknesses ranging from more than 2.0 s TWT close to the continental slope, progressively decreasing to about 1.0 s TWT toward the more distal areas. From SP 4800 to SP 5400, the sedimentary cover progressively thickens toward the continental slope, where it shows a distinct depositional architecture. At the base of the slope, the chaotic, semitransparent, wedge-shaped facies lying above a 20° landward dipping oceanic basement, has been interpreted as an assemblage of sediments accreted at the base of the continental slope and deformed within an accretionary prism [*Lodolo et al.*, 1997]. On the upper continental rise the seismic sequence shows high-amplitude, gently northwestward dipping reflectors, with a variable

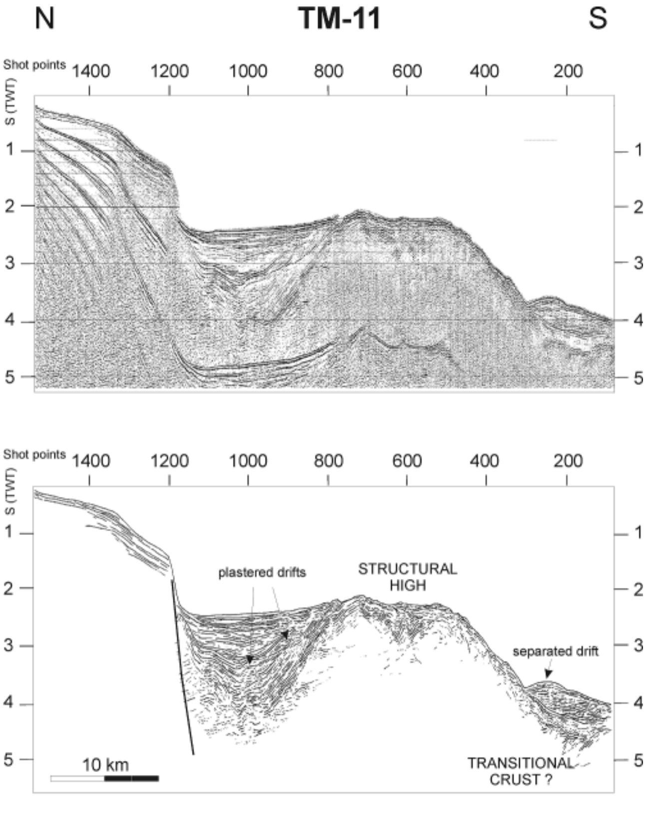

**Figure 5.** (top) Multichannel seismic profile TM-11 and (bottom) interpreted line drawing across the Tierra del Fuego margin in the western Scotia Sea. Location of the corresponding profile is shown in Figure 1.

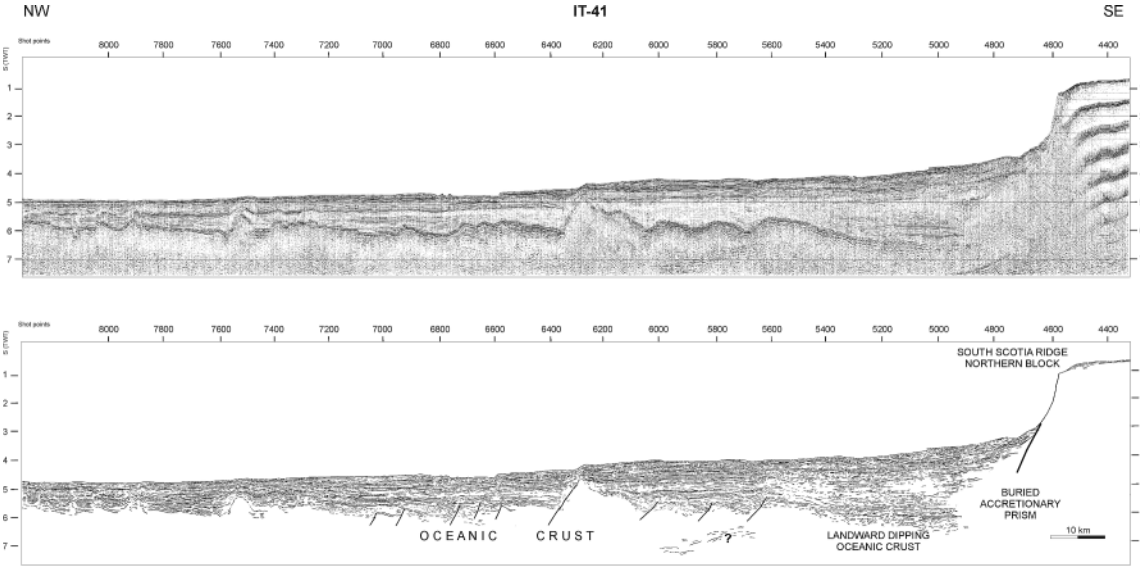

**Figure 6.** (top) Multichannel seismic profile IT-41 and (bottom) interpreted line drawing across the southern margin of the western Scotia Sea. Location of the corresponding profile is shown in Figure 1.

lateral continuity. Locally, hummocky facies have been identified at different levels of the stratigraphic sequence. Between SP 5650 and SP 6300 the sedimentary sequence appears very well layered and constituted by two main units. The lower sequence is represented by low-amplitude, almost continuous reflectors, whose configurations appear to mimic the rough topography of the basement. The upper 500 ms TWT thick sequence shows high-amplitude, continuous reflectors, displaying general subparallel configurations. On the lower rise the stratigraphic sequence is characterized by medium-to-high amplitude reflectors, showing slightly wavy geometries, that could represent inherited features because of their progressive upward reduction in relief.

[17] Seismic line IT-154 (Figure 7) runs almost parallel to the previously described profile IT-41, about 50 km to the east. It shows the complex architecture of the northern part of the South Scotia Ridge, represented by a southward dipping basement block, cut by minor fault scarps. This area is almost sediment-starved. The continental slope is very steep as observed on line IT-41. However, along this profile the transition from the continental to the oceanic domain is less abrupt and is represented by an intermediate zone (SPs 1000–400) of highly deformed and rotated blocks separated by mostly northward dipping extensional faults. A major, subvertical fault separates the continental block from this belt composed of transitional-type crust. At SP 600, an anomalous, mound-shaped structural high is interpreted as a sea mount. The basement, whose top is marked by a high-amplitude, discontinuous reflector, abruptly deepens toward the oceanic area. Along this profile, no evidence of a buried and deformed prism of sediments has been found, as seen on line IT-41. A thick (about 1.5 s TWT, SPs 900–600), almost symmetric sediment body, lies on the upper continental rise, and has a mounded external shape with an irregular surface topography. Within this body, a bottom simulating reflector (BSR) was detected at about 800 ms TWT below the seafloor. The almost symmetric shape of this mounded feature, internally constituted of continuous, subparallel reflectors and the occurrence of two moats along its flanks, suggests that it represents a detached drift, following *Stow et al.* [2002]. Farther to the north (SP 200), at a depth of about 5.4 to 5.0 s TWT, sediment waves formed.

[18] Seismic profile IT-155 (Figure 8) shows that the steep northern flank of the South Scotia Ridge is separated from the oceanic domain by an almost subvertical fault (SP 1300). As for the profile IT-154, there is little evidence of a transitional-type crust between the continental block and the oceanic crust. At the base of the slope/rise transition, the basement comprises asymmetric, tilted blocks bounded by north-verging faults. Farther toward the oceanic area, the basement is almost unaffected by tectonism. The sedimentary cover in the oceanic domain reaches a maximum thickness of about 2.0 s TWT. Between the base of the South Scotia Ridge northern flank and the SP 1900, discontinuous, high-amplitude reflectors dominate. Only in the uppermost levels, upward growing bedforms developed, as the mounded feature deposited at SP 1400. Its internal character and its position at the base of the slope appears to be very similar to that deposited in correspondence to the Wyville-Thomson Ridge (Hebrides slope) and interpreted as a separate sediment drift [*Faugeres et al.*, 1999]. From SP 1900 to SP 2200 the lowermost stratigraphic levels are characterized by subhorizontal configurations, onlapping the basement relief. Between SP 2000 and SP 2400 a mound-shaped feature is identifiable, with a thickness of about 800 ms TWT and a width of 12 km. Internally, it shows subparallel reflectors, which pinch out toward both the continental slope and the continental rise, where two moats are identifiable. It could be interpreted as a detached drift [*Faugeres et al.*, 1999].

[19] Seismic lines IT-156 and IT-123 (Figure 9), juxtaposed in a single profile here, show that the South Scotia Ridge in this part is formed by two distinct blocks separated by the narrow Hesperides Deep. This trough is flanked by

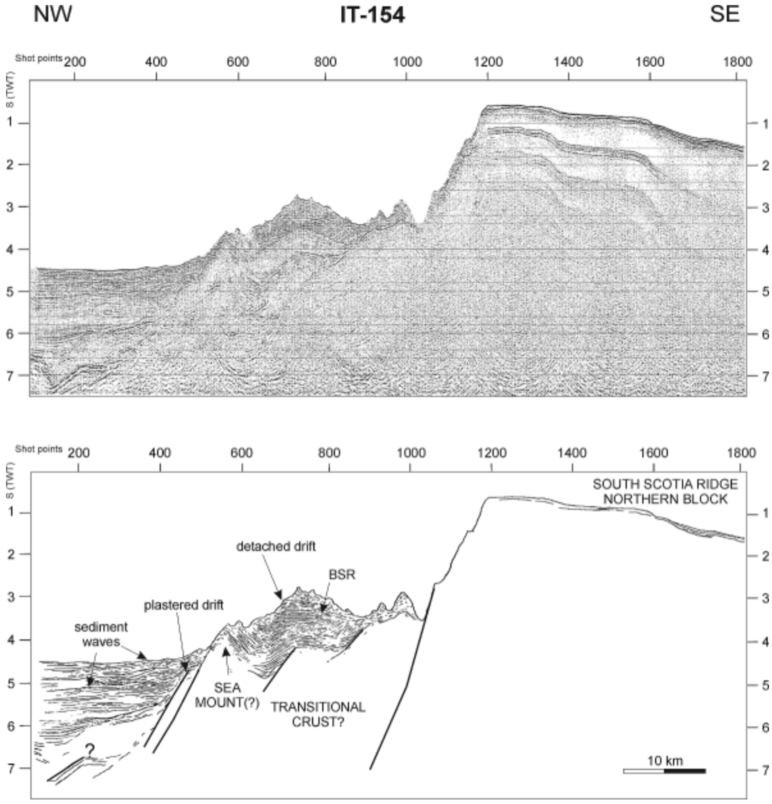

**Figure 7.** (top) Multichannel seismic profile IT-154 and (bottom) interpreted line drawing across the southern margin of the western Scotia Sea. Location of the corresponding profile is shown in Figure 1.

very steep, and quite symmetric slopes, possibly representing the traces of major faults. The thickness of the sedimentary sequence on these profiles is highly variable. In the Hesperides Deep, the sedimentary cover is about 1.0 s TWT thick, and is cut by a vertical fault that reaches the seafloor. The wide (Line IT-156, SP 1600–1200) depressed area on the seafloor separates the northern block from the basement high farther to the north, and represents a mainly erosional area as suggested by frequent reflector truncations. North of the basement high, at SP 800, the internal geometries of the stratigraphic sequence appear gently northward dipping, with the lowermost levels being more transparent and downlapping the basement. The wavy geometries identified in this area represent not only inherited features but also upward developing symmetric bedforms, interpreted as sediment waves.

## 5. Discussion

### 5.1. Morphological and Structural Contrasts Between the Western Scotia Sea Continental Margins

[20] The comparison between the pair of conjugate passive margins of the western Scotia Sea reveals major differences in their morphology, structure, and sedimentary setting. Seismic data here presented show that the Tierra del Fuego continental margin is typical of a classic rifted passive margin. All along the margin, the transition between the continental and the oceanic crust is gradual and generally occurs through a ∼30- to 40-km-wide zone in which the basement displays internal characters of a transitional-type crust. The occurrence of subvertical faults, widely affecting the continental slope and showing displacements of about 1.0 s TWT, reflect the dominance of an extensional tectonic regime. Broadly E-W-trending, very deep, and sometimes narrow erosional sea valleys and canyons that cut the entire sedimentary sequence and, in some cases, the basement, also characterize the continental slope. These distinctive features found on the Tierra del Fuego continental margin may represent the seafloor expression of tectonic lineaments identified onshore further north on Tierra del Fuego Island [*Caminos et al.*, 1981; *Dalziel and Brown*, 1989; *Cunningham*, 1993; *Klepeis*, 1994; *Lodolo et al.*, 2003]. The most important of these predominantly strike-slip structures is represented by the Magallanes-Fagnano fault system, which traverses the entire Tierra del Fuego Island [*Lodolo et al.*, 2003]. This fault is a major segment of the present-day South America–Scotia plate boundary, and accommodates the relative displacement between these two plates.

[21] Along the southern continental margin of the western Scotia Sea, data presented here largely confirm the features already found by other authors [e.g., *Galindo-Zaldívar et al.*, 1996; *Acosta and Uchupi*, 1996]. The main peculiarity of this margin is the abrupt and narrow transition between the continental crust of the northern flank of the South Scotia Ridge and the oceanic domain of the western Scotia Sea. This transition is generally characterized by very steep slopes, which would represent the trace of subvertical normal faults, and generally occurs in less than 8–10 km, a distance which is at least 1 order of magnitude less than in classic passive continental margins. The steep slope at the

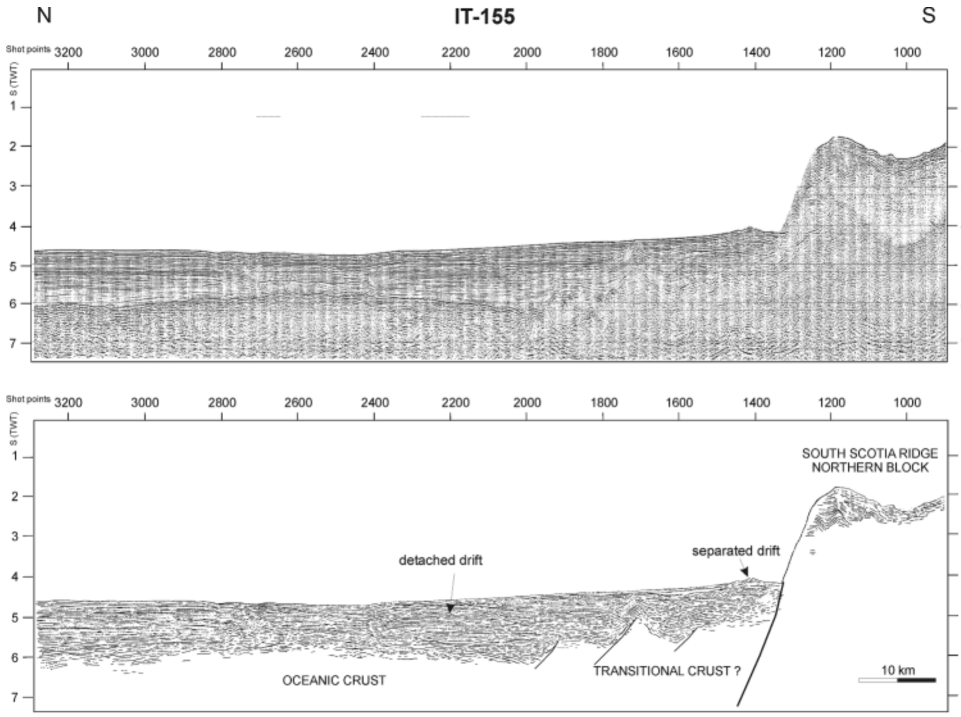

**Figure 8.** (top) Multichannel seismic profile IT-155 and (bottom) interpreted line drawing across the southern margin of the western Scotia Sea. Location of the corresponding profile is shown in Figure 1.

boundary between the two types of crust would be caused by isostatic forces, as also suggested by *Galindo-Zaldívar et al.* [1996]. This structural configuration was the result of a mainly transcurrent tectonic regime, more intense along the present southern sector of the western Scotia plate because it was favored by the "weak zone" composed of stretched continental blocks surrounded both to the north and south by oceanic and/or intermediate crust. The westernmost part

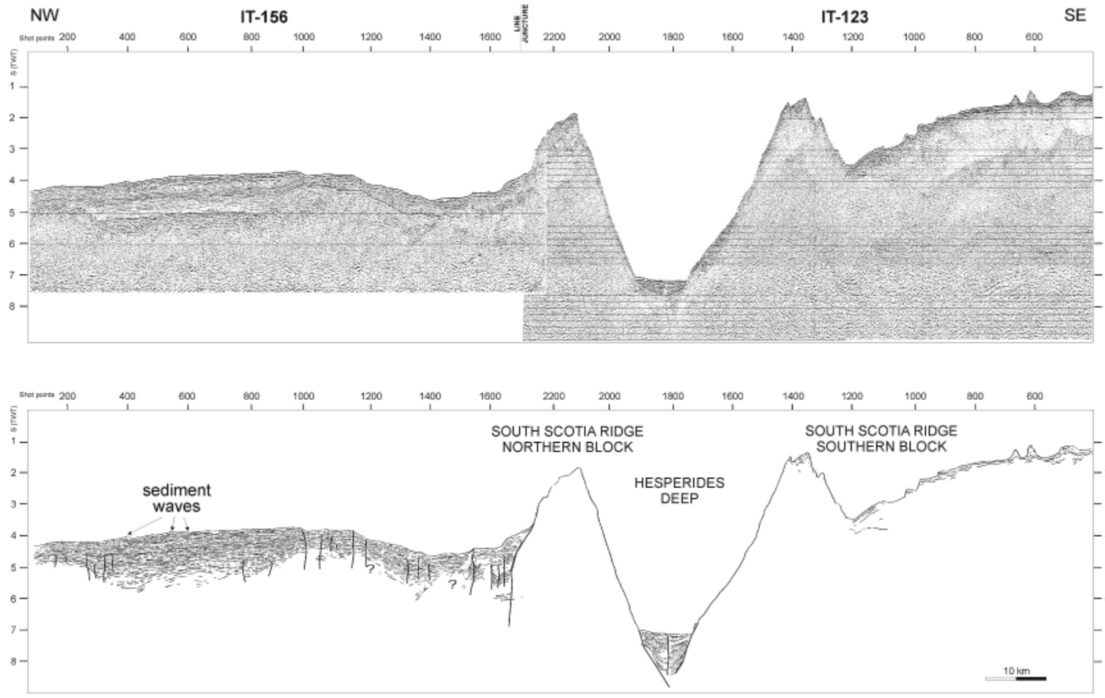

**Figure 9.** (top) Multichannel seismic profiles IT-156 and IT-123 and (bottom) interpreted line drawing across the southern margin of the western Scotia Sea. Location of the corresponding profile is shown in Figure 1.

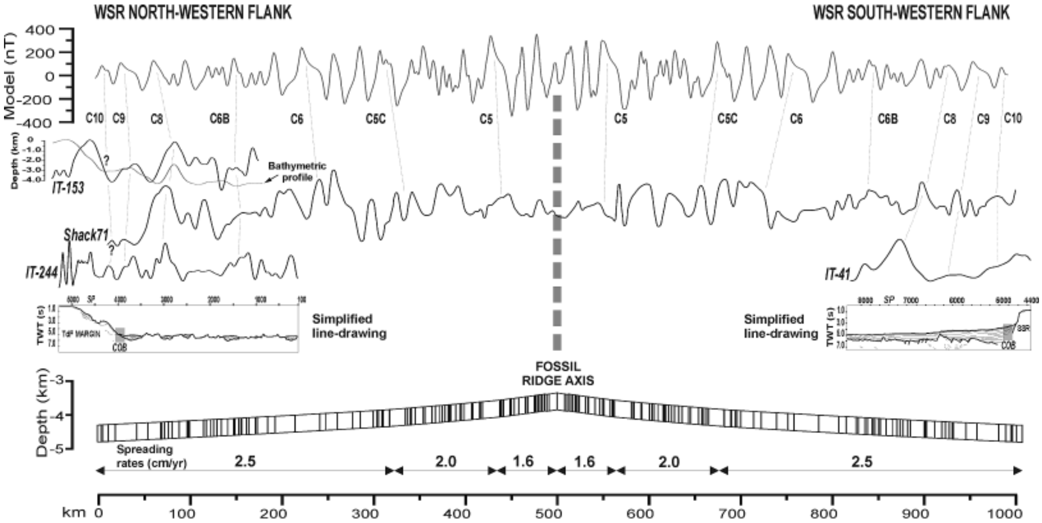

**Figure 10.** Magnetic anomaly distribution in the westernmost spreading corridors of the Scotia Sea, along magnetic profiles IT-41, IT-153, IT-244, and Shack71 (see Figure 1 for location), compared to a model (top of the figure) obtained assuming symmetrical spreading rates on both ridge flanks. Along line IT-153,* the bathymetric profile is also displayed. The COB is the continent-ocean boundary determined from seismic data, reported here as line drawing along lines IT-244* and IT-41. TdF, Tierra del Fuego; SSR, South Scotia Ridge. See text for further details.

of the northern flank of the South Scotia Ridge just to the east of Elephant Island shows the most pronounced and abrupt contact between the oceanic crust and the continental block. Along this segment, the left-lateral transpressional character and the southward dipping of the boundary caused the overthrusting of the continental blocks onto the western Scotia Sea oceanic crust [*Galindo-Zaldívar et al.*, 1996; *Lodolo et al.*, 1997]. The pre-Oligocene structure and geometry of the old margin were completely disrupted and subdued along the western continental blocks constituting the present South Scotia Ridge. A clear southward dipping of the oceanic crust, with the development of a buried subduction-like accretionary prism is visible along seismic profiles IT-41 in this region (see Figure 6), and farther to the west, in the vicinity of the intersection of the Shackleton Fracture Zone with the South Shetland platform [*Aldaya and Maldonado*, 1996]. Those authors interpreted this feature as generated by the subduction of the fracture zone relief below the South Shetland forearc. On the other profiles to the east of profile IT-41, the contact between the continental blocks of the South Scotia Ridge and the oceanic crust is mostly represented by a very narrow belt of highly faulted and rotated blocks of possible transitional-type crust.

### 5.2. Palaeo-Current-Related Deposits and Bedforms Within the Drake Passage

[22] Within the stratigraphic sequence of both western Scotia Sea margins, widespread erosional features and depositional bedforms diagnostic of bottom-current-related processes, have been detected. These features do not appear to characterize the entire stratigraphic sequence. In fact, the lowermost stratigraphic units, constituted of subparallel reflectors onlapping the basement highs, appear to represent a classic hemipelagic deposition. The onset of the drift formation occurs on almost all the seismic lines above an unconformity represented by a high-amplitude, continuous reflector. The thickness of the sedimentary cover off the two margins above all in the abyssal plain is remarkably different. It reaches up to 2.0 s TWT in the southern sector of the western Scotia Sea, whereas only occasionally it is 0.8 s TWT within confined basins, in the northern sector. This difference would be partly related to the different regime of the bottom currents.

[23] Off the Tierra del Fuego margin, bottom-current activity was particularly vigorous, with the formation of deep canyons emplaced in correspondence with tectonic lineaments. The lack of tie lines prevents a detailed characterization of the bottom current-related deposits, which would lead to the reconstruction of the palaeo-current setting. Nevertheless their origin may be related to the main clockwise circulation presently sweeping the Drake Passage, i.e., the ACC main flow path. This appears to be consistent with the progressive growth of the sediment drifts identified within the stratigraphic sequence of the northern sector of the western Scotia Sea.

[24] In the southern part of the western Scotia Sea, the internal characters of the identified morphologic features record the activity of along-slope, westward directed bottom currents of the Weddell Sea Deep Water branch flowing along this sector of the margin [*Pudsey and Howe*, 1998, 2002]. The Weddell Sea Deep Water would have been present since the onset of the Antarctic glaciation close to the Eocene-Oligocene boundary [*Benson*, 1975; *Barker and Thomas*, 2004]. Then it is possible that the westward flow would account for the formation of not only the most recent drifts deposited on the present seafloor, but also for those identified within the stratigraphic sequence.

## 6. Magnetic Anomalies Adjacent to the Western Scotia Sea Continental Margins

[25] Figure 10 shows representative magnetic profiles acquired across both the northern and southern margins of

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*The line numbers are correct here. The article as originally published is online.

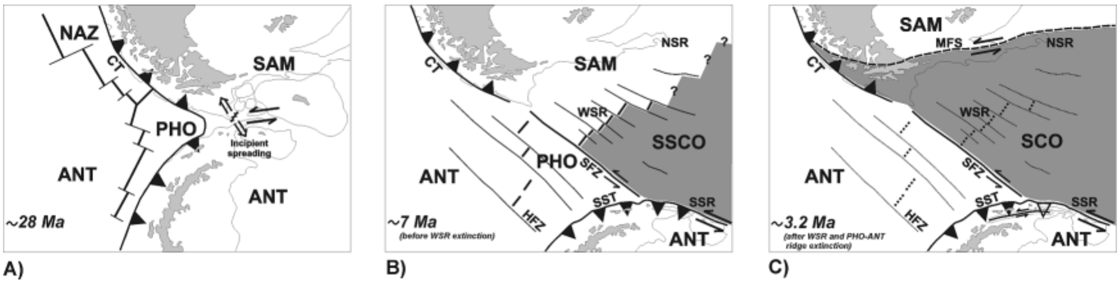

**Figure 11.** Sketches of three tectonic stages of evolution of the western Scotia Sea and surrounding regions, at (a) ~28 Ma, (b) ~7 Ma, and (c) ~3.2 Ma. NAZ, Nazca plate; PHO, Phoenix plate; SAM, South America plate; ANT, Antarctic plate; CT, Chile Trench; SSCO, South Scotia plate; NSR, North Scotia Ridge; SSR, South Scotia Ridge; SFZ, Shackleton Fracture Zone; HFZ, Hero Fracture Zone; WSR, western Scotia ridge system; SST, South Shetland Trench; MFS, Magallanes-Fagnano transform system.

the western Scotia Sea (see Figure 1 for location). Those magnetic profiles, running broadly orthogonal to the spreading axis, have been chosen because they are conjugate in their own spreading corridors marked W1 and W2 by *Eagles et al.* [2005, Figure 4], which represent the two westernmost spreading corridors of the Scotia Sea. Ridge offsets along the westernmost part of the western Scotia spreading system are relatively small (no more than 15–20 km), as seen from satellite-derived free-air gravity anomalies [*Sandwell and Smith*, 1997], to longitude 56°W. For this reason, the magnetic anomaly correlations between adjacent profiles may be confidently performed.

[26] The youngest anomaly identified along profile Shack71 falls within the normal polarity parts of chron C3A (6.6–5.9 Ma), as interpreted by *Maldonado et al.* [2000] across the westernmost extinct ridge axis of the western Scotia Sea. The oldest confidently identified magnetic anomaly along this profile [*Barker and Burrell*, 1977] is anomaly 8, but these authors suggested that anomalies 9 and 10 might be present near the Tierra del Fuego passive margin because about 50 km of oceanic crust is present between the anomaly 8 peak and the base of the continental slope [*British Antarctic Survey*, 1985], as also seen from the seismic profile IT-244, where the continent-ocean transition is easily identifiable. *LaBrecque* [1985] suggested that there is some evidence of spreading at least as old as anomaly 10, off the Tierra del Fuego margin. Toward the east, anomaly 8 lies consistently far from the South America passive margin (about 100 km) on the northern flank [*Eagles et al.*, 2005]. We have interpreted the subdued asymmetric peak at the northern end of the Shack71 profile as anomaly 9, and this correlates well with anomaly peaks along the two profiles IT-153 and IT-244 (see Figure 10). The possible presence of anomaly 9 along profile Shack71 has also been proposed by *Eagles et al.* [2005] in their Figure 2. Anomaly 10, or at least the youngest part of it, may occur on the two magnetic profiles IT-153 and IT-244, but the signature of this anomaly is not easily recognizable [*Geletti et al.*, 2005]. In the southern sector of the spreading corridor, the oldest identified anomaly along profile Shack71 is anomaly 8 [*Barker and Burrell*, 1977], but *Eagles et al.* [2005] suggest, although subdued, the presence of anomaly 9. Comparing this profile with the IT-41 data, it is evident that the entire anomaly 9 is present, and possibly part of anomaly 10, as originally proposed [*Lodolo et al.*, 1997]. Note that about 150 km of oceanic crust is present between the peak of anomaly 8 and the base of the South Scotia Ridge northern flank, which represents the continent-ocean transition (see line drawing of seismic line IT-41 in Figure 10). This supports the presence of anomaly 9 and part of anomaly 10 close to the continental margin.

[27] The small amplitude characterizing anomaly 9 (and 10) on both edges of spreading corridor W1 can be explained considering the combined effect of several polarity intervals at very slow spreading rates, as was found along the Pacific margin of the Antarctic Peninsula south of the Hero Fracture Zone [*Larter and Barker*, 1991]. Moreover, an unusual magmatic regime with reduced emplacement of igneous rocks associated with the early phase of oceanic crustal accretion can account for the low amplitude of these magnetic anomalies [*Lodolo et al.*, 1997]. Tectonic disturbance, with significant strike-slip displacement and diffuse faulting possibly accompanied the early development of the oceanic crust in this sector of the Scotia Sea. Extrapolation of spreading rates of 2.5 cm/yr for the opening phase between C8 and C6 produces an estimate of 30 Ma (chron C11) for the oldest oceanic crust at the foot of the Tierra del Fuego continental slope [*Livermore et al.*, 2005]. Assuming slower rates for incipient spreading, as is frequently the case just after continental separation, this age estimate could be significantly greater.

## 7. Western Scotia Sea Tectonic Evolution

[28] A significant number of reconstructions for the Scotia plate have been proposed (*Maldonado et al.* [2000], *Barker* [2001], and *Eagles et al.* [2005], among the most recent), mostly on the basis of magnetic anomaly identifications and modeled flow lines. Here a tectonic evolution of the western Scotia Sea from chron C10 (at about 28 Ma) up to 3.2 Ma is proposed, using the results derived from our data analysis, and particularly from seismic profiles (Figure 11). This reconstruction aims to emphasize the important role played by strike-slip tectonism since the early development of the Scotia plate, and after cessation of spreading processes along the western Scotia ridge system. The reconstruction involves different episodes

of transcurrent-type faulting coeval with possibly chaotic, diffuse oceanic accretion, and subsequent normal seafloor spreading organized in a classic ridge-transform configuration. Marine magnetic anomalies identified at the base of both margins of the western Scotia Sea, and along spreading corridors, provide a record of spreading extending back to about 28 Ma.

[29] Before the Drake Passage opening and the creation of the western Scotia ridge, the South America–Antarctica relative motion was mostly accommodated by continental deformation in southern Patagonia, with predominant left-lateral shear [*Cunningham et al.*, 1995]. The motion between these two plates over the past 50 Myr has been slow, and at about 20 Ma the South America–Antarctic spreading ridge direction changed from 120°–300° to the present-day W-E [*Barker and Lawver*, 1988]. This probably led to a major reorganization within the Scotia Sea, involving the initiation of spreading processes at the East Scotia Ridge [*Livermore*, 2003]. Up to the Late Eocene, the continental regions of southern South America and Antarctic Peninsula were possibly not yet physically separated within Gondwana. These two plates were in contact, in the future region of the Scotia plate, via a left-lateral system of transcurrent fault zone, located along the modern South Scotia Ridge. The numerous continental blocks now dispersed around the periphery of the Scotia Sea were probably together during this time, and they acted as a structurally complex boundary between the forming Scotia plate and the Antarctic plate. At chron C10 (see Figure 11a), seafloor spreading in the region was active only in the Pacific sector, where three ridge systems (Nazca-Antarctic ridge; Phoenix-Nazca ridge; Phoenix-Antarctic ridge) were present. When seafloor spreading in the western Scotia Sea initiated at ∼28 Ma, the Shackleton Fracture Zone separated two spreading systems: The Phoenix ridge system to the west and the western Scotia ridge system to the east. During the time span ∼28–6 Ma, E-W left-lateral, and N-S divergent motion between South America and Antarctica was accommodated by the now extinct spreading centers of the western Scotia Sea, and by intense faulting, stretching, and tectonic rotation within the South Scotia Ridge blocks. During that period, two main tectonic events occurred: The Phoenix-Nazca ridge was subdued beneath the Chile Trench, owing to the eastward migration of the ridge-ridge-ridge triple junction, and ridge-trench collisions occurred along the Pacific margin of the Antarctic Peninsula owing to the progressive subduction of the Phoenix oceanic crust [*Larter and Barker*, 1991].

[30] The data presented here, suggest that no motion occurred along the western part of the North Scotia Ridge (its southern flank, corresponding to the Tierra del Fuego margin, shows a geometry of a classic passive margin, and the strike-slip features developed well after spreading stopped), and the South America plate formed part of the northwest flank of the western Scotia ridge. This proposed configuration differs from *Eagles et al.* [2005], who postulate the presence of a plate (Magallanes plate), occupying the northwest flank of the western Scotia ridge since the time of chron C6/C5C. There are no magnetic anomalies marginward of anomaly 6 in spreading corridor W7 [*Eagles et al.*, 2005, Figure 4], suggesting that spreading did not start there until around chron C6, and so a two-plate system is likely to have been confined to corridors W1-W6 before then [*Eagles et al.*, 2005]. Observed transpressional deformation in sediments from seismic records acquired across the North Scotia Ridge and in the Falkland Trough, in the area to the east of longitude 58° W [*Ludwig and Rabinowitz*, 1982; *Lorenzo and Mutter*, 1988; *Cunningham et al.*, 1998; *Bry et al.*, 2004], may support the presence of a plate boundary there, but no age constraints are available to precisely date its formation. The tectonic convergence may provide an explanation for the obliteration of pre-C6 anomalies by thrusting in the area to the east of the Burdwood Fracture Zone (see Figure 1), but no evidence of deformation associated with a plate boundary was found to the west of the spreading corridor W6.

[31] While the western Scotia ridge was active, the oceanic crust of the South Scotia plate (SSCO in Figure 11b) occupied the southeast flank of the ridge, and the plate boundary between Antarctica and the SSCO was located within the modern South Scotia Ridge. When spreading along the western Scotia ridge system ceased at about 6 Ma, the SSCO plate and the South America plate became a single plate (see Figure 11c). At this time, the Magallanes-Fagnano transform system started to develop [*Lodolo et al.*, 2003], and this fault became the western segment of the South America–Scotia plate boundary. Between 6 and 3.2 Ma, the Shackleton Fracture Zone separated the still active Phoenix ridge system (separating the Phoenix and Antarctic plates), and the extinct western Scotia ridge system. When spreading at the Phoenix ridge system stopped at about 3.2 Ma, the Phoenix and Antarctic plates became a single plate (Antarctic plate). Between 3.2 Ma to the present time, Shackleton Fracture Zone separated the Antarctic plate from the Scotia plate, and the Scotia plate moved between two left-lateral, dominantly strike-slip fault zones on the South Scotia Ridge–Shackleton Fracture Zone and North Scotia Ridge–Magallanes-Fagnano transform system [*Thomas et al.*, 2003].

[32] Following cessation of spreading, rollback of the subducting slab beneath the present-day South Shetland margin led to the opening and development of the Bransfield Basin, an elongated Late-Pliocene-to-recent back-arc basin [e.g., *Gambôa and Maldonado*, 1990; *Gracia et al.*, 1996a, 1996b; *Barker and Austin*, 1998]. Some authors have proposed that the rift extends and merges eastward into an active fault zone within the South Scotia Ridge and accommodates the left-lateral transcurrent deformation acting along this continental segment [*González-Casado et al.*, 2000; *Galindo-Zaldívar et al.*, 2004].

## 8. Conclusions

[33] Multichannel seismic reflection profiles and magnetic anomaly data presented in this study have provided new insights into the structure and evolution of the western sector of the Scotia Sea. The comparison of the conjugate continental margins, once adjacent before the Drake Passage opening, has constrained the events that occurred immediately after breakup, and the successive tectonic development. The opening of this gateway had profound consequences on water circulation, as testified by the presence of widespread bottom-current-related deposits found on the seismic data, which contain important

palaeo-oceanographic records. Some specific findings are summarized below.

[34] 1. The continental margin off the Tierra del Fuego Island appears generally as a classic rifted passive margin cut by major and broadly E-W-trending transcurrent lineaments on which narrow and steep canyons are superimposed.

[35] 2. The southern margin of the western Scotia Sea, which morphologically corresponds to the northern flank of the South Scotia Ridge, is characterized by steep slopes that generally coincide with fault scarps. These faults separate the continental crust of the South Scotia Ridge from the oceanic crust of the western Scotia Sea abruptly.

[36] 3. The comparison between the two margins shows that they are remarkably different in both their topographic profile and structure. This configuration was generated by the intense strike-slip tectonic activity that affected the southern margin of the western Scotia Sea since its early development. On the Tierra del Fuego margin, strike-slip tectonism occurred only in a later time, during the Late Miocene development of the Magallanes-Fagnano transform system and associated lineaments.

[37] 4. The oldest marine magnetic anomaly identified at the foot of the Tierra del Fuego continental margin, corresponds to chron C10. The same anomaly is found at the base of the northern flank of the South Scotia Ridge, supporting the concept that the two margins are conjugate. The low amplitude of the oldest magnetic anomalies along both the margins may imply that spreading processes were highly disorganized during the early phase of opening.

[38] 5. The thickness of the sedimentary cover off the two margins is remarkably different. This difference may be ascribed to the different regimes of the bottom-current flow, which affected the western Scotia Sea now and in the past. The sedimentary cover in the oceanic domain off the Tierra del Fuego Island is generally confined in small areas bordered by structural highs. Most of these deposits reflect the vigorous activity of the ACC main flow. In the southern sector of the western Scotia Sea, the sedimentary sequences are thicker than those of the northern sector, and generally record the activity of the westward directed water bottom currents of the Weddell Sea Deep Water branch.

[39] 6. A proposed tectonic reconstruction (from ~28 to 3.2 Ma) of the western Scotia Sea and surrounding areas, based on the seismic structural setting of the two conjugate margins and the oldest identified marine magnetic anomalies, highlights the prominent role played by strike-slip tectonism since the early development of the Scotia plate, mostly occurring along the modern South Scotia Ridge. The northern boundary of the forming Scotia plate developed as a passive margin until the cessation of spreading (at about 6 Ma) along the western Scotia ridge system, when transcurrent motion transferred to the Magallanes-Fagnano fault system. Since then, this transform system acted as the western segment of the left-lateral South America–Scotia plate boundary.

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