

Extensional deformation and development of deep basins associated with the sinistral transcurrent fault zone of the Scotia–Antarctic plate boundary

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Abstract: The Scotia–Antarctic plate boundary extends along the southern branch of the Scotia Arc, between triple junctions with the former Phoenix plate to the west (57°W) and with the Sandwich plate to the east (30°W). The main mechanism responsible for the present arc configuration is the development of the Scotia and Sandwich plates from 30–35 Ma, related to breakup of the continental connection between South America and the Antarctic Peninsula. The Scotia–Antarctic plate boundary is a very complex tectonic zone, because both oceanic and continental elements are involved. Present-day sinistral transcurrent motion probably began 8 Ma ago. The main active structures that we observed in the area include releasing and restraining bends, with related deep extensional and compressional basins, and probable pull-apart basins. The western sector of the plate boundary crosses fragmented continental crust: the Western South Scotia Ridge, with widespread development of pull-apart basins and releasing bends deeper than 5000 m, filled by asymmetrical sedimentary wedges. The northern border of the South Orkney microcontinent, in the central sector, has oceanic and continental crust in contact along a large thrust zone. Finally, the eastern sector of the South Scotia Ridge is located within Discovery Bank, a piece of continental crust from a former arc. On its southern border, strike-slip and normal faults produce a 5500-m-deep trough that may be interpreted as a pull-apart basin. In the eastern and western South Scotia Ridge, despite extreme continental-crustal thinning, the basins show no development of oceanic crust. This geometry is conditioned by the distinctive rheological behaviour of the crust involved, with the bulk concentration of deformation within the rheologically weaker continental blocks.

The development of the Scotia Arc between the major South America and Antarctic plates constitutes the main tectonic event in the SW Atlantic since the Oligocene. The former continental connection between South America and the Antarctic Peninsula was broken during the development of the Scotia Arc, leading to dispersal of continental blocks and the joining of the Atlantic and Pacific oceans (Barker & Burrell 1977; King & Barker 1988; Barker *et al.* 1991; Livermore *et al.* 1994; Aldaya & Maldonado 1996; Galindo-Zaldívar *et al.* 1996;

Maldonado *et al.* 1998; Barker 2001). The internal part of this tectonic arc is formed by two minor plates – the Scotia and the Sandwich plates – mainly composed of oceanic crust and separated by the East Scotia Ridge, an active spreading axis (Fig. 1). The northern and southern branches of the Scotia Arc constitute the east–west-oriented boundaries of these minor plates, accommodating the present-day relative sinistral motion between the South America and Antarctic plates. However, the eastern and western boundaries of the tectonic

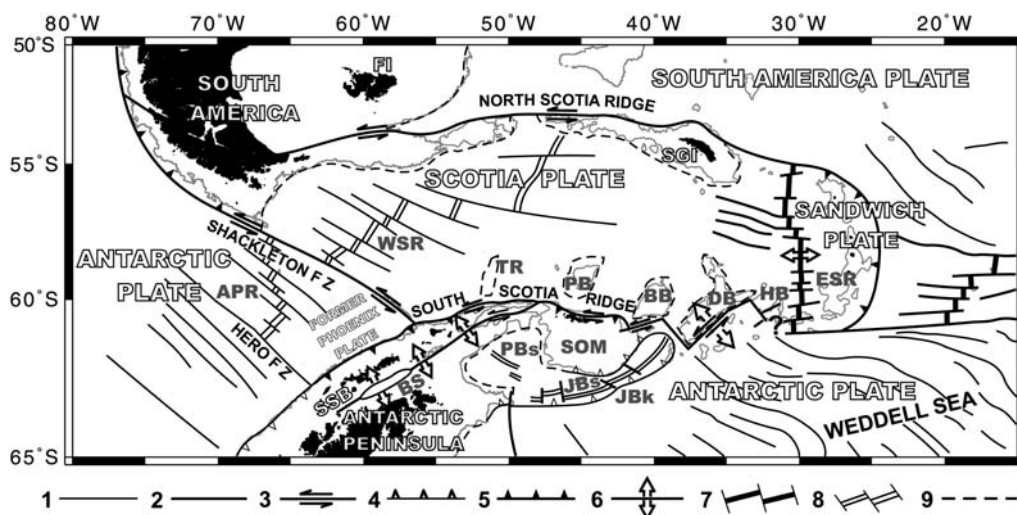


Fig. 1. Geological setting of the study area within the Scotia Arc (modified from Galindo-Zaldívar *et al.* 2002). 1, inactive fracture zone; 2, active fracture zone; 3, transform or transcurrent fault; 4, inactive subduction zone or reverse fault; 5, active subduction zone; 6, rift; 7, active spreading axis; 8, inactive spreading axis; 9, continental–oceanic crustal boundary; APR, Antarctic–Phoenix Ridge; BB, Bruce Bank; DB, Discovery Bank; ESR, East Scotia Ridge; FI, Falkland Islands; FZ, fracture zone; HB, Herdman Bank; JBk, Jane Bank; JBs, Jane Basin; PB, Pirie Bank; PBs, Powell Basin; SGI, South Georgia Island; SOM, South Orkney microcontinent; SSB, South Shetland Block; TR, Terror Rise; WSR, West Scotia Ridge.

arc have different characteristics. While the eastern boundary is determined by the present subduction of the South America plate below the Sandwich plate (Livermore *et al.* 1997; Larter *et al.* 2003; Livermore 2003), the western boundary is located at the Shackleton fracture zone, which is an intra-oceanic active sinistral transpressive NW–SE-oriented fault zone with sharp positive relief and small basins (Maldonado *et al.* 1998; Livermore *et al.* 2000, 2004; Fig. 1).

The tectonic evolution related to the plate boundary has determined the individualization and assemblage of a large amount of oceanic and continental elements. The southern part of the Scotia plate is a large oceanic basin formed by the oceanic spreading of the West Scotia Ridge and several small basins (Protector, Dove and Scan basins) bounded by thinned continental blocks (Terror Rise, and Pirie, Bruce and Discovery banks). The South Shetland Block constitutes an independent tectonic continental element separated from the northern Antarctic Peninsula by the Bransfield Strait (Aldaya & Maldonado 1996; Fig. 1). The Antarctic plate is also formed by continental and oceanic crusts. Northeastward of Antarctic Peninsula continental crust, lies the small oceanic Powell Basin, formed by the eastward drifting of the South Orkney microcontinent (SOM; King & Barker 1988; Barker *et al.* 1991; Rodríguez-Fernández *et al.* 1994, 1997;

Eagles & Livermore 2002). The Jane Basin and Jane Bank, constituting an arc–back–arc system related to the subduction of the oceanic crust of the Weddell Sea, are located at the SE border of the SOM. Towards the east, a complex array of continental blocks south of the Discovery Bank shows evidence of tectonic activity associated with the present-day plate boundary (Maldonado *et al.* 1998; Galindo-Zaldívar *et al.* 2002; Fig. 1).

The plate boundaries around the Scotia Arc are highlighted by the distribution of earthquake epicentres (Fig. 2). Most seismic activity takes place at the eastern part of the arc, where the South America plate bends below the Sandwich plate in an active subduction zone. All deep (>150 km) and most intermediate (50–150 km) events are concentrated here, while the other boundaries are mainly described by shallow events (0–50 km). In addition, a second area of significant seismic activity is located at the Western South Scotia Ridge (WSSR), between the South Shetland Islands and South Orkney Islands (Fig. 2). Analysis of earthquake focal mechanisms indicates a regional stress regime characterized by NE–SW compression, with local stress perturbations (Pelayo & Wiens 1989; Galindo-Zaldívar *et al.* 1996; Giner-Robles *et al.* 2003; Thomas *et al.* 2003).

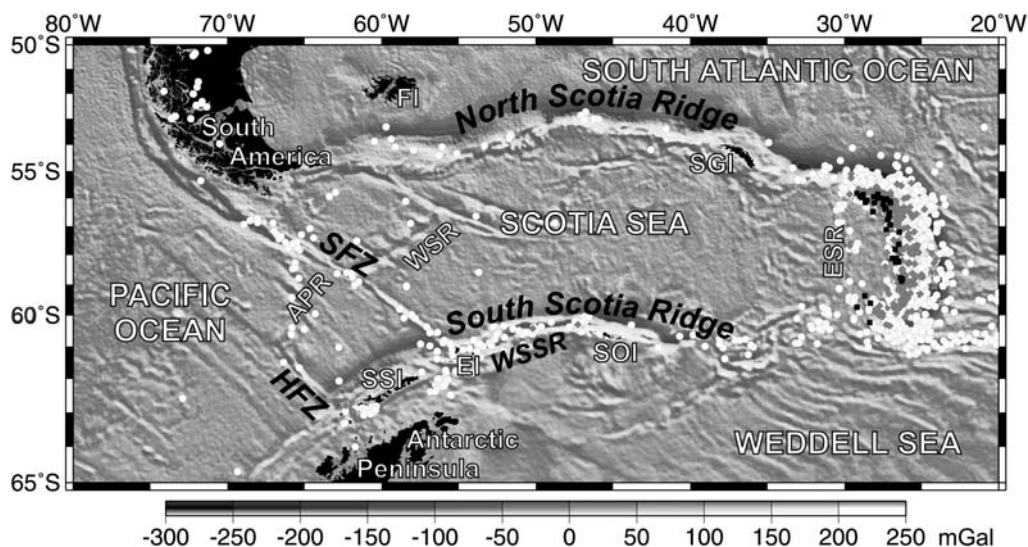


Fig. 2. GEOSAT free-air gravity anomaly map (Livermore *et al.* 1994; Sandwell & Smith 1997) including location of earthquake epicentres (1973–2004) (NEIC – National Earthquake Information Center; USGS <http://www.neic.cr.usgs.gov>). Shallow events (<50 km), white circles; intermediate (50 to 150 km), grey diamonds, and deep (>150 km), black squares. APR, Antarctic–Phoenix Ridge; EI, Elephant Island; ESR, East Scotia Ridge; FI, Falkland Islands; SFZ, Shackleton fracture zone; SGI, South Georgia Island; SOI, South Orkney Islands; SSI, South Shetland Islands; WSSR, Western South Scotia Ridge.

The aim of this contribution is to analyse in detail and summarize the deformation related to the Scotia–Antarctic plate boundary, focusing mainly on the development of deep extensional releasing-bend- and pull-apart basins within fragments of continental crust. We describe the main structures of the South Scotia Ridge on the basis of bathymetric, gravimetric and multi-channel seismic profiles, together with global gravity and bathymetry derived from satellite images (Sandwell & Smith 1997; Smith & Sandwell 1997). Seismicity data are also taken into account in determining present-day tectonic activity.

Data and methodology

Over the last 15 years, a number of cruises aboard the Spanish Vessel B/O *Hespérides* have made it possible to gather an important geophysical data-set along the southern branch of the Scotia Arc. This body of knowledge includes multi-channel seismic (MCS), gravity, magnetic and swath bathymetry data recorded along profiles orthogonal and parallel to the Scotia–Antarctic plate boundary. Most of the data used in this work stem from the HESANT92–93 and SCAN97 cruises.

The MCS profiles were obtained with a tuned array of 5 BOLT air guns with a total volume of 22.4 l, using a streamer with a total length of 2.4 km and 96 channels. The shot interval was

50 m. Data were recorded with a DFS V digital system and a sampling record interval of 2 ms with 10-s record lengths. The data were processed in sequence, including migration using a DISCO/FOCUS system; the processed profiles have a fold of 24. Swath bathymetry data were obtained using a SIMRAD EM12 multi-beam sounder.

Gravity data were acquired only during the SCAN97 cruise, with a Bell Aerospace TEXTRON BGM-3 marine gravimeter. The free-air anomaly was determined using Lanzada software (A. Carbó pers. comm. 2006). In addition, free-air gravity and bathymetric data from GEOSAT (Sandwell & Smith 1997; Smith & Sandwell 1997) were considered. Gravity models were developed by means of the GRAVMAG program (Pedley *et al.* 1993) using the free-air anomaly and taking into account the geometry obtained from MCS profiles, which locally also allow determination of the position of the Moho. Densities for gravity modelling were attributed according to the mean values of each lithology (Telford *et al.* 1990) and the probable nature of crustal elements, providing for minor variation during modelling to reach the best fit (mantle, 3.35 g cm^{-3} ; continental-crust basement, 2.67 g cm^{-3} ; intermediate crust, 2.80 g cm^{-3} ; oceanic crust basement 2.88 to 3.00 g cm^{-3} ; sediments, 2.30 to 2.50 g cm^{-3} and sea-water 1.03 g cm^{-3}). These density values are in agreement with gravity models developed in the southern

Weddell Sea (Ferris *et al.* 2000), in a similar tectonic setting.

The Scotia–Antarctic plate boundary along the South Scotia Ridge

The southern boundary of the Scotia Arc is formed by a complex chain of high blocks and narrow, small basins developed in stretched continental crust, which together constitute the South Scotia Ridge (SSR), which extends from the NE end of Bransfield Strait as far as Discovery Bank. This continental barrier separates the oceanic crusts of the Scotia and Antarctic plates and represents part of the former continental connection between South America and the Antarctic Peninsula (Fig. 1).

Present-day tectonic deformation in this ridge, as evidenced by seismicity and MCS profiles, is mostly the result of sinistral faults of variable character. From east to west, they deform the central and southern part of Discovery Bank, located at the eastern part of the SSR, then continue along the northern boundary of the South Orkney microcontinent at the central SSR (Fig. 3). At the continental blocks of the western South Scotia Ridge, they show a sinistral transtensive character (Acosta & Uchupi 1996; Galindo-Zaldívar *et al.* 1996); and finally the displacement is transferred to the normal faults in the Bransfield Strait, located between the South Shetland Block and the Antarctic Peninsula (Acosta & Uchupi 1996; Aldaya & Maldonado 1996; Galindo-Zaldívar *et al.* 1996, 2004;

González-Casado *et al.* 2000; Figs 1 & 3). The northern boundary of the central and western South Scotia Ridge is defined by a subduction zone or a reverse fault that superposes the continental block of the ridge over the oceanic crust of the Scotia plate. The westward extremity of the South Scotia Ridge is a complex region where the Shackleton fracture zone intersects the ridge. The thickened oceanic crust of the Shackleton fracture zone, with related positive relief that constitutes the boundary between the Antarctic and Scotia plates, is subducted along the northern boundary of the South Shetland continental block. This subduction produces crustal thickening and uplift of Elephant Island, where blueschists crop out (Trouw *et al.* 2000; Figs 1 & 3). Westward, this subduction zone and related South Shetland Trench are more active, separating the Antarctic plate (former Phoenix plate) from the South Shetland Block (Fig. 1).

Discovery Bank

Discovery Bank constitutes the largest continental fragment of the eastern part of the South Scotia Ridge (Figs 3–7). The available data suggest that this high is of a continental nature, as demonstrated by the shallow bathymetry of up to 700 m depth, the presence of large magnetic anomalies, due to massive basic igneous rocks intruded in the continental crust, typical of the Pacific margin of the Antarctic Peninsula (Garrett *et al.* 1987), the seismic tomography velocities (Vuan *et al.* 2005), and seismic facies observed in multi-channel

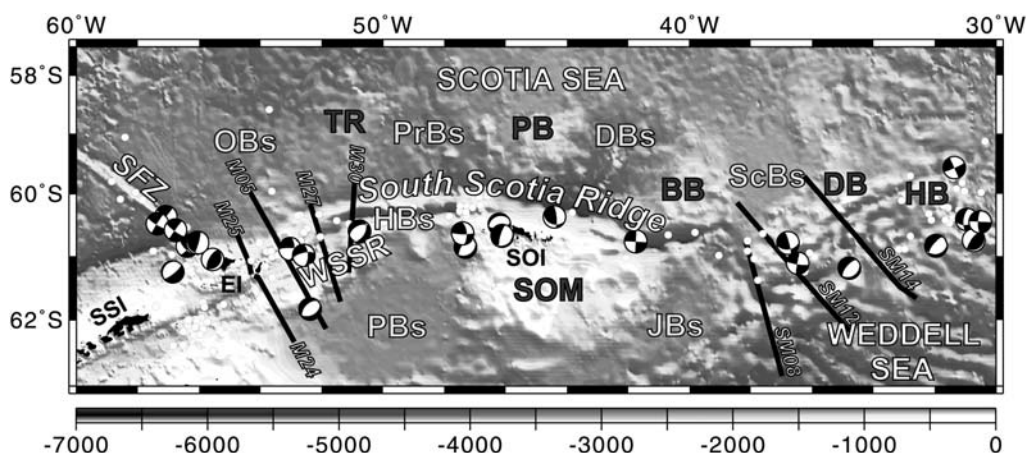


Fig. 3. Satellite-derived bathymetric map of the studied area (Smith & Sandwell 1997) including the location of HESANT92-93 and SCAN97 cruises lines. Earthquake focal mechanisms from CMT (Dziensewski *et al.* 1981). BB, Bruce Bank; DB, Discovery Bank; DBs, Discovery Basin; EI, Elephant Island; HB, Herdman Bank; JB, Jane Basin; OBs, Ona Basin; PB, Pirie Bank; PBs, Powell Basin; PrBs, Protector Basin; ScBs, Scan Basin; SFZ, Shackleton fracture zone; SOI, South Orkney Islands; SOM, South Orkney microcontinent; SSI, South Shetland Islands; TR, Terror Rise; WSSR, Western South Scotia Ridge.

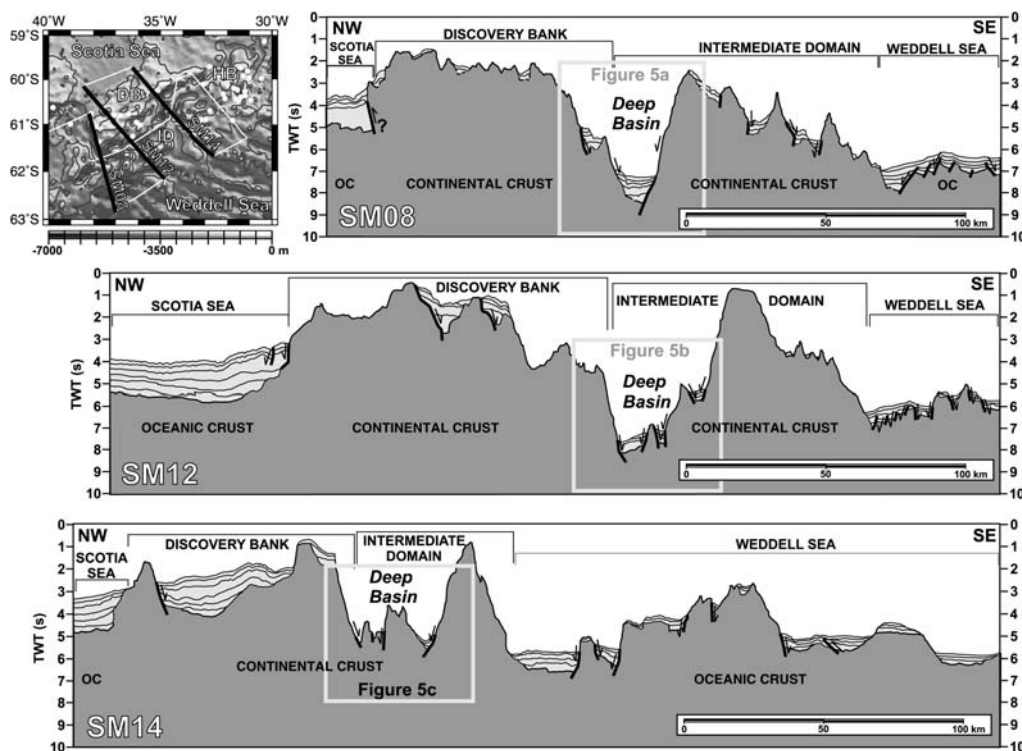


Fig. 4. SM08, SM12 and SM14 multi-channel seismic profiles and interpretation. Location given in Figure 3 and inset map. OC, oceanic crust. The positions of SMC details in Figure 5 are indicated. The bathymetry map includes the location of SMC profiles.

seismic profiles (Galindo-Zaldívar *et al.* 2002; Vuan *et al.* 2005). Previous methods do not, however, directly indicate the geometry of the Moho discontinuity. Gravimetric models developed along several profiles, together with the SMC profiles (Figs 4–6), led us to determine a crustal thickness of at least 14 km in the central part of the bank. North of the Discovery Bank is the oceanic crust of the Scotia Sea; this boundary is now covered by a thick practically undeformed sedimentary sequence (Fig. 4) that might represent an older passive margin. Some reverse or subvertical NE–SW-trending normal faults are identified locally.

The southern margin, meanwhile, is more complex: Discovery Bank is deformed by large normal faults with related scarps reaching up to 4500 m, isolating several perched basins, and developing a narrow, deep basin that may reach –5500 m in depth. Seismic profiles, gravity anomalies and available bathymetric data suggest that faults have ENE–WSW strikes and dip generally SE along the margin. The basin is bathymetrically irregular along strike; whereas to the west (profile SM08) the southern boundary is the sharpest boundary. In

the central part (profile SM12) the basin is slightly tilted northward, with irregular borders. To the east (profile SM14), the basin becomes roughly symmetrical with a central high (Figs 4 & 5).

The thickness of the sedimentary record of this basin decreases progressively northeastward (Figs 4 & 5). Although the basement reaches great depths, the seismic profiles (Figs 4 & 5) show the basin to be floored by continental crust. Gravity models confirm that the basement is of a continental or intermediate nature, with a very shallow mantle position (Fig. 6).

Another secondary elongated high, parallel to the basin and to the southern border of the Discovery Bank, is identified, with gravity and MCS data suggesting its correspondence to an intermediate crustal domain (Figs 4 & 6). This high is largely deformed by normal faults. Towards the NE it is very narrow, while southwestward it becomes wider and asymmetrical, with progressive southern slopes where small perched basins are developed.

This intermediate crustal domain is bordered to the south by the oceanic crust of the Weddell Sea, which is slightly deeper than the Scotia Sea

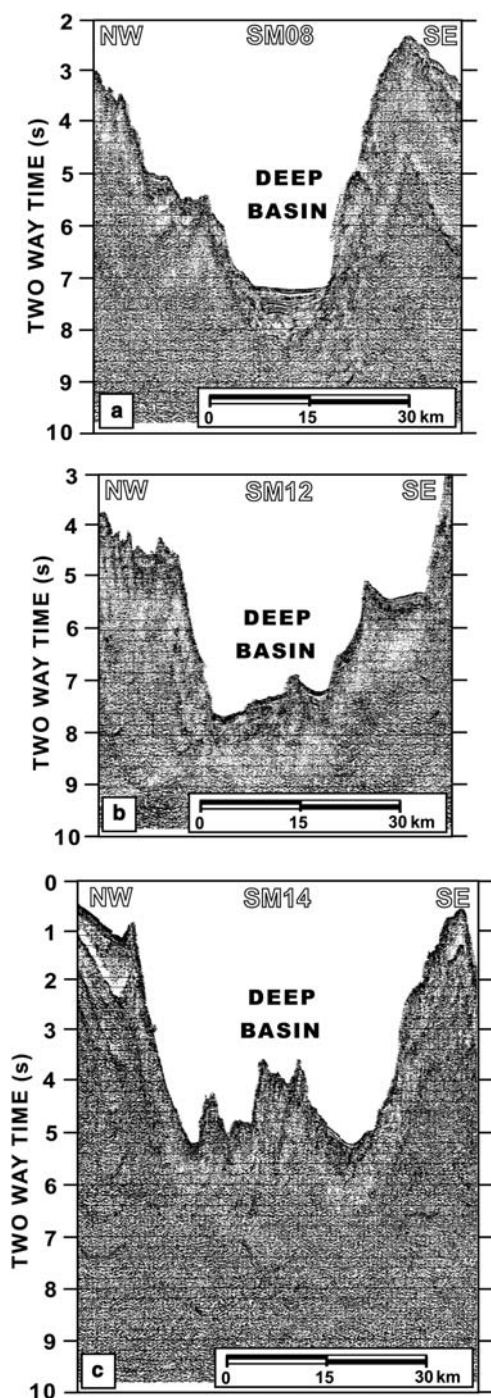


Fig. 5. Enlarged view of SM08 (a), SM12 (b) and SM14 (c) multi-channel seismic profiles showing the deep basin inside Discovery Bank. Locations are given in Figure 4.

oceanic crust (Figs 4 & 6). The sedimentary cover in the Weddell Sea is scarce and probably determined by oceanic currents (Maldonado *et al.* 2005).

South of Discovery Bank, the seismicity and exposed fault scarps indicate Recent and present-day activity on faults that border the Deep Basin (Figs 4–5 & 7). However, the continental–oceanic boundaries (northward with the Scotia Sea and southward with the Weddell Sea) are generally covered by sediments, indicating that these major contacts are tectonically inactive.

Although the geometry of the faults is determined by seismic profiles, gravity anomalies and available bathymetric data, the kinematics of the present-day active faults may be established on the basis of the vertical displacements observed from MCS profiles (Figs 4–5), and the earthquake focal mechanisms established by Pelayo & Wiens (1989) and CMT (Dziewonski *et al.* 1981; Harvard Seismology Centroid Moment Tensor Catalog (Fig. 3). In the eastern and central part of the southern border of the Discovery Bank, Intermediate Domain and Deep Basin, faults have a NE–SW orientation and accommodated normal-sense slip responsible for crustal thinning and basin development. Yet towards the SW part and inside the Discovery Bank, strike-slip earthquake focal mechanisms are dominant. The active faults are probably sinistral ENE–WSW to east–west faults, consistent with one of the nodal planes of the focal mechanisms (Figs 3–5 & 7). If the fault plane were north–south oriented, the fault would be dextral, producing displacements of the basin borders and closure of the eastern part of the Deep Basin. Because this is not supported by the observed data, we have to discard the latter interpretation.

South Orkney microcontinent

The South Orkney microcontinent (SOM) represents the largest (70 000 km²) continental fragment of the southern part of the Scotia Arc. It is formed by low-grade metamorphic rocks of Triassic age, part of an accretionary wedge, and unconformable Upper Jurassic conglomerates that crop out in the South Orkney Islands (Trouw *et al.* 1997; Fig. 3). In the southern and eastern sector of the SOM and on the eastern margin of the Powell Basin, magnetic anomaly data show a high-amplitude anomaly (500–1000 nT) related to igneous basic rocks that may belong to the Pacific Margin Anomaly (Garrett *et al.* 1987; King & Barker 1988; Surinac *et al.* 1997) or to the subduction of the Weddell Sea below the SOM (Bohoyo *et al.* 2002). In addition, alkaline basalts, Pliocene

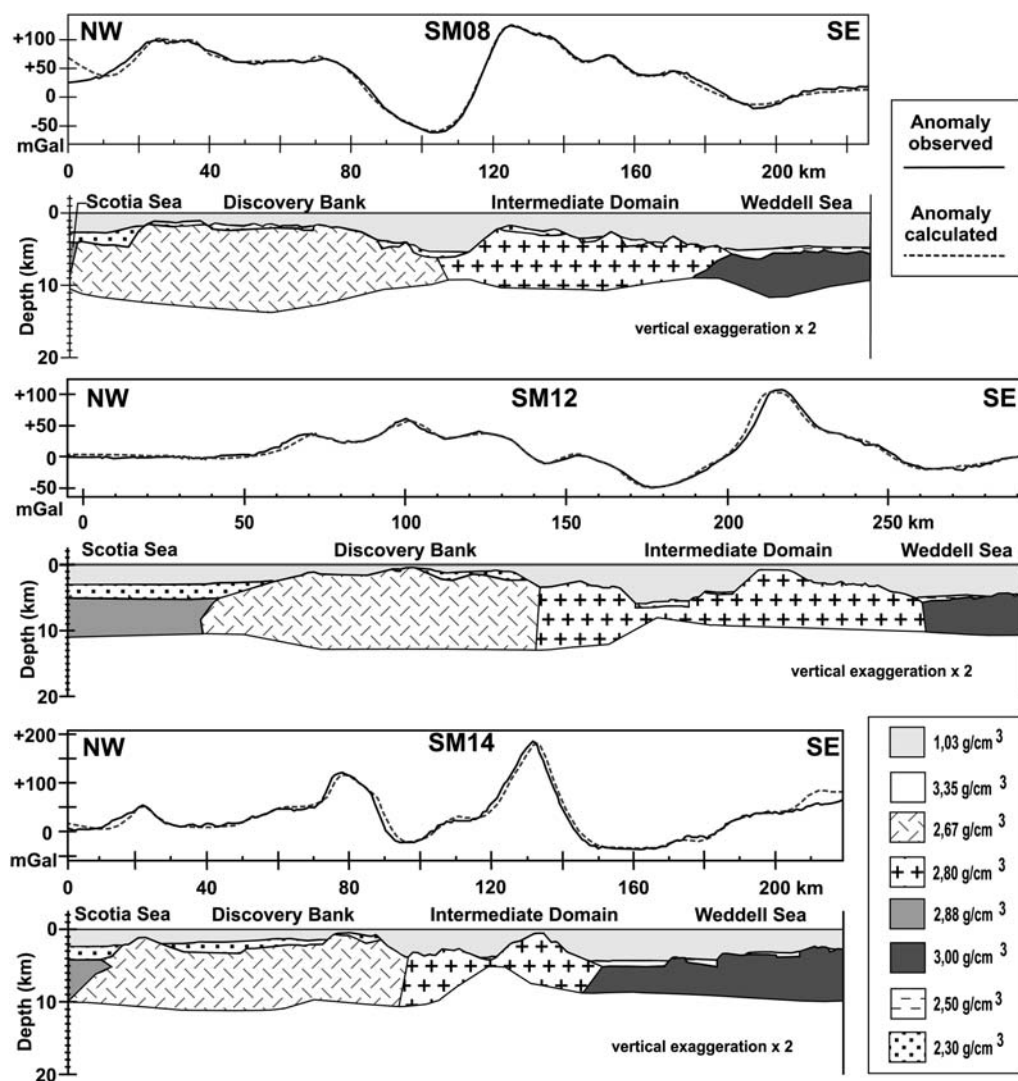


Fig. 6. Free-air gravity profiles and models of the Discovery Bank. See text for discussion.

to Recent in age, have been dredged in the northern and southern margins of the Powell Basin (Barber *et al.* 1991). The SOM is affected by normal faults that produce elongate horst and graben structures that determine the variability of the sedimentary cover from the Eocene to the present day. The more recent basins in the SOM are oriented north-south and are related to Oligocene rifting associated with the opening of the Powell Basin (King & Barker 1988).

The northern margin of the SOM is characterized by an active sinistral transcurrent fault zone affecting a curved plate boundary. Oblique relative motions produce differential strain with

compressional, pure strike-slip and extensional sectors, depending on the boundary orientation with respect to the relative plate motion. Generally, the northern border of the SOM is characterized by a linear depression associated with a gravity minimum (Figs 2 & 3), that may be related to thrusting or sinistral transcurrent displacement of the SOM with respect to the Scotia Sea. Between the SOM and Bruce Bank, an east-west oriented depression with seismic activity and a strike-slip earthquake focal mechanism points to a purely sinistral regime on east-west oriented faults (Fig. 3). The NNE margin of the SOM, with WNW-ESE orientation, is characterized by a

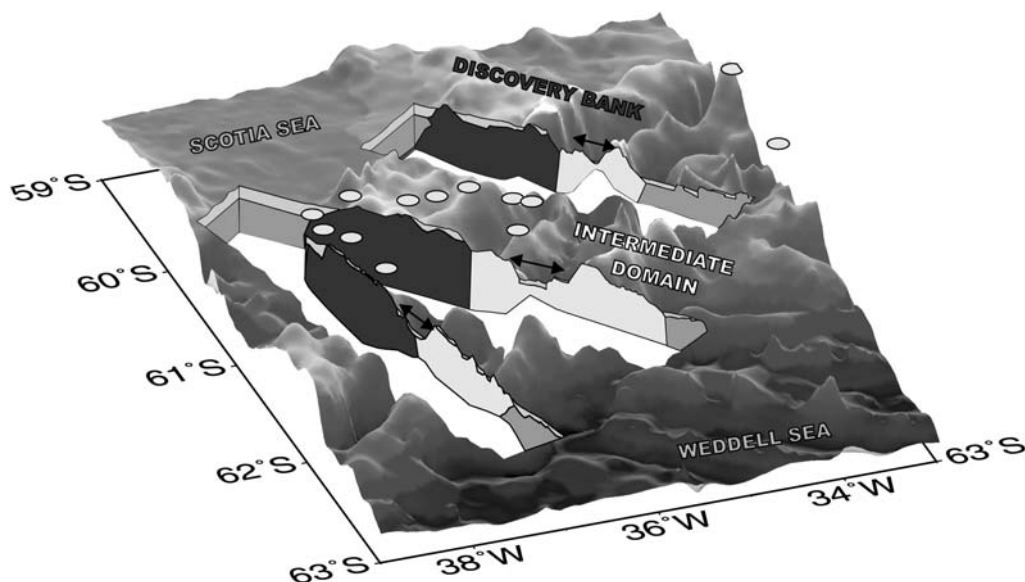


Fig. 7. Three-dimensional block of the Discovery Bank. In cross-sections the oceanic domains and sedimentary cover are represented in medium grey; the Discovery Bank continental domain are shown in dark grey; and the Intermediate Domain is shown in light grey. Earthquake epicentres are also indicated (light-grey circles).

convergent component that produces the subduction of the Scotia plate below the Antarctic plate, as proposed by Kavoun & Vinnikovskaya (1994); Klepeis & Lawver (1996); Lodolo *et al.* (1997); Maldonado *et al.* (1998) and Busetti *et al.* (2000). Towards the NW – even though the seismic activity is located near the continental–oceanic boundary – active faults with seismicity deform the continental margin, and also are located within the SOM, determining a cluster of epicentres (Fig. 3).

The structure of the internal regions of the SOM and the southern margin result from a heterogeneous continental fragmentation process, now inactive, with seismically inactive faults overlapped by uncut sediments. The process of thinning and stretching of continental crust through the eastward drifting of the SOM relative to the Antarctic Peninsula, between the Late Eocene and the Early Miocene (35–18 Ma), opened Powell Basin and defined the western boundary of the SOM. The oceanic spreading occurred between 26 and 17.6 Ma (Coren *et al.* 1997), although older ages have been proposed (29.7 to 21.1 Ma, Eagles & Livermore 2002). Discontinuous NW–SE extinct oceanic ridges are present in the middle part of the basin (King & Barker 1988; Coren *et al.* 1997; Rodríguez-Fernández *et al.* 1997); whereas fragmentation of the southern and eastern boundaries is tied to the development of the Jane Basin and the subduction of the oceanic crust of the Weddell Sea below the southern margin of the SOM

(Bohoyo *et al.* 2002; Bohoyo 2004). The inactivity of the eastern, southern and western margins of the SOM, along with the oceanic spreading in Powell and Jane basins, determine that all these tectonic elements are included in the Antarctic plate from 14 Ma onwards (Rodríguez-Fernández *et al.* 1997; Bohoyo *et al.* 2002).

Western South Scotia Ridge

The Western South Scotia Ridge (WSSR; Fig. 3) is formed by continental crust, probably of a nature similar to that of the Antarctic Peninsula, located to the west, and to that of the SOM situated to the east (Fig. 3). Magnetic anomaly data (Suriñach *et al.* 1997) show the southern part of the ridge to be intruded by basic igneous rocks corresponding to the NE prolongation of the PMA (Pacific Margin Anomaly belt, Garrett *et al.* 1987). The basement is generally exposed in the highs (Fig. 8). The ages of the sediments that fill the internal basins are unknown.

The continental ridge is bound to the north by oceanic crust of the Ona and Protector basins, as well as the thinned continental crust of the Terror Rise that gave rise to the SW Scotia Sea (Fig. 3). The oceanic crust of the Ona Basin abyssal plain was formed by the extinct West Scotia Ridge, located in the centre of the Drake Passage (BAS, 1985). The magnetic anomaly chron C8r (27.027 Ma) is well identified (BAS, 1985; Eagles

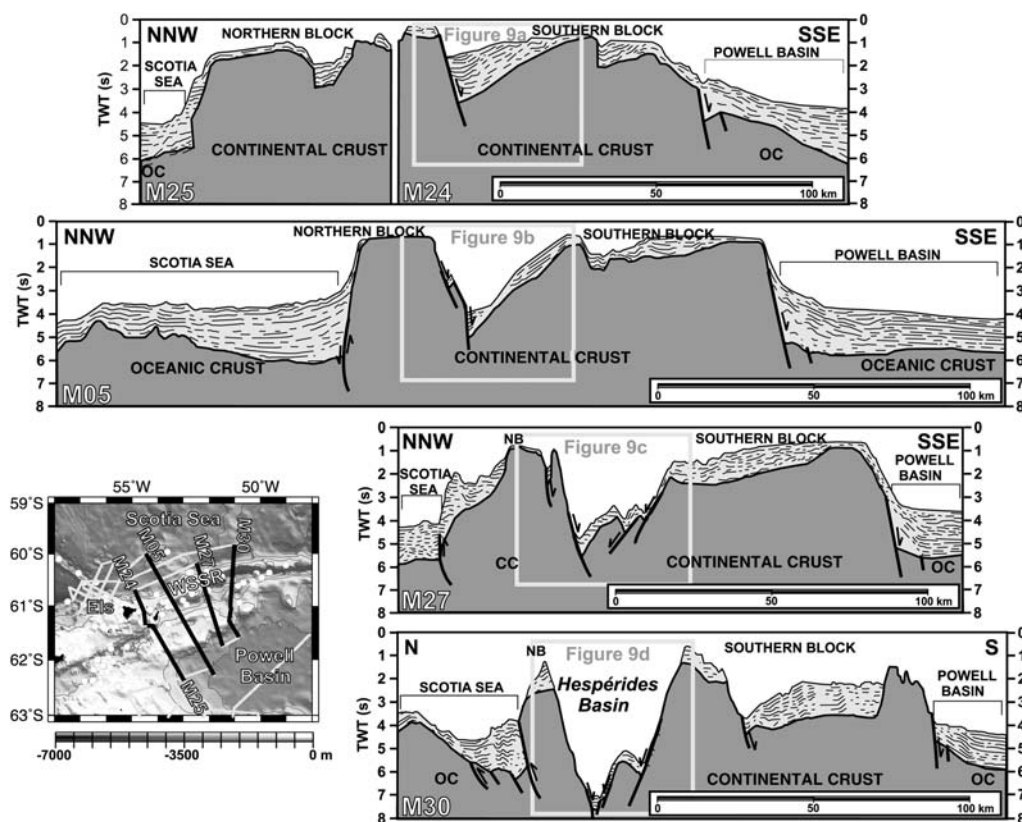


Fig. 8. M25, M24, M05, M27 and M30 multi-channel seismic profiles and interpretation. Location in Figure 3. OC, oceanic crust; CC, continental crust; and NB, Northern Block. The position of SMC details in Figure 9 are indicated. The inset bathymetric map includes the locations of SMC profiles.

et al. 2005), although chron C10 (28.7 Ma) has been recognized closest to WSSR (Lodolo *et al.* 1997; Geletti *et al.* 2005). The Terror Rise (Fig. 3), formed by thinned continental crust, represents a NNE–SSW-elongated elevation between 2000 m and 3500 m in depth separating the Ona and Protector basins. The Protector Basin (Fig. 3) is approximately 250 km wide and corresponds with an abyssal plain with water depths in the range of 3000 to 4000 m. Magnetic anomalies point to oceanic spreading between anomaly chron C5Dn (17.6 Ma) and C5ACn (14 Ma) (Galindo-Zaldívar *et al.* 2006).

The northern boundary of the WSSR continental crust is produced by a southward-dipping reverse fault, related to ancient subduction (Aldaya & Maldonado 1996; Lodolo *et al.* 1997); and locally, by an accretionary prism, covered by the most recent sediments (Fig. 8). Moreover, east of 52° W, there is evidence of recent compressive deformation and development of an east–west (Fig. 3). The reverse faults associated with this

boundary have approximately east–west to WNW–ESE strikes (Galindo-Zaldívar *et al.* 1996).

The seismicity and well-exposed fault scarps observed in MCS profiles (Figs 3 & 8) indicate that most of the active deformation occurs in the axial depression formed by several connected basins, crossing the ridge in a slightly oblique sense. This axial depression is characterized by deep basins (e.g. the Hesperides Basin, among others) locally over 5500 m in depth and associated with high seismicity (Figs 3, 8 & 9). The depression is related to fault surfaces dipping southward, with great scarps that in the bathymetry show WSW–ENE and SW–NE strikes. The SW internal basins are characterized by northward tilted blocks and a wedge-shaped infilling typical of half-grabens. The sediments onlap the southern margins, where progressive unconformities develop, whereas they are affected by normal faults on the northern margins (profiles M24–25 and M05; Figs 8–10). Fault geometry and earthquake focal mechanisms indicate an active sinistral transtensive regime for the fault

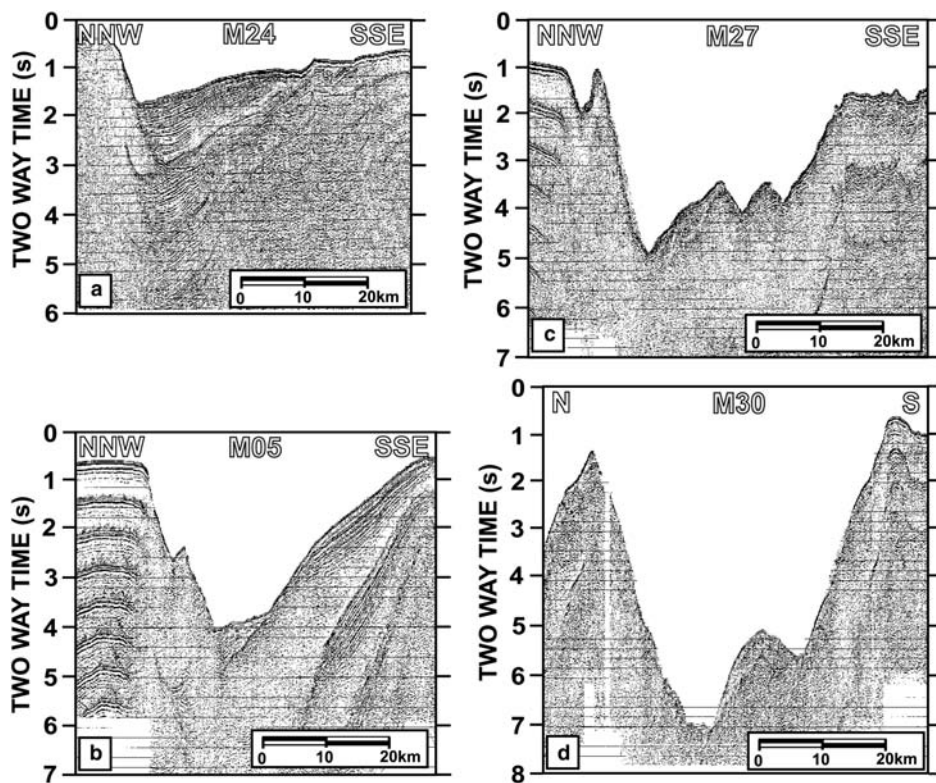


Fig. 9. Enlarged view of M24 (a), M05 (b), M27 (c) and M30 (d), multi-channel seismic profiles showing the internal basins and Hespérides Basin inside the Western South Scotia Ridge. Location in Figure 8.

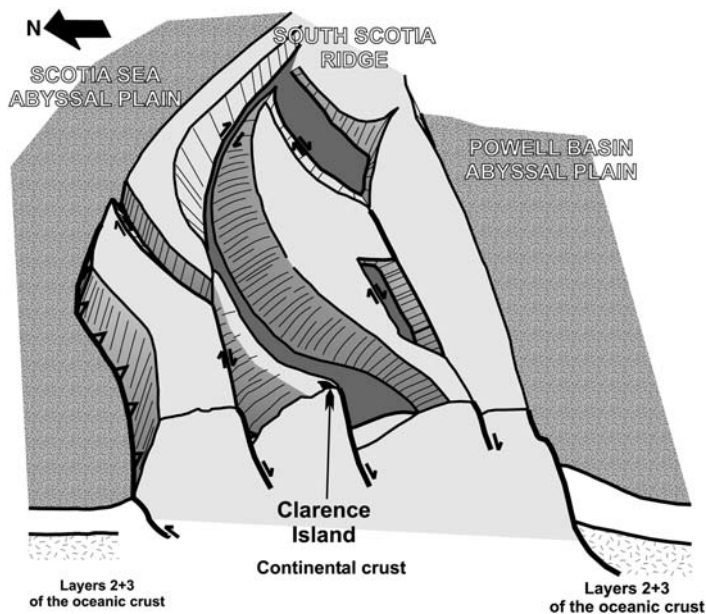


Fig. 10. Three-dimensional block model of the Western South Scotia Ridge.

system, although locally transpressive areas may develop in the eastern part of the ridge (Galindo-Zaldívar *et al.* 1996).

The southern crustal block of the Western South Scotia Ridge is connected with the oceanic crust of the Powell Basin, bounded by an inactive transform fault that extends eastward towards the South Orkney microcontinent. This transform fault was active during the opening of the Powell Basin (King *et al.* 1997; Figs 8 & 10).

The stress field, deduced from the P- and T-axes of earthquake focal mechanisms in the South Scotia Ridge, reveals a steeply inclined maximum compression and subhorizontal extension with a NW–SE trend, in agreement with the transtensive sinistral regime of the deformed zone, i.e. roughly east–west oriented. The axial depression of the WSSR extends to the Bransfield Strait rift and allows the definition of the South Shetland Block as a continental block that lies at the boundary between the Antarctic plate, the Scotia plate and the former Phoenix plate (Aldaya & Maldonado 1996).

Discussion and conclusions

The South Scotia Ridge traces the location of the Scotia–Antarctic plate boundary. A regional NE–SW compression and NW–SE extension in the Scotia Arc is evidenced by the analysis of earthquake focal mechanisms (Pelayo & Wiens 1989; Galindo-Zaldívar *et al.* 1996; Giner-Robles *et al.* 2003; Thomas *et al.* 2003). Furthermore, the entire South Scotia Ridge has been described as a sinistral transcurrent zone in accordance with the east–west orientation and the Scotia Arc stress regime. The tectonic models derived from such research predict the development of variable geological structures, including NW–SE extension in the WSSR and the easternmost SSR (Discovery Bank), and some segments of purely transcurrent

sinistral faults at the NNE border of the SOM. Giner-Robles *et al.* (2003) suggest a transtensive regime located NNW of these islands. The fault sets that are in agreement with this general regime are N45°E-oriented normal faults, N135°E reverse faults, and strike-slip faults of intermediate orientations, according to their theoretical slip models.

The tectonic elements located near the plate boundary are heterogeneous in nature and constitute a very complex structure (Table 1). The rocks cropping out on the Antarctic Peninsula, South Shetland and South Orkney Islands (BAS 1985); the scarce direct data from ODP dredges and cores (Barker *et al.* 1984; Barber *et al.* 1991; Mao & Mohr 1995) and the geophysical data (gravity, magnetic, MCS) underline the continental nature of the submerged banks. While the Scotia plate is mainly formed by oceanic crust with submerged continental banks, some continental blocks are highly stretched, like the Terror Rise. In the Antarctic plate there are dominantly continental crustal elements corresponding to the NE promontory of the Antarctic Peninsula and the SOM. Other areas of oceanic crust (Powell Basin and Jane Basin) constitute small oceanic basins older than 14 Ma (Rodríguez-Fernández *et al.* 1997; Bohoyo *et al.* 2002; Bohoyo 2004).

This heterogeneous distribution of tectonic elements gives way to different rheological behaviour on the part of the continental, oceanic and intermediate blocks when subjected to an external stress field. The strength profiles proposed by Ranalli & Murphy (1987) for continental extensional and oceanic regions, indicate that the stress necessary to produce brittle deformation of continental lithosphere is lower than for oceanic lithosphere. The comparatively low resistance to deformation of continental crust favours the regional concentration of plate-boundary-related tectonic deformation within continental fragments

Table 1. Main submerged banks around the Southern Scotia Arc and published sources that document their continental nature

Submerged bank	Main references
Western South Scotia Ridge (WSSR)	Garrett <i>et al.</i> (1987); Acosta & Uchupi (1996); Galindo-Zaldívar <i>et al.</i> (1996); Suriñach <i>et al.</i> (1997); Maldonado <i>et al.</i> (1998)
South Orkney microcontinent (SOM)	Garrett <i>et al.</i> (1987); Barker & King (1988); Bohoyo <i>et al.</i> (2002); Bohoyo (2004)
Terror Rise and Pirie Bank (TR & PB)	Bohoyo (2004); Galindo-Zaldívar <i>et al.</i> (2006)
Bruce Bank (BB)	Mao & Mohr (1995); SCAN2004 cruise preliminary report
Discovery Bank (DB)	Garrett <i>et al.</i> (1987); Galindo-Zaldívar <i>et al.</i> (2002); Vuan <i>et al.</i> (2005)

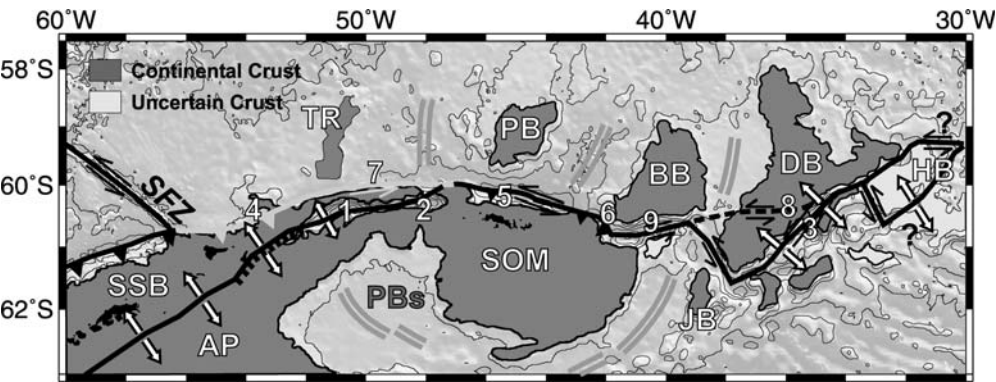


Fig. 11. Geological sketch of the main tectonic structures and the crustal nature of the submerged banks. Numbers referring to main tectonic features are shown in Table 2. Active structures shown as black lines, and inactive structures as grey lines. AP, Antarctic Peninsula; BB, Bruce Bank; DB, Discovery Bank; HB, Herdman Bank; JB, Jane Bank; PB, Pirie Bank; PBs, Powell Basin; SFZ, Shackleton fracture zone; SOM, South Orkney microcontinent; SSB, South Shetland Block; TR, Terror Rise.

(Galindo-Zaldívar *et al.* 2002). The current sinistral transcurrent boundary became active after the opening of all the small basins in the southern Scotia Sea (Galindo-Zaldívar *et al.* 2006).

In the eastern part of the SSR, the seismicity and the active faults are clearly concentrated in

Discovery Bank and the Intermediate Domain. Although most of the active faults are associated with the development of the Deep Basin, there is also tectonic activity inside the Discovery Bank, producing incipient E–W scarps and epicentre alignments (Figs 4–5, 7 & 11).

Table 2. Main tectonic structures associated with the present Scotia–Antarctic plate boundary

Extensional regime: pull-apart basin and normal faults (location numbers shown in Fig. 11)	Location	Main references
1	Western South Scotia Ridge basins	Galindo-Zaldívar <i>et al.</i> (1996); this study
2	Hespérides basin in WSSR	Acosta & Uchupi (1996); Galindo-Zaldívar <i>et al.</i> (1996); this study
3	Deep basin on Discovery Bank	Galindo-Zaldívar <i>et al.</i> (2002); this study
Compressive regime: subduction, thrusting and folding (ID in map)		
4	WSSR	Galindo-Zaldívar <i>et al.</i> (1996); Lodolo <i>et al.</i> (1997); this study
5	Northern SOM	Kavoun & Vinnikovskaya (1994); Maldonado <i>et al.</i> (1998); Bussetti <i>et al.</i> (2000)
6	NE SOM	Leitchenkov pers. comm.
Pure strike-slip regime: transcurrent faults		
7	WSSR	Galindo-Zaldívar <i>et al.</i> (1996); this study
8	Discovery Bank	Galindo-Zaldívar <i>et al.</i> (2002); this study
9	NE SOM	This study

The active structures continue westward along the northern border of the SOM, where a present-day active oceanic–continental boundary and related trench and compressive structures are recognized (Maldonado *et al.* 1998; Busetti *et al.* 2000) (Fig. 11). Westward, in the WSSR, the contact between the oceanic crust of the Scotia Sea and the northern continental block of WSSR is a reverse fault. However, this part of the oceanic–continental boundary appears inactive, and no well-developed trench is present (Fig. 11). The inactivity along the boundary, and the presence of oceanic crust in the Powell Basin to the south would have favoured the localization of deformation within the WSSR continental blocks.

The distribution of continental crustal blocks between regions of oceanic crust gives rise to a different trend for each sector of the Scotia–Antarctic plate boundary, which is in turn responsible for the development of transtensive, pure strike-slip, and transpressive structures (Table 2). Whereas E–W oriented faults are generally subvertical and accommodate a purely sinistral regime, where the faults are oriented in a more northeasterly direction, they become progressively more transtensional, and conjugate fault sets dipping NW and SE accommodate development of deep basins within the continental blocks. This structural situation is observed both in the eastern part of the SSR, where the Deep Basin develops south of the Discovery Bank, and in the western sector, where an elongated deep basin (Hespérides Basin and other connected basins) divides the WSSR into its northern and southern ridges (Figs 8–11).

These basins are asymmetrical in the WSSR, featuring sedimentary wedge infill above hanging walls that tilt to the north. The Deep Basin located south of the Discovery Bank is more symmetrical. This contrasting behaviour may be due to the geological nature of the deformed blocks, which are continental in the WSSR and include previous structural heterogeneities, but one of an intermediate crustal nature in the Deep Basin of southern Discovery Bank.

The available present-day data do not allow for a more detailed study of these sectors. Interpretations of free-air gravity anomalies for the region (Livermore *et al.* 1994; Sandwell & Smith 1997; Fig. 2) suggest that the deep basins of the WSSR develop mainly as a consequence of releasing bends of fault zones; while in the Deep Basin of Discovery Bank we may invoke a pull-apart basin model confined, at least to the SW, by a transform fault (Fig. 11). We conclude that the behaviour of deep basins developing inside continental blocks is similar: they attain depths of over 5000 m, surpassing the depths of the surrounding oceanic crust, and show no evidence of oceanic spreading.

The evolution of these basins, formed in regional transcurrent tectonic regimes, can be clearly differentiated from the classic development of passive margins during continental stretching.

The Scotia–Antarctic plate boundary, along the southern boundary of the Scotia Arc, therefore constitutes an exceptional example of complex interplate deformation driven by regional tectonic stresses and influenced in a complex way by the different rheological behaviour of oceanic and continental crust.

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