Development of deep extensional basins associated with the sinistral transcurrent fault zone of the Scotia-Antarctic plate boundary

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Summary The Scotia-Antarctic plate boundary is a very complex tectonic zone because both oceanic and continental elements are involved. The main active structures that we observed in the area include releasing and restraining bends, with related deep transtensional and probable pull-apart basins. The western sector of the plate boundary crosses fragmented continental crust, the Western South Scotia Ridge, with wide development of pull-apart basins and releasing bends deeper than -5000m, filled by asymmetric 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. In 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 involved crusts, with the bulk concentration of deformation within the rheologically weaker continental blocks.

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Introduction

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 the dispersal of continental blocks and the joining of the Atlantic and Pacific oceans (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 E–W 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 arc have different characters. While the eastern boundary is controlled by the present subduction of the South America Plate below the Sandwich Plate (Larter et al., 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 internal basins (Maldonado et al., 1998; Fig.1). The plate boundaries around the Scotia Arc are outlined by the distribution of earthquake epicentres. The analysis of earthquake focal mechanisms points to a regional stress regime characterized by a NE–SW compressive trend, with local stress perturbations (Pelayo & Wiens, 1989; Galindo-Zaldívar et al., 1996 and Thomas et al., 2003).

Data and methodology

Over the last 15 years, a number of cruises by the Spanish Vessel B/O Hespérides have made it possible to acquire an important geophysical dataset in the southern branch of the Scotia Arc. This dataset includes multichannel seismic (MCS), gravity, magnetic and swath bathymetry data recorded along profiles that are both orthogonal and parallel to the Scotia–Antarctic plate boundary. Most of the data used in this work stems from the HESANT92-93 and SCAN97 cruises.

The Scotia-Antarctic plate boundary along the South Scotia Ridge

The South Scotia Ridge (SSR) traces the location of the Scotia–Antarctic plate boundary. Regional NE–SW compression and NW–SE extension in the Scotia Arc is demonstrated by the analysis of earthquake focal mechanisms using different approaches (Pelayo & Wiens, 1989; Galindo-Zaldivar et al., 1996 and Thomas et al., 2003). Furthermore, the entire SSR has been described as a sinistral transcurrent zone, consistent with the E–W 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 west SSR and in the easternmost SSR (Discovery Bank), and some segments of purely transcurrent sinistral faults at the NNE border of the South Orkney Microcontinent (SOM).

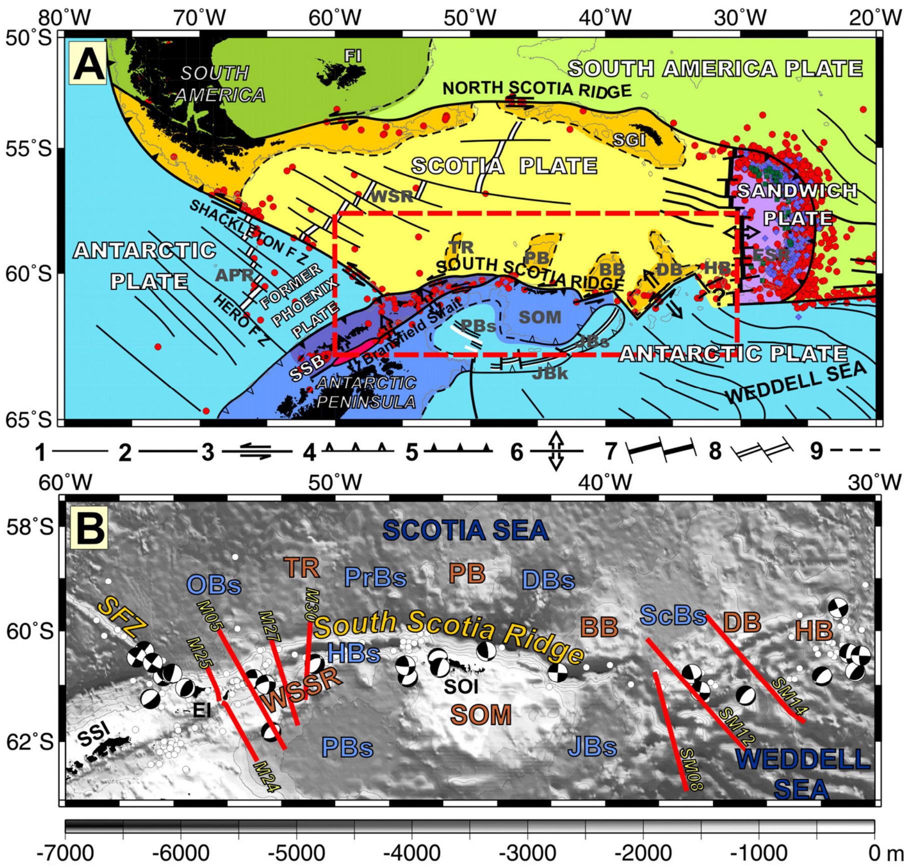

Figure 1. A) Geological setting of the study area within of the Scotia Arc (Modified from Galindo-Zaldívar et al. 2002). 1, inactive fracture zone. 2, active fracture zone. 3, transform or transcurrent fault. 4, inactive subduction zone or reverse fault. 5, active subduction zone. 6, rift. 7, active 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. Red circles (shallow < 50 km), blue diamonds (intermediate 50-150 km) and green squares (deep > 150 km) indicate earthquakes epicenters. Study area (B) in red box.
B) Bathymetry map of the studied area including location of HESANT92-93 and SCAN97 MCS lines. Earthquake focal mechanisms from CMT. DBs, Dove Basin. EI, Elephant island. OBs, Ona Basin. PrBs, Protector Basin. ScBs, Scan Basin. SFZ, Shackleton fracture zone. SOI, South Orkney Islands. SSI, South Shetland Islands. WSSR, Western South Scotia Ridge.

The tectonic elements adjacent to the plate boundary are heterogeneous in nature and constitute a very complex structure. The rocks cropping out in the Antarctic Peninsula, South Shetland and South Orkney Islands, the scarce direct data from dredges and ODP cores, and the geophysical data (gravity, magnetic, MCS) underline the continental nature of the submerged banks. While the Scotia Plate is mainly composed of oceanic crust with submerged continental banks, some continental blocks are highly stretched like the Terror Rise. On the Antarctic Plate there are dominantly continental crustal elements corresponding to the NE prolongation 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).

This heterogeneous distribution of tectonic elements gives way to different rheological behaviour on the part of the continental, oceanic and intermediate nature 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 clearly lower than for oceanic lithosphere. The

comparatively low resistance to deformation of continental crust favours the regional concentration of plate boundary-related tectonic deformations in crust of this type (Galindo-Zaldivar et al., 2002). The current sinistral transcurrent boundary became active after the opening of all the small basins in the southern Scotia Sea (Galindo-Zaldivar 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, a tectonic domain with intermediate features, both in position and nature, between continental and oceanic crusts. Although most of the currently active faults are associated with the development of the Deep Basin, there is also tectonic activity within the Discovery Bank, producing incipient E–W scarps and earthquake epicentre alignments (Fig. 2).

The active structures continue westwards 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). To the west, in the west SSR, the contact between the oceanic crust of the Scotia Sea and the northern continental block of the west SSR is a reverse fault. However, this part of the oceanic–continental boundary appears to be currently inactive, and there is no well developed trench present. The inactivity of this boundary and the presence of oceanic crust from the Powell Basin to the south would have favoured the concentration of deformation within the west SSR continental blocks.

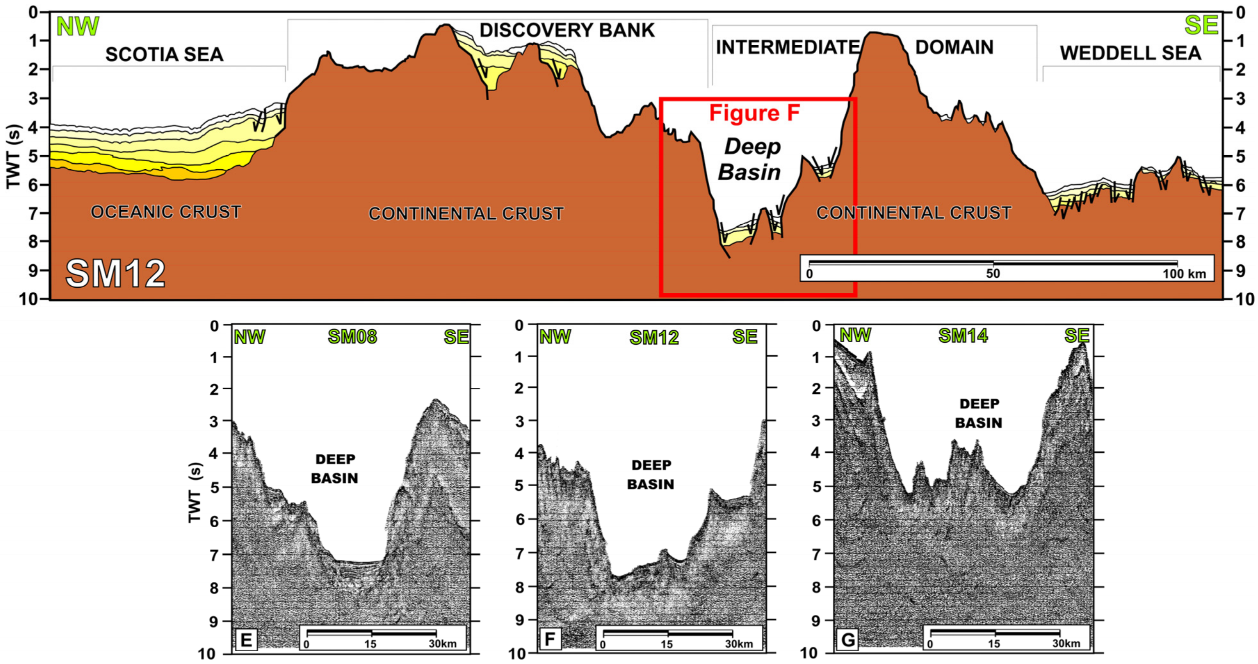

Figure 2. Interpretation of the multichannel seismic profile SM12 (SCAN97 cruise). Location of MCS profiles in Figure 1B.

The distribution of continental crustal blocks in between areas of oceanic crust gives rise to variable trends for each sector of the Scotia–Antarctic plate boundary; in turn, these are responsible for the development of transtensional, pure strike–slip and transpressional structures. Whereas E–W oriented faults only show sinistral motion and generally are sub-vertical, when the faults are oriented toward NE–SW they become progressively transtensional, with two conjugate fault sets dipping to the NW and SE, allowing the development of deep basins within the continental blocks. This setting 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 west SSR into its northern and southern ridges (Fig. 3).

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

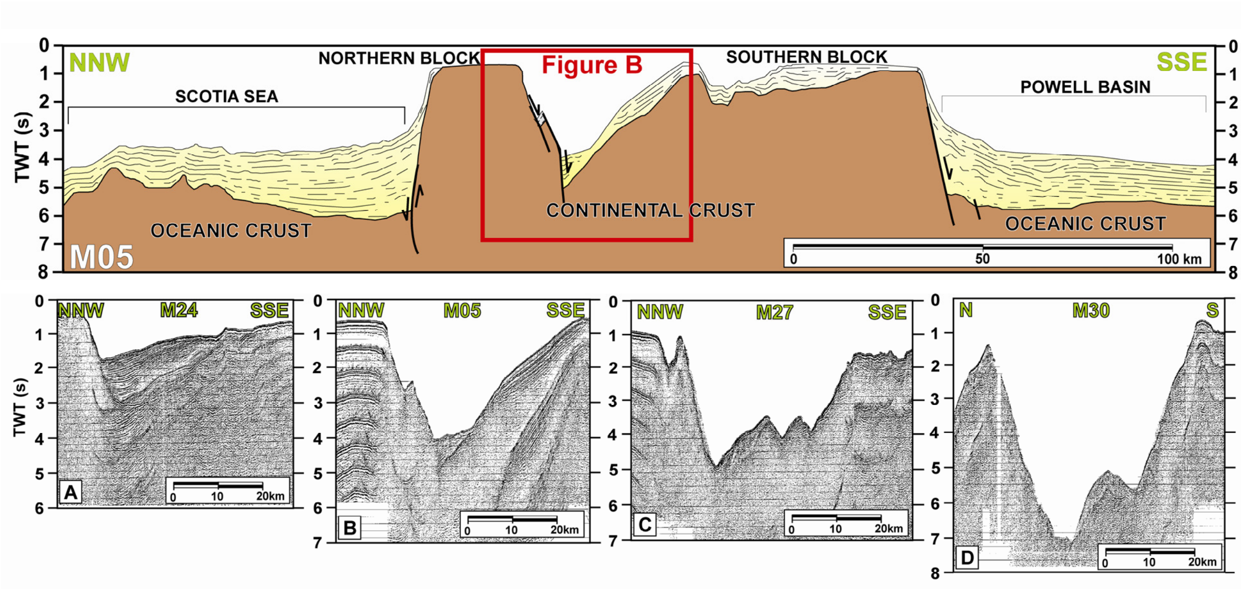

Figure 3. Interpretation of the multichannel seismic profile M05 (HESANT92-93 cruise). Location of MCS profiles in Figure 1B.

Conclusions

The available data do not allow for a more detailed study of the Scotia–Antarctic plate boundary. Interpretations of free-air gravity anomalies for the region (Livermore et al., 1994) suggest that the deep basins of the west SSR developed mainly as a consequence of fault zone releasing bends. However, to the east in the Deep Basin of Discovery Bank, we interpret a pull-apart basin bounded, at least to the SW, by a transform fault. We conclude that the behaviour of deep basins developing within continental blocks is similar: they attain depths of over 5000 m, which is greater than the depth of oceanic crust in the region, and they show no evidence of oceanic spreading. The evolution of these basins, formed in a regional transcurrent tectonic regime, can be clearly differentiated from the classic development of passive margins during continental stretching.

The Scotia–Antarctic plate boundary, at the southern branch of the Scotia Arc, therefore constitutes an exceptional example of deformation that is driven both by regional stresses and by the contrasting rheological behaviours of oceanic and continental crust during a complex tectonic evolution.

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