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The Scotia–Antarctica plate boundary from 35°W to 45°W

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ABSTRACT

A compilation of available multichannel seismic profiles acquired along the southern margin of the Scotia Sea east of the South Orkney microcontinent has allowed identifying and mapping the main morphological and structural features of the central segment of the Scotia–Antarctica plate boundary. This margin is composed by several bathymetric highs of variable size and uncertain crustal nature, separated by deep troughs and restricted oceanic basins. Some of these troughs represent pull-apart basins. Three main segments oriented WNW–ESE (the western sector), ENE–WSW (the central sector, here named Bruce Deep), and NE–SW (the eastern sector), have been described. These segments are separated by NNW–SSE-trending release zones, disposed in an *en-echelon* geometry, which represent mostly strike–slip faults. The western segment corresponds to the northern margin of the South Orkney microcontinent, where a subduction zone seems to be present, even if its present-day activity is unclear. The segment further to the east corresponds to an ENE-oriented basin (Bruce Deep), which separates the Bruce Bank from the eastern promontory of the South Orkney continental platform. To the south of the Bruce Deep, a wide deformation zone with N-verging folds and thrusts (here named Jane Thrust Belt), has been identified from seismic data. The eastern segment of the plate boundary is structurally the less constrained, and may be composed by a series of tectonic lineaments of different lengths. From the Bruce Bank to the east, focal mechanisms maintain a prevalent left-lateral strike–slip motion combined with an extensional component. In this sector, earthquakes are located in a 150 km wide area and on a local scale are difficult to follow unambiguously at the plate boundary. Lithologic analyses on dredged material recovered along a flank of one of the morphological relieves present south of the Discovery Bank to 35°W (here collectively named Irizar Highs), yielded a dominant granitic composition. A similar composition characterizes the rocks collected in the southern flank of the south-easternmost Jane Bank. This suggests a continental crust nature for these bathymetric highs, now dispersed along this sector of the Scotia–Antarctica plate boundary. We propose here a tectonic evolution for this margin, dominated since the Early Miocene by the northward subduction of the Weddell Sea oceanic crust. The development of a dextral, *en-echelon* transform fault system facilitated the process of fragmentation and dispersion of the crustal blocks, dismembered the subduction zone, and possibly inverted the direction of convergence: Therefore, the Scotia plate would subduct beneath the Antarctic plate, in the western sector, and Weddell Sea would subduct beneath Scotia plate, in the eastern sector. Finally, the activation of left-lateral transtensional strike–slip lineaments generated narrow pull-apart basins in the fore-arc sectors of the convergent zones.

1. Introduction

The evolution of the Scotia Sea (Fig. 1), initiated in the Oligocene, has determined the formation and assemblage of a large number of oceanic, transitional, and continental elements. The blocks that were once part of the continental link between the southern South America and the Antarctic Peninsula, and now distributed along the periphery of the Scotia Sea, have been severely stretched and deformed during the processes responsible for the Scotia Sea formation (Barker et al., 1991; Barker, 2001, and references therein). This was particularly relevant along the southern margin of the nascent Scotia Sea, where intense strike–slip tectonism was active since its early development (Lodolo et al., 2006). This margin (Fig. 2) is presently composed by a series of relatively shallow and thinned blocks (South Orkney microcontinent, Terror Rise, Pirie Bank, Bruce Bank, Discovery Bank and Herdman Bank) and small basins (Protector, Dove and Scan basins) developed in stretched continental crust, which together constitute the South Scotia Ridge (Galindo-Zaldívar et al., 2002; Eagles et al., 2005; Eagles et al., 2006; Galindo-Zaldívar et al., 2006; Bohoyo et al., 2007, among others). The southern boundary of the Scotia Sea became the left-lateral Scotia–Antarctica plate boundary since the early development of the oceanic plate (Pelayo and Wiens, 1989). East of the Discovery Bank, the plate boundary is structurally much less constrained because of the paucity of geophysical and geological data,

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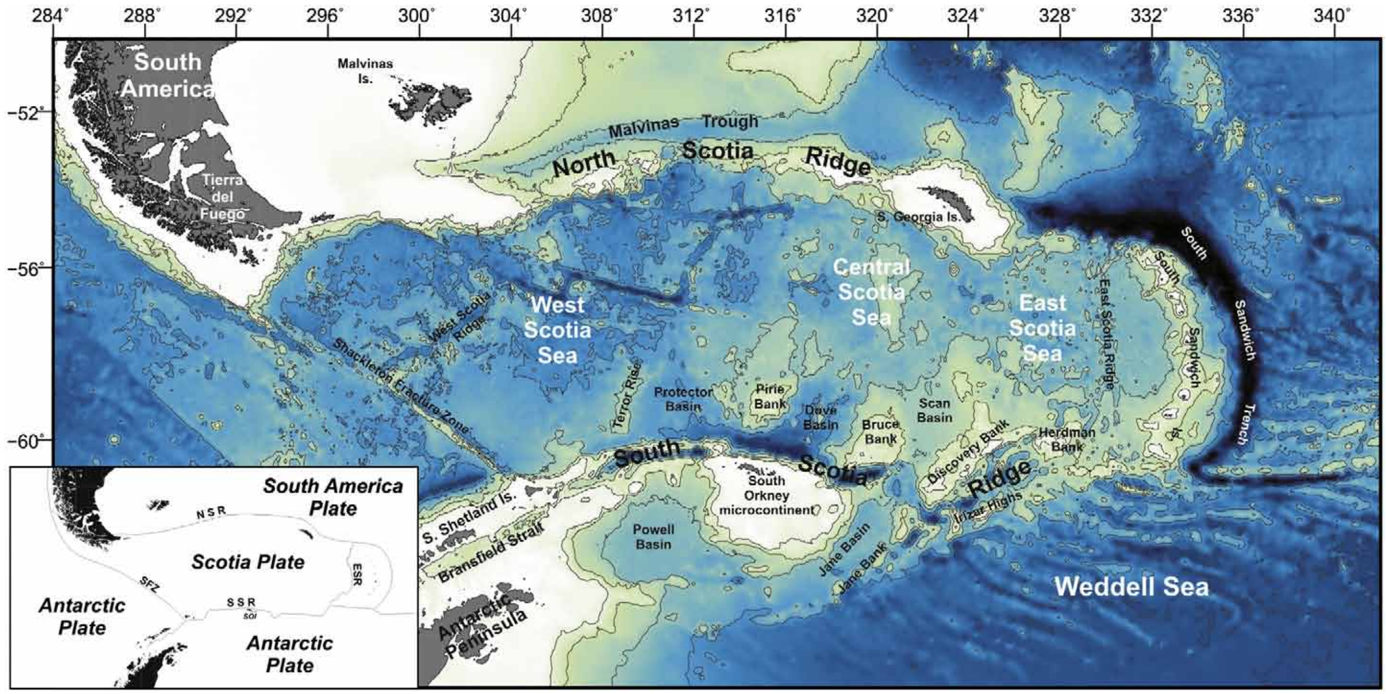

Fig. 1. Bathymetric contour map of the Scotia Sea (based on satellite-derived data of Smith and Sandwell, 1997). Inset shows present-day plate tectonic setting. Abbreviations are as follows: NSR, North Scotia Ridge; SSR, South Scotia Ridge; ESR, East Scotia Ridge; SOI, South Orkney Islands; SFZ, Shackleton Fracture Zone.

and its inherent complexity, as seen from satellite-derived bathymetric maps (Smith and Sandwell, 1997).

We present here a reappraisal of all the available multichannel seismic profiles, combined with fault-plane solutions derived from seismic events, and recently-acquired lithologic information. These data are used to derive a general structural map of the South Scotia Ridge sector located east of the South Orkney microcontinent, and analyze the complex style of deformation of the southern margin of the Scotia Sea, which was generated by the combination and superposition of both compressional and transcurrent tectonic events.

2. Structural setting of the southern margin of the Scotia Sea

The process of fragmentation and successive dispersion of the continental bridge between the southern South America and the Antarctic Peninsula, occurred during Oligocene and Miocene times,

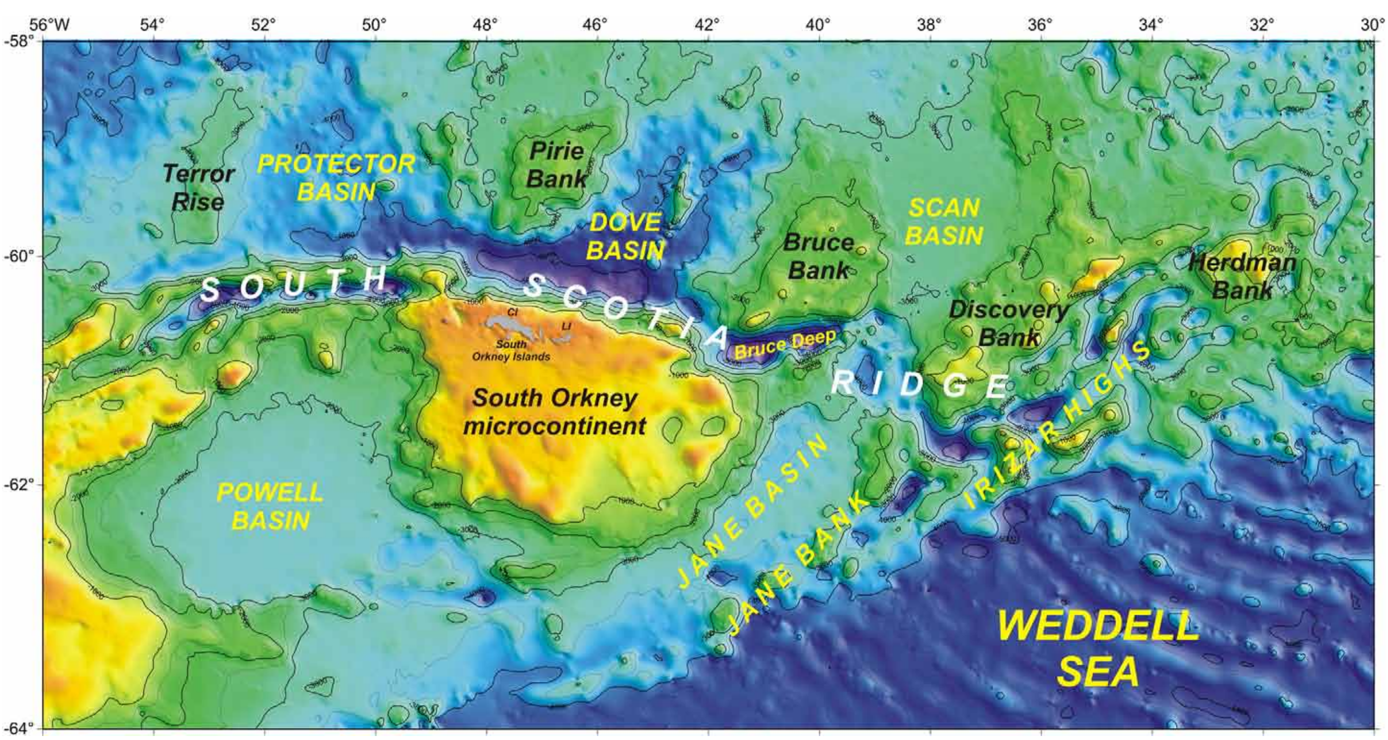

Fig. 2. General physiographic map of the southern margin of the Scotia Sea, with the principal geological provinces discussed in the text. Bathymetric contours from satellite-derived data. Abbreviations are as follows: CI, Coronation Island; LI, Laurie Island (Smith and Sandwell, 1997).

initiated with the opening of the Drake Passage by oceanic spreading at the now extinct west Scotia Ridge (Livermore et al., 2005; Geletti et al., 2005; Eagles et al., 2005; Lodolo et al., 2006). Significant wrench tectonism and associated deformation may have however occurred prior to the Early Tertiary, with development of important, broadly E–W trending transcurrent lineaments, particularly developed in the southernmost South America and Tierra del Fuego region (Cunningham, 1993; Cunningham et al., 1995; Lodolo et al., 2003). The former continental barrier now constitutes the South Scotia Ridge, and separates the oceanic crust of the Scotia and Antarctic plates.

The structural setting of the westernmost part of the South Scotia Ridge is partially known from multichannel seismic profiles published by Galindo-Zaldívar et al. (1996), Acosta and Uchupi (1996), Coren et al. (1997) and Lodolo et al. (2006). To the east of the South Orkney microcontinent, only few seismic profiles have been acquired, some of them published (Maldonado et al., 1998; Galindo-Zaldívar et al., 2002; Vuan et al., 2005). The most complete archive of seismic data for this sector of the Antarctic region is the Antarctic Seismic Data Library System (SDLS), available at the web site: http://snap.ogs.trieste.it/SDLS/. It works under the auspices of *Scientific Committee on Antarctic Research (SCAR)* to provide open access to all multichannel seismic reflection data collected south of 60°S. The following general overview of the structure of the southern margin of the Scotia Sea is derived from published data, and analysis of profiles available from the SDLS (Fig. 3).

To the north of the South Scotia Ridge, three small, deep (3500–4000 m in water depths) basins, are present. From west to the east, these are: the Protector Basin, Dove Basin and Scan Basin. These basins lie between four shallow topographic highs. The westernmost of these highs, Terror Rise, is a crustal block where the sea-floor shoals to about 3000 m from surrounding depths of about 3500 m. The approximately 200 km wide Protector Basin separates Terror Rise from the shallow (about 2000 m in water depths) Pirie Bank, a morphologically complex high bounded by major normal faults. In the southern sector, its width is about 250 km and it narrows northwards until it disappears into the abyssal zones of the Scotia Sea. Dove Basin, which is also about 200 km wide, lies to the east of Pirie Bank and separates it from the shallow (about 2000 m in water depths) Bruce Bank. Its north-western margin is gently faulted and gradually slopes to the Dove Basin, whereas the south-western and southern margins present very steep slopes. A narrow and deep trough (6000 m water depth) is present at the base of the margin. Scan Basin is the easternmost depocenter, located between the Bruce Bank and Discovery Bank.

The crustal nature of the Terror Rise, Pirie Bank, and Bruce Bank are not known with certainty. Seismic reflection profiles over all three highs show a basement reflector that lacks the numerous diffractions characteristic of the basaltic surface of oceanic crust. Dredge hauls have returned rocks of continental affinity from Pirie Bank (Udintsev et al., 1999), although it is not clear whether or not these all represent glacial drop stones, while a piston core taken from the southern edge of Bruce Bank yielded evidence of shallower paleo-depths and a nearby terrestrial source in Paleogene and Cretaceous times (Mao and Mohr, 1995). These highs exhibit a high amplitude positive magnetic anomaly, which gridded magnetic data (Eagles et al., 2005) shows in each case to have an N–S width of about 100 km. These anomalies

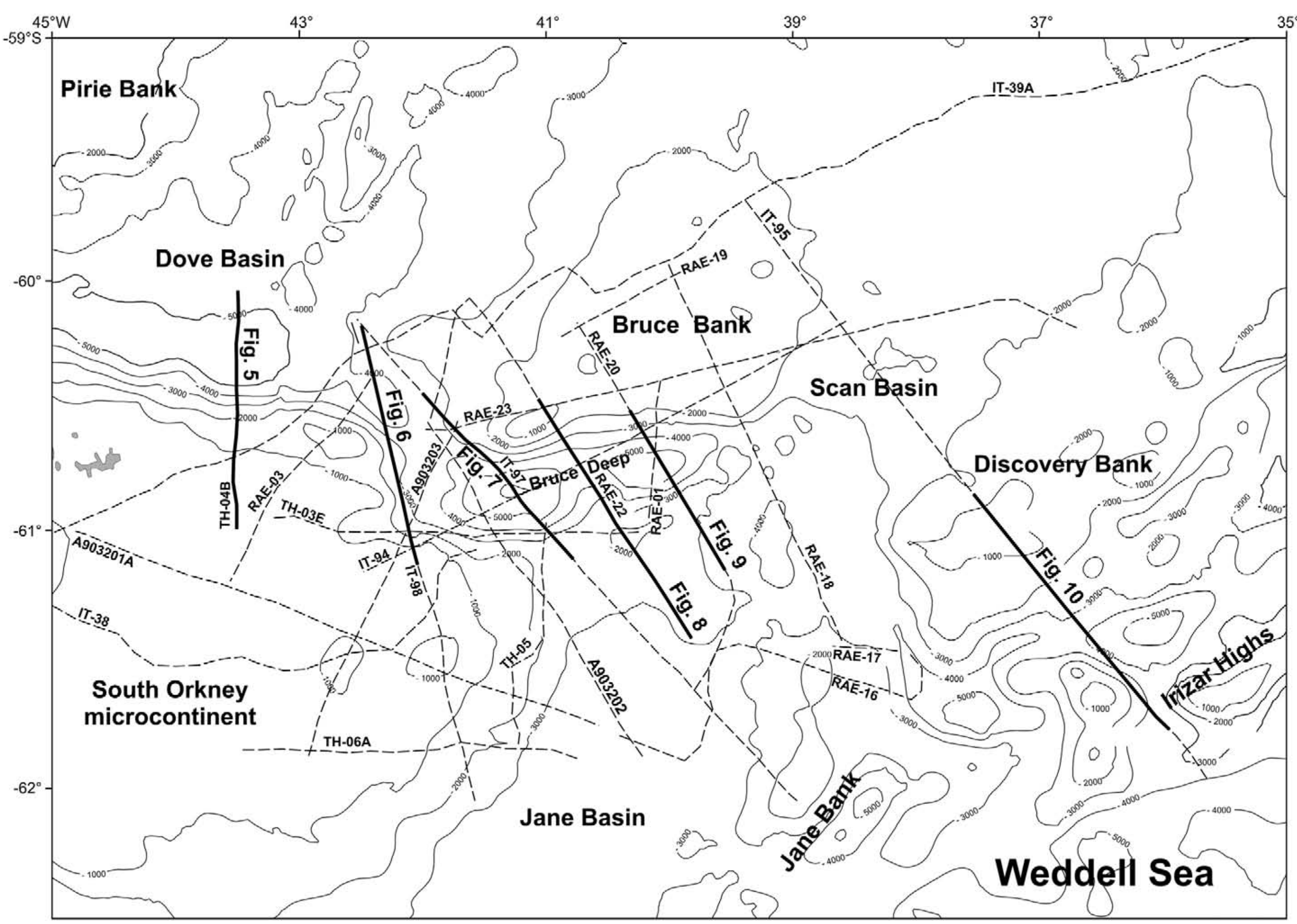

Fig. 3. Seismic lines location map. Thick segments indicate the corresponding figures presented. Bathymetric contours every 1000 m.

would have formed a continuous belt before the opening of the intervening basins. A reconstruction of the west Scotia Sea (Eagles et al., 2005) juxtaposes this belt with a magnetic anomaly of similar amplitude and width in and offshore of Tierra del Fuego. Terror Rise, Pirie Bank, Bruce Bank, and possibly south-western Discovery Bank, is therefore likely to be extensions of continental Tierra del Fuego that have been distributed across the southern Scotia Sea during its opening (Eagles et al., 2005; Lodolo et al., 2006).

The South Orkney microcontinent represents the largest (70,000 km^2) continental fragment of the southern part of the Scotia Sea. The emerged part of the platform (South Orkney Islands) is formed by low-grade metamorphic rocks, Upper Paleozoic–Lower Mesozoic metasedimentary and metavolcanic rocks, overlain by Upper Jurassic or Lower Cretaceous and Tertiary strata. They are interpreted to represent a subduction complex that was accreted along the South America and Antarctic Peninsula active margins of Gondwana during the Early Mesozoic (Trouw et al., 1997b).

The northern margin of the South Orkney microcontinent presents a curved shape. In its western part, an accretionary prism is probably present at the base of the slope (Kavoun and Vinnikovskaya, 1994; Maldonado et al., 1998). Evidence is mainly given by the smooth step morphology and abrupt change in the seismic facies occurring at the outer deformation front and continent-ward dipping reflectors (Busetti et al., 2000). Toward the east, the convergence appears less evident, producing mainly compressional structures with folds and reverse faults. The convergence seems to terminate at the north-eastern corner of the South Orkney microcontinent. A deep trough up to 6000 m deep separates the South Orkney microcontinent from the Bruce Bank, suggesting the interpretation that it is possibly a shifted continuation of the South Orkney trough, from which it is separated by a shoulder of about 3000 m in depth (Busetti et al., 2000).

Along the south margin of the South Orkney microcontinent is located the Jane Bank (also known as Jane Arc)–Jane Basin system. This system is the result of the subduction of the Weddell Sea oceanic crust below the South Orkney continental platform (Bohoyo et al., 2002). Jane Basin and Jane Bank were interpreted as a back-arc basin and an island arc, respectively (Barker et al., 1984). The inactivity of the Jane Bank and back-arc system is determined by the absence of seismicity in the region (Galindo-Zaldívar et al., 1996; Maldonado et al., 1998).

Discovery Bank is located to the east of the South Orkney microcontinent, and constitutes the largest fragment of the eastern part of the South Scotia Ridge. This bank is separated from the Bruce Bank to the N–W by the 65 km wide, 3000 m deep Scan Basin (Hernández-Molina et al., 2007). Available data suggest that this high is of a continental nature, as demonstrated by the shallow bathymetry, the seismic tomography velocities (Vuan et al., 2005), and seismic facies observed in multichannel seismic profiles (Galindo-Zaldívar et al., 2002; Vuan et al., 2005). Moreover, gravimetric models (Bohoyo et al., 2007) seem to confirm that the basement is of a continental or transitional nature, with a very shallow mantle. Discovery Bank is constituted by two distinct morphological highs, separated by a steep,

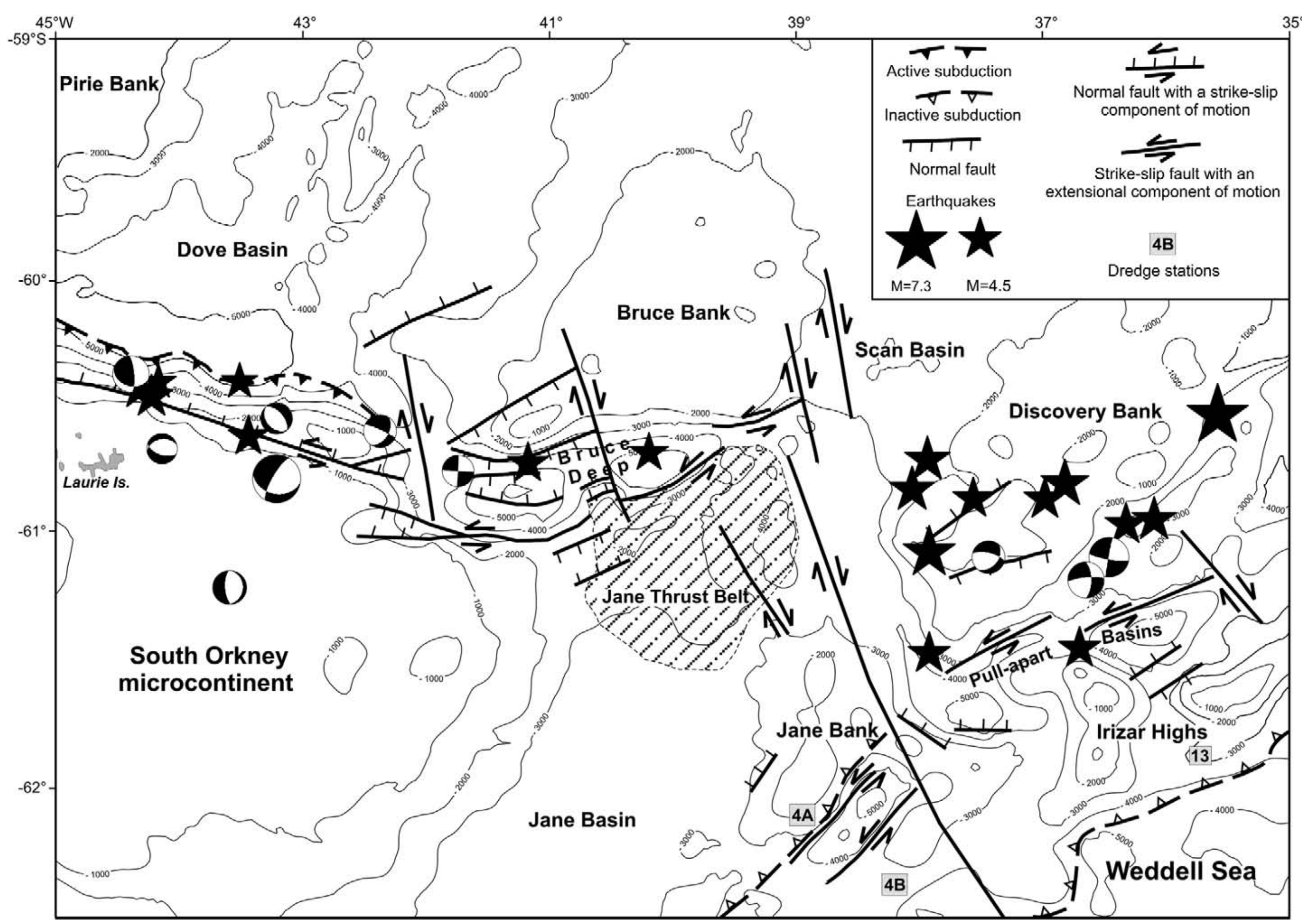

Fig. 4. Structural map and earthquake data of the Scotia–Antarctica plate boundary along the south Scotia Sea margin. Seismic foci (1961–2006) are taken from Engdahl et al. (1998). Focal mechanisms from the Global Centroid Moment Tensor database, formerly known as the Harvard CMT catalog http://www.globalcmt.org/CMTsearch.html. Dredge locations are also shown.

symmetric trough. The shallower water depth reached by the rise is 490 m, comparable to the water depths of most of the South Orkney microcontinent. The north-western flank of the rise is gentler than the south-eastern flank, and appears down-faulted by some normal faults, in a manner similar to a rifted continental margin.

The province located between 38°W and 33°W, south of the Discovery Bank, is constituted by a series of relatively narrow and steep elevations. These structural elevations are here collectively named as Irizar Highs, after the Argentine main support vessel and ice-breaker *"Almirante Irízar"*, which performed several scientific cruises in the Argentine sector of Antarctica since 1980. The geometry and the morphological continuity along strike of these highs are only inferred from satellite-derived data (Smith and Sandwell, 1997) because the paucity of underway geophysical profiles available. Only two multichannel seismic profiles have been up to now acquired across this remote region (Bohoyo, 2004). Data show that the structural highs are significantly different each others in terms of width, length and slope morphology. They are elongated broadly SW–NE and appear to be structurally linked with the eastern part of the Jane Bank, where they constitute its morphological prolongation. Seismic data show the cross-sectional framework of two of these elevations, and image the main morphological features of their flanks, which are significantly steep and of varying complexity (Bohoyo, 2004). The sequence of deep troughs and narrow depressions

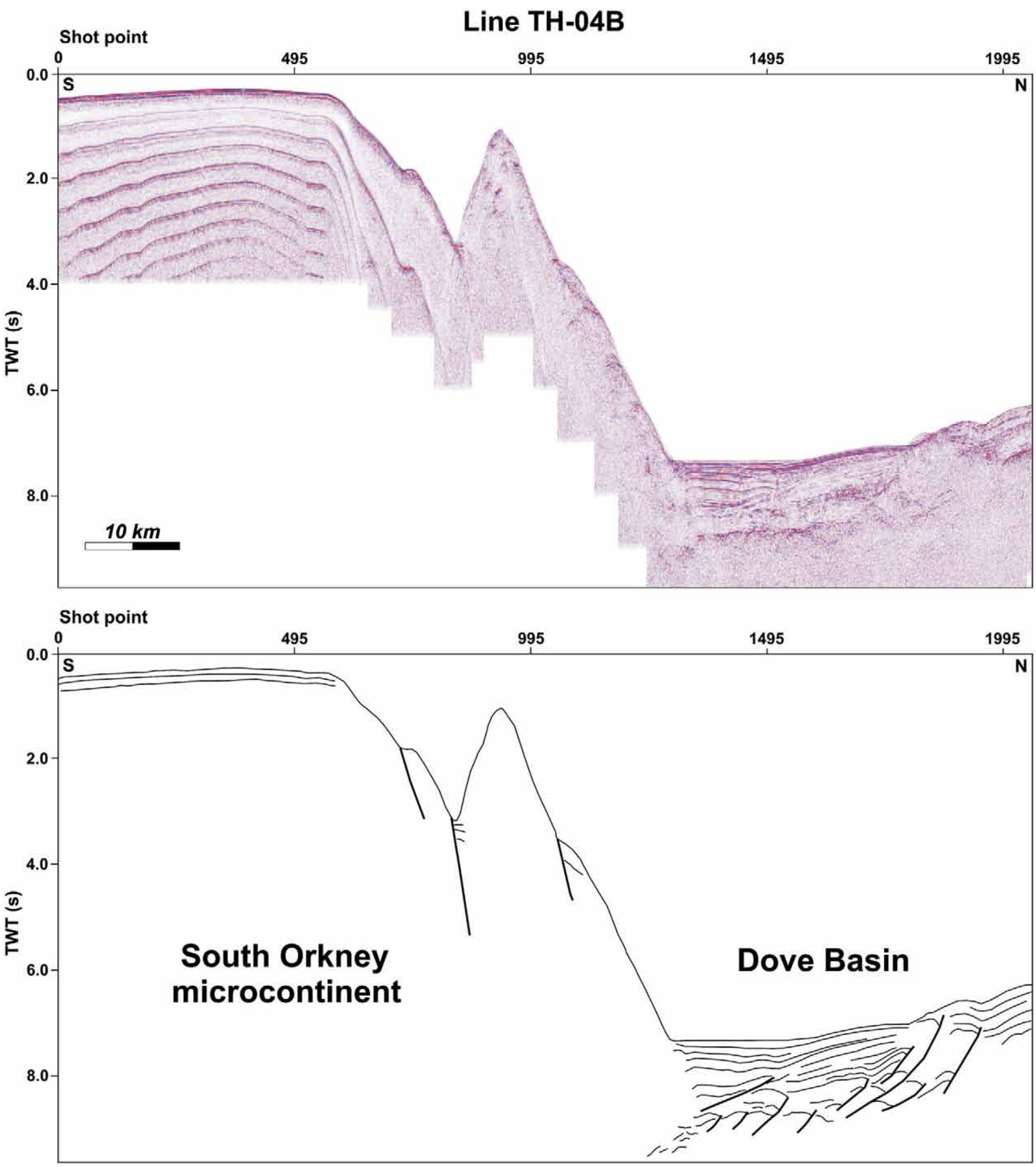

Fig. 5. Multichannel seismic profile TH-04B (top) and interpreted line drawing (bottom). Location of the corresponding profile in Fig. 3.

separating the structural highs are associated with the presence of normal and/or strike–slip faults that in this sector of the easternmost South Scotia Ridge mark the Scotia–Antarctica plate boundary.

Herdman Bank is the easternmost shallow bank pertaining to the southern margin of the Scotia Sea. It is centered at 60°S, 32°W and is separated from the north-eastern margin of the Discovery Bank by a narrow and steep trough. To the east, it connects in some ways to the southern termination of the East Scotia Ridge. Its crustal nature, structural setting, and tectonic history is almost unknown because the absence of underway data. Most of the information comes from satellite-derived data (Smith and Sandwell, 1997) and a single seismic profile (Bohoyo, 2004) which crosses the south-western part of the bank. The morphology of the Herdman Bank is particularly rough and presents several relative highs possibly bounded by normal faults.

3. Earthquake data

The plate boundaries around the Scotia plate are highlighted by the distribution of earthquake epicenters. Most of seismic activity takes place at the eastern edge of the Scotia Sea, where the South America plate bends below the South Sandwich plate in an active subduction zone. All deep (>150 km) and most intermediate (70–150 km) events are concentrated here, while the other boundaries of the Scotia plate are mainly described by shallow events (0–70 km). However, in the seismicity maps, because of the difficulties in accessing the Antarctic and sub-Antarctic regions, we expect some bias as a consequence of the paucity of seismic stations and the high permanent microseismic noise. Earthquake locations by seismic agencies and their seismicity patterns are generally acceptable only for a body wave magnitude threshold greater than 5.0 (Rouland et al., 1992). Below this magnitude threshold, there are many earthquakes that are not detected, and this makes the seismicity used for tracing the plate boundaries inhomogeneous. Although uncertainties could be large, discrepancies observed by comparing bulletins from different agencies, having different seismic stations patterns (NEIC, IDC, ISC, EHB, etc...), are limited horizontally to 10–20 km (International Seismological Centre, 2009). Similar uncertainties are consistent with the error ellipses given in Pelayo and Wiens (1989) for relocated historical earthquakes (from 1958 to 1962). Earthquake depths due to the lack of local seismic stations are still not well constrained in this remote region of the Southern Hemisphere.

The earthquakes considered in this analysis (Fig. 4) are taken from the EHB bulletin (Engdahl et al., 1998; Engdahl, 2006). EHB has two main advantages: (1) it uses a proper reference Earth model (AK135,

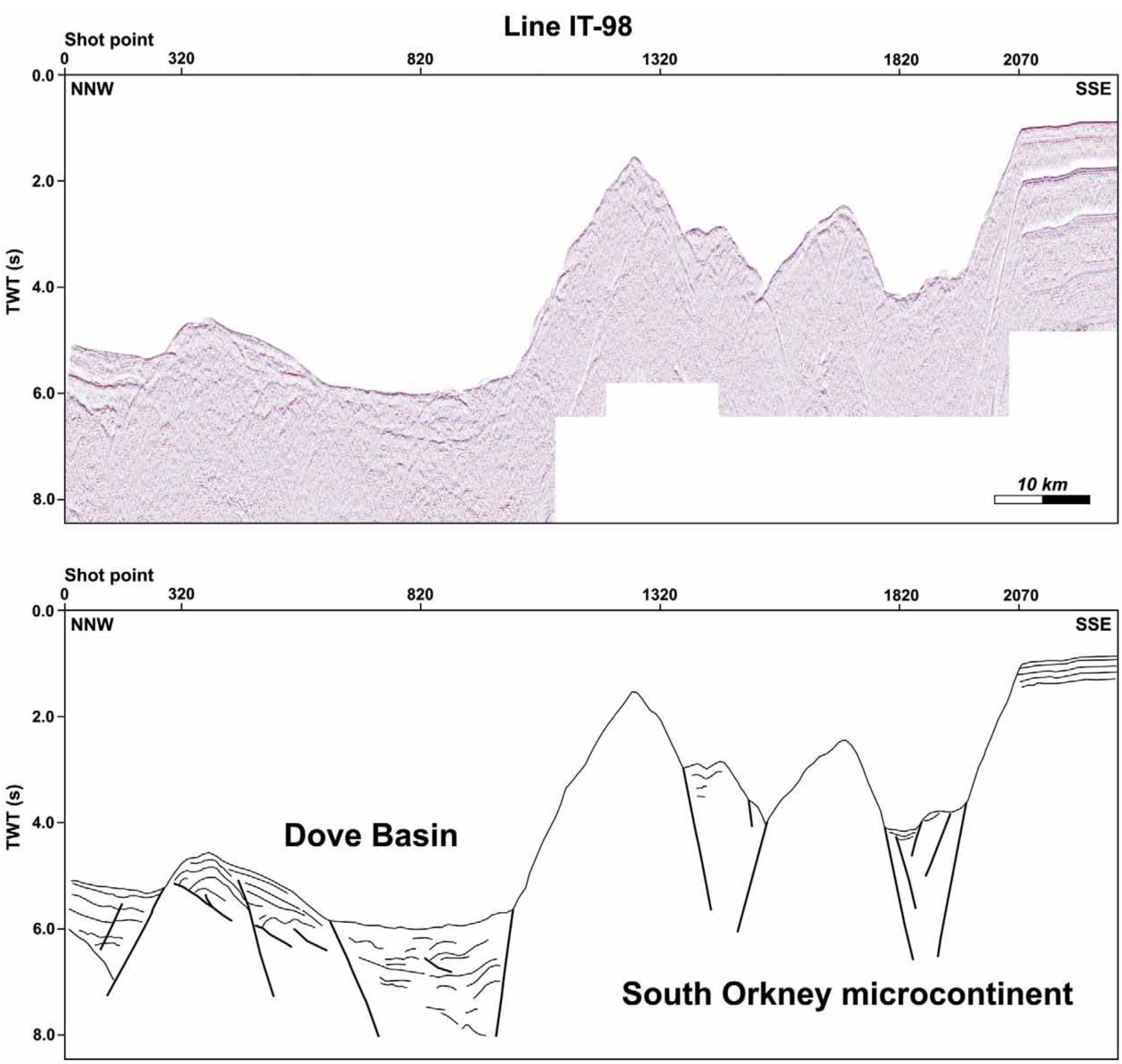

Fig. 6. Multichannel seismic profile IT-98 (top) and interpreted line drawing (bottom). Location of the corresponding profile in Fig. 3.

Kennett et al., 1995) and, (2) it limits the events of interest only to those that are well constrained teleseismically. Moreover, the EHB location procedures has significantly improved by using iterative relocation with dynamic phase identification, use of teleseismic depth phases, and selection criteria for events having ten or more observations at teleseismic distances (>28°) and a teleseismic secondary azimuth gap (<180°).

Here below we describe the recorded seismicity and available focal mechanisms that could help in interpreting seismic data along the South Scotia margin from the South Orkney microcontinent to the Herdman Bank. From W to E, the seismicity pattern of the area shows two distinct behaviors: The plate boundary from the South Orkney microcontinent to the S–E margin of the Bruce Bank is well defined by the seismicity pattern that assumes a general W–E alignment. Toward E from the Discovery Bank to Herdman Bank, earthquakes are located in a 150 km wide area and on a local scale are difficult to follow unambiguously along the plate boundary. Seismicity is diffuse all along the border of Discovery Bank, beneath it, and close to the eastern termination of Jane Bank and in the area occupied by the Irizar Highs. The focal mechanisms for both areas maintain a prevalent left-lateral, strike–slip motion combined with an extensional component. The 65 km wide Scan Basin that separates the Bruce Bank from Discovery Bank represents the area where seismicity patterns seem to change.

According to some authors (Kavoun and Vinnikovskaya, 1994; Maldonado et al., 1998; Busetti et al., 2000), the northern margin of the South Orkney microcontinent shows a convergent setting, produced by

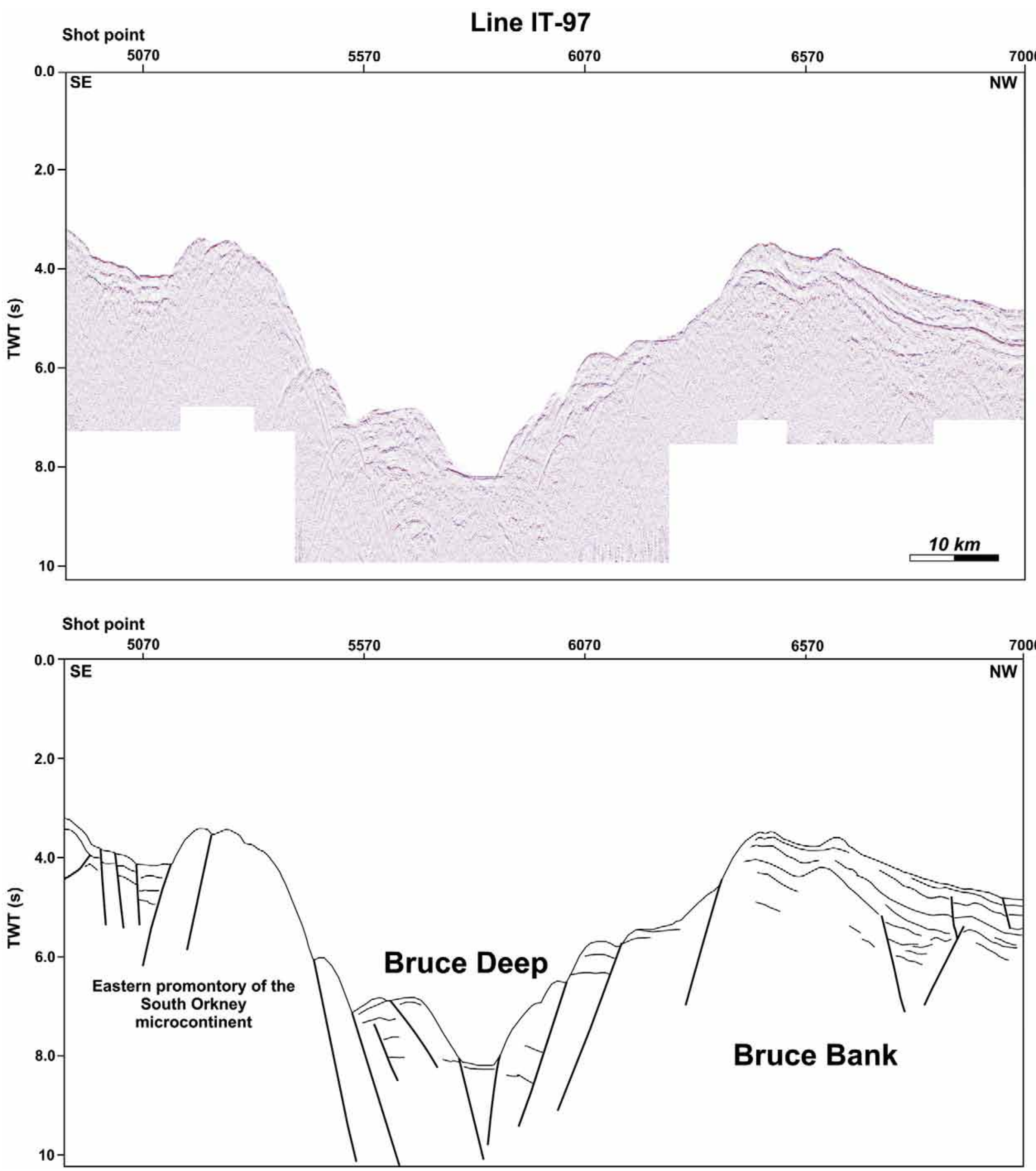

Fig. 7. Multichannel seismic profile IT-97 (top) and interpreted line drawing (bottom). Location of the corresponding profile in Fig. 3.

the subduction of the Scotia Sea oceanic crust beneath the continental platform. However, the Harvard CMT catalog contains only a focal mechanism showing reverse faulting (1991/05/24, Mw = 5.7). The size of this event is quite smaller than the Mw = 7.6 (2003/08/04) earthquake occurred 75 km E from the South Orkney Islands, and characterized by a normal faulting with a strike–slip component. The moment tensor source inversion of the 2003 earthquake aftershocks confirms the extension along a WNW–ESE fault plane (Plasencia, 2007). Principally E-directed, co-seismic displacement associated with the $M = 7.6$ earthquake confirms accumulation of slip consistent with a left-lateral transform plate boundary (Smalley et al., 2007).

Between the South Orkney microcontinent and Bruce Bank, an E–W oriented depression with seismic activity and a strike–slip earthquake focal mechanism points to a purely left-lateral regime on E–W oriented faults. East of Bruce Bank up to Discovery Bank, where reliefs are separated by a NNW–SSE-trending fault system, the EHB catalog does not report earthquakes. Other catalogs (e.g. NEIC, ISC) that do not respect the selection criteria of EHB in terms of azimuthal coverage and number of useful phases, display some medium size earthquakes, probably not so strong to be well recorded at teleseismic distances. Toward S–W and inside the Discovery Bank, left-lateral, strike–slip earthquakes with an extensional component are dominant. The active faults are probably left-lateral lineaments trending ENE–WSW to E–W, consistent with one of the nodal planes of the focal mechanisms (Galindo-Zaldívar et al., 2002).

South of Discovery Bank, the seismicity and exposed fault scarps indicate present-day activity on faults that border the Deep Basin (see Fig. 3 of Galindo-Zaldívar et al., 2002), which is located at the base of the southern margin of the Discovery Bank. The kinematics of the present-day active faults may be established on the basis of the vertical displacements observed on seismic profiles and from earthquake focal mechanisms (Dziewonski et al., 1981; Pelayo and Wiens, 1989). In the eastern and central parts of the southern border of the Discovery Bank, Intermediate Domain and Deep Basin (see Fig. 3 of Galindo-Zaldívar et al., 2002), faults have a NE–SW orientation and accommodated normal sense slip responsible for crustal thinning and basin development.

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 (De Mets et al., 1990, 1994; 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. These results are quite similar to recently-acquired GPS crustal data, combined with earthquake slip vector, transform azimuth, and spreading rates from the Scotia and South Sandwich plates (Smalley et al., 2007). The relative motion of these two major plates is presently

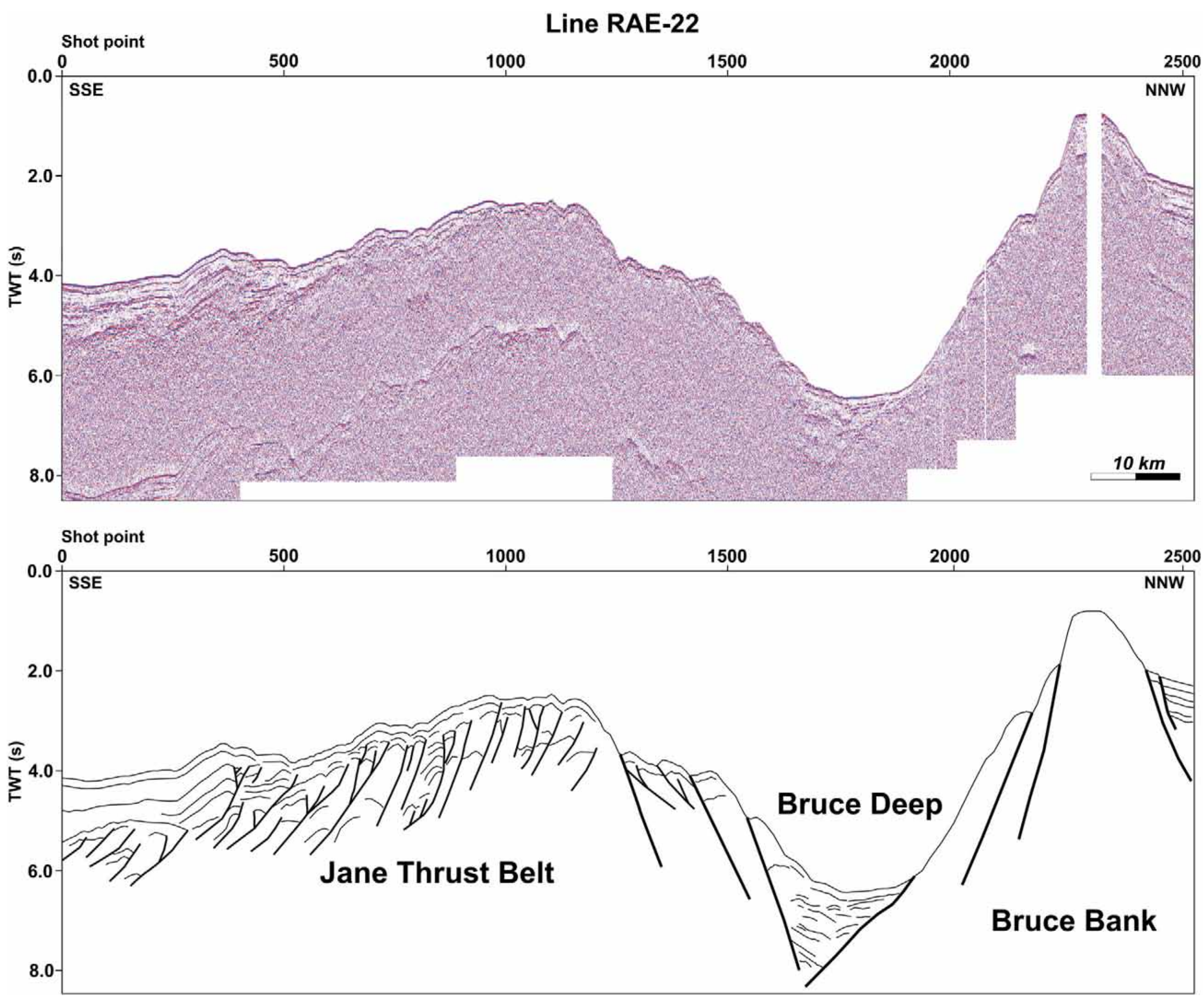

Fig. 8. Multichannel seismic profile RAE-22 (top) and interpreted line drawing (bottom). Location of the corresponding profile in Fig. 3.

partitioned along the left-lateral, strike–slip northern and southern boundaries of the Scotia plate (Pelayo and Wiens, 1989).

4. Seismic images of the plate boundary east of the South Orkney microcontinent

The tectonic framework of the boundary between the Scotia and Antarctic plates falling in the sector between the Orkney Islands to the west and the Discovery Bank to the east (between 45°W and 35°W, and 59°S and 62°S) has been analyzed by a series of multichannel seismic reflection profiles available from the SDLS, and published here for the first time.

On a broad scale, this part of the plate boundary shows a very complex configuration in which different types of tectonic environments are juxtaposed, forming a puzzle of bathymetric highs separated by small basins and deep and relatively narrow trenches

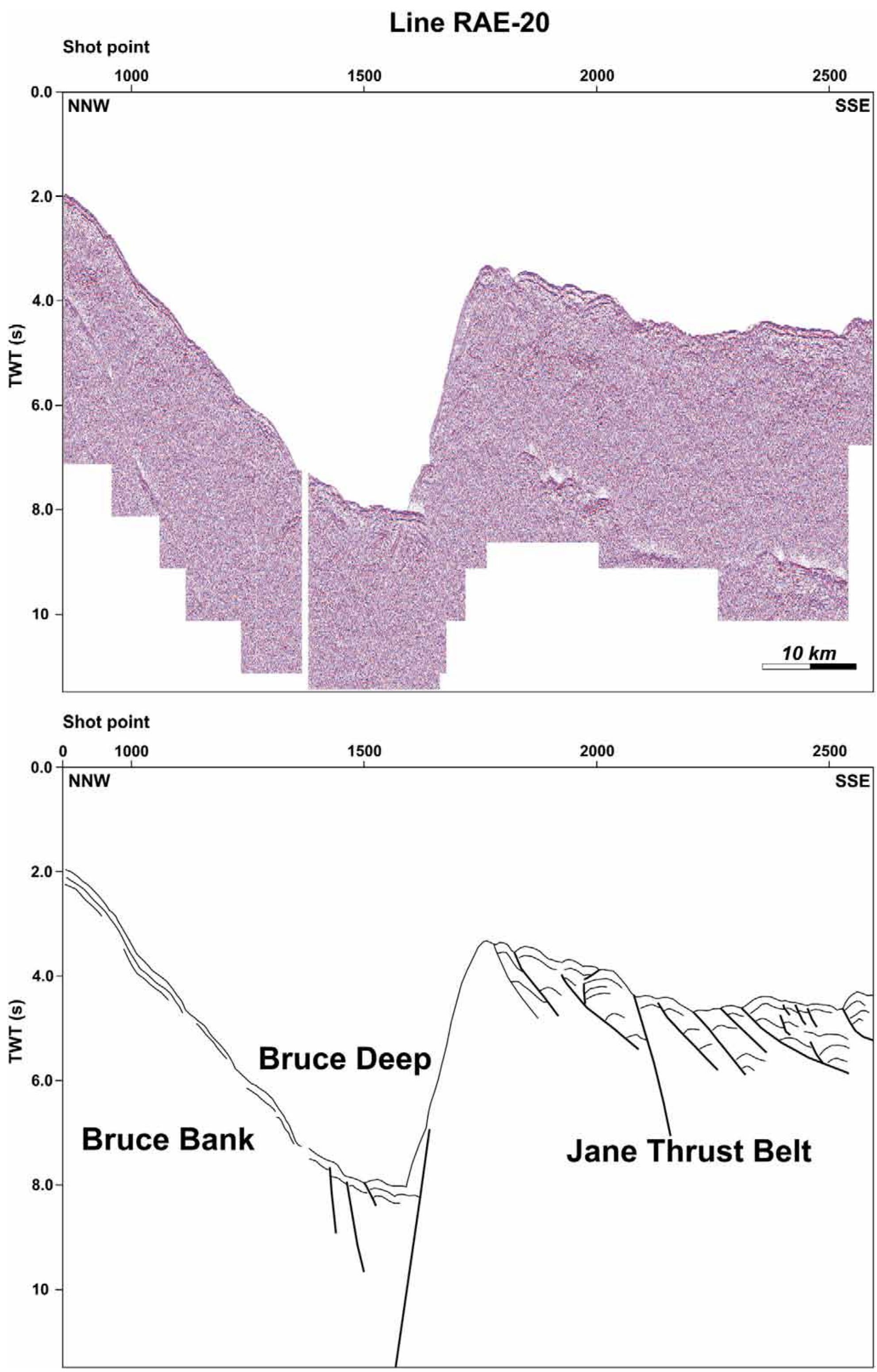

Fig. 9. Multichannel seismic profile RAE-20 (top) and interpreted line drawing (bottom). Location of the corresponding profile in Fig. 3.

and troughs. Along this part of the South Scotia margin it is possible to recognize three main segments (see the structural map presented in Fig. 4), oriented WNW–ESE (in the western sector), ENE–WSW (in the central sector, here named Bruce Deep), and NE–SW (in the eastern sector), and disposed in an *en-echelon* geometry. These segments are separated by NNE–SSW-trending release zones, which correspond to mostly strike–slip faults.

We present here some seismic profiles that cross the various segments composing the Scotia–Antarctica plate boundary from the South Orkney microcontinent to the east. Seismic line TH-04B (Fig. 5) crosses the eastern part of the northern margin of the South Orkney microcontinent. The bulk of the continental block appears undeformed in the uppermost sequences where sub-horizontal sedimentary successions are present. Toward the slope, two major sub-vertical faults generate a steep and very narrow V-shaped trough which separates the block from a symmetric structural high. This high trends parallel to the northern border of the South Orkney microcontinent and it is limited by a regional fault which shows a prevalent normal motion, with a left-lateral, strike–slip component, as seen from earthquake data. At the base of the structural high, between shot points (SP) 1300–1400 and at about 9.0 s two-way travel time (TWT) in depth, a reflector gently inclined toward south might represent the top of the Scotia Sea oceanic crust which merges beneath the South Orkney microcontinent. In the northern part of the seismic profile, deformed sedimentary layers are present. In particular, there is evidence of compression because the presence of folding linked to N-verging thrusts which in some cases would seem to deform the seafloor (at SP 1900). A presence of a subduction zone along the northern margin of the South Orkney microcontinent has been already proposed by Kavoun and Vinnikovskaya (1994) and by Busetti et al. (2000), where they describe also a possible accretionary prism at the base of the slope.

Seismic line IT-98 (Fig. 6) crosses the boundary between the Scotia and the Antarctic plates in correspondence of the eastern border of the South Orkney microcontinent, where the plate boundary curves. The line crosses the edges of the two WNW–ESE and ENE–WSW segments described above. The seismic section can be divided in three parts. The southern one, from SP 2070 to the edge of the line, corresponds to the undeformed sedimentary cover of the South Orkney microcontinent. It is bordered to the north by a very steep slope which represents the western termination of the left-lateral transtensional fault bordering the eastern edge of the Bruce Deep (see Fig. 4). The second part of the line, from SP 1070 to SP 2070, shows a complex morphology where structural highs with steep slopes are separated by symmetric troughs (up to 3000 m in water depth). The steep slopes would represent the trace of extensional faults with some left-lateral component of movement. The third part of the section is occupied by the Scotia Sea (Dove Basin) where the sedimentary cover

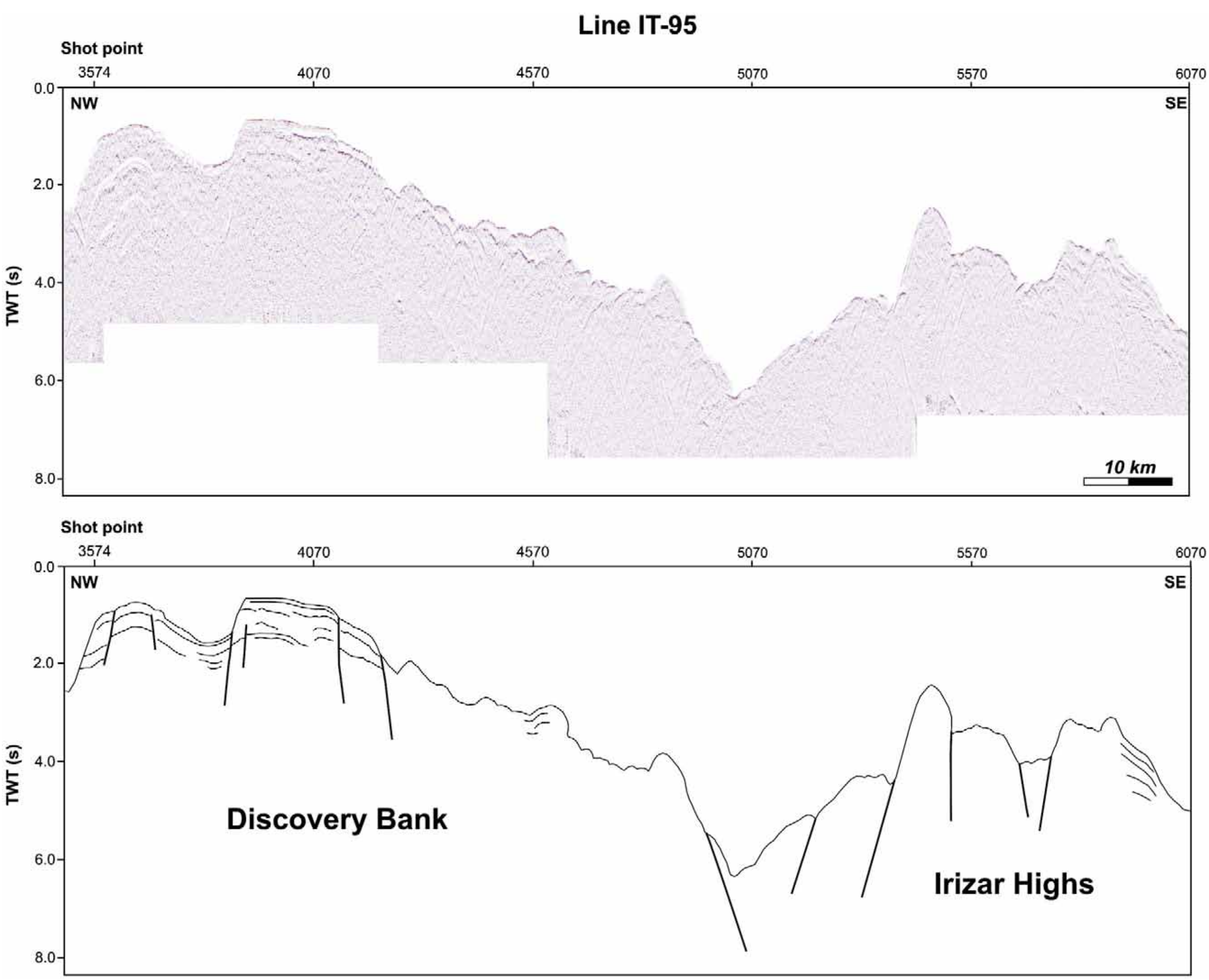

Fig. 10. Multichannel seismic profiles IT-95 (top) and interpreted line drawing (bottom). Location of the corresponding profile in Fig. 3.

seems to be affected by N-verging folding and thrusting. A large anticline, which deforms the sea-floor, is located between SPs 400 and 700. Several normal faults cut the compressional structures.

Moving eastward, we enter in a relatively narrow trough, the Bruce Deep. This trough appears divided into two distinct sub-basins by broadly E–W-trending tectonic lineaments. The western part of the Bruce Deep is symmetric, as seen from seismic line IT-97 (Fig. 7). It is bounded to the south by a set of sub-vertical faults oriented WSW–ENE, which exhibit a left-lateral motion with an extensional component, as derived from earthquake data. Other steep faults are present along the northern side of the Bruce Deep where they constitute a staircase structure, developed from SP 5800 to SP 6400. The extensional character of these faults is clearly visible observing the throws, which are of the order of several hundreds of meters. The basin floor reaches, in the western sector, more than 6000 m in water depth. Line RAE-22 (Fig. 8) crosses the central part of the Bruce Deep, where it changes its internal geometry, and acquires a more pronounced asymmetry. The eastern part of the Bruce Deep, imaged by the seismic profile RAE-20 (Fig. 9), is strongly asymmetric, with a very steep southern edge and a gentler northern edge. The southern flank of the basin is bounded by a left-lateral master fault which shows a steep slope. As a whole, this elongated depression might represent a complex pull-apart basin. To the south of the pull-apart basin, seismic profiles RAE-22 and RAE-20 (Figs. 8 and 9), show the presence of a wide area affected by compression and interpreted to represent an accretionary prism (here called Jane Thrust Belt). It is constituted by overlapping folded thrust sheets separated by general N-verging thrusts. In many cases, those thrusts affect the sea-floor. From SP 1200 to SP 1700 along line RAE-22, the frontal part of the wedge seems to be collapsed due to the action of a series of normal faults, with moderate displacements, dipping towards the Bruce Deep. The northern part of the line RAE-22 crosses the southern margin of the Bruce Bank (SPs 2000–2500), where a structural high bordered by normal faults is present. The sedimentary sequence filling the Bruce Deep appears to be tilted toward north. The basin could be interpreted as the fore-deep of the Jane Thrust Belt, which was successively deformed by left-lateral strike–slip tectonism that generated the present-day pull-apart geometry. This succession of events is particularly visible on line RAE-20 at SP 1800 (Fig. 9) where the master fault of the southern side of the Bruce Deep truncates the Jane Thrust Belt.

The eastern sector of the study area, between the Discovery Bank and the Herdman Bank, is structurally very complex. It is composed by a puzzle of small elevated fragments (here called Irizar Highs) separated by a series of narrow and restricted basins which may be formed as a consequence of the N-verging subduction of the Weddell Sea oceanic crust beneath the Discovery Bank (Galindo-Zaldívar et al., 2002). Line IT-95 (Fig. 10) crosses the westernmost part of this area. From SP 3500 to SP 4200, data show the morphology and structure of the south-western Discovery Bank, which is composed by two main structural highs covered by a relatively thick sedimentary sequence. The southern flank of the bank shows a peculiar seismic facies with several diffractions possibly generated by on-line and/or lateral very rough and steep surfaces. At the base of this margin, a broadly

Fig. 11. (top) Two examples of rocks recovered at site 4A (see dredge location in Fig. 4). (left): metamorphic rocks (gneiss) with quartz veins; (right): plutonic samples (granitoids) mainly composed by grey feldspars. (bottom) Some examples of rocks (schists and metaquartzites) recovered at site 13 (see dredge location in Fig. 4).

symmetric basin is present (centered at SP 5000), bounded to the north by a left-lateral transtensional fault oriented ENE–WSW. This basin is interpreted in literature (Galindo-Zaldívar et al., 2002) as a pull-apart basin. From SP 5000 to SP 6070 the line crosses the Irizar Highs, where the structural style is recognizably difficult because the presence of several morphological elevations separated by mostly normal faults.

5. Lithological data

Most of the tectonic reconstructions proposed for the Scotia plate postulate the presence of a continental connection between the southernmost South America and Antarctic Peninsula prior to the Scotia Sea opening; this bridge was successively fragmented and dispersed during the evolution of the region. The crustal nature of some of these fragments, which now are part of the southern margin of the Scotia Sea, has been clearly identified, whereas uncertainties remain for the series of bathymetric highs present to the east of the South Orkney microcontinent. Several lithofacies of the continental connection represent a subduction-related accretionary wedge (the Scotia Metamorphic Complex) developed on the western margin of Gondwana, with metamorphism and tectonism continuing after break-up of the supercontinent (Tanner et al., 1982; Trouw et al., 1997a). In the South Orkney Islands, it differs from many other accretionary complexes in the Scotia Sea region in its higher metamorphic grade and unconformable contact with overlying fossiliferous sequences. The Greywacke Shale Formation outcropping on the easternmost Coronation Island, and on Laurie and Powell Islands (all pertaining to the South Orkney Islands), a sedimentary protolith with a wholly continental provenance (Andreis et al., 1997), shares an early polyphase tectonic history with the Scotia Metamorphic Complex (Meneilly and Storey 1986; Trouw et al., 1997b).

On January 2009, some dredge sites have been surveyed (Tassone et al., 2009) in order to verify the continental/transitional nature of the prominent morpho-bathymetric elevations that form the eastern Jane Bank and the Irizar Highs (see Fig. 4 for dredge locations). These sites have been previously individuated taking into account the available bathymetric data (mainly satellite-derived data) and seismic information, in order to appropriately locate the dredging operations. Here below, we present a preliminary description of three of these sites where the rock recovery was successful.

Dredge 4A is located along the southern flank of the eastern Jane Bank, crossed by the seismic line IT-97, at depths of about 3100 m. Dredge recovered a large amount of rocks, and 35% of them represent consolidated rocks. The percentage of the consolidated rocks is as follows: 40% of igneous (mostly siliceous) fragments; 30% of shales that can be related to the Greywacke Shale Formation; 25% of fine-grained schists often with thin quartz veins, possibly part of the Scotia Metamorphic Complex; the remainder 5% is mostly composed by basic volcanic rocks. Even some of them may not represent *in-situ* rocks but dropstones carried out by icebergs and/or glaciers, metamorphic and igneous samples predominate (Fig. 11). Textural characteristic of the igneous specimens, performed on three representative thin sections, are shown in Fig. 12. Micrography of Fig. 12(A) represents a fine- to medium-grained biotitic leucogranite, somewhat porphyric of hypidiomorphic texture. The primary magmatic texture is slightly overprinted by sub-magmatic to high-*T* microstructures (i.e., local pockets of very fine-grained quartz–feldspar mosaics, myrmekite thin belts, and chess-board sub-grains in quartz). Other specimens correspond to a granitic orthogneiss with a clear foliation defined by mechanically-oriented biotite-amphibole. The fabric is dominated by sub-solid microstructures characterized by old feldspar crystals, somewhat rounded, displaying internal deformation (sub-grains, uneven pericline twinning), partially enveloped by wide-spread pockets and belts of quartz–feldspar of polygonal texture (Fig. 12(B)). Micrography of Fig. 12(C) represents a porphyric dacite with plagioclase, quartz, amphibole and minor clinopyroxene phenocrystals.

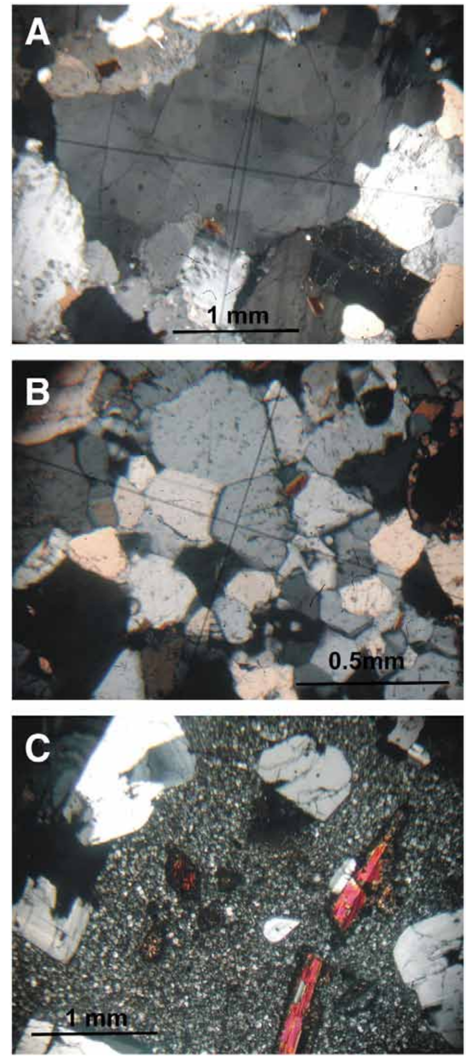

Fig. 12. (A, B, C). Photomicrographs of some representative samples recovered by dredge 4A XPL light. See text for lithologic characteristic of each sample.

Dredge 4B, located along the slope of the outermost flank of the Jane Bank, recovered only few samples of small size, most of them are metamorphic rocks similar to those obtained in site 4A.

Dredge 13 is the easternmost dredging site analyzed during this Campaign. It is located along the southern flank of one of the western relieves of the Irizar Highs, crossed by the seismic line IT-95, at depths of about 3200 m. The majority of the recovered rocks are metamorphic and variably-foliated igneous rocks; these represent >90% of the specimens of the dredge. Only a minor part of the samples may be considered as dropstones and reworked rock samples, because the majority of them do not present rounded angles and/or grind surfaces which indicate reworked material. Micrography of Fig.13(A) shows a fine- to medium-grained biotite-amphibole (±clinopyroxene) banded gneiss; mafic minerals show a strong iso-orientation whereas plagioclase displays sub-tabular to ameboidal shapes; coarser-grained leucocratic layers are common. Fig. 13(B) illustrates samples of fine-grained quartz-amphibolites, characterized by bluish-green amphibole and polygonal plagioclase accompanied by thin strings of opaque minerals parallel to foliation planes; scarce thin veins of coarser-grained quartz are also found. Both gneisses and amphibolites show a well developed foliation, suggesting medium-grade metamorphic conditions. Micrography of Fig. 13(C) shows a porphyric leucogranite with euhedral feldspar large

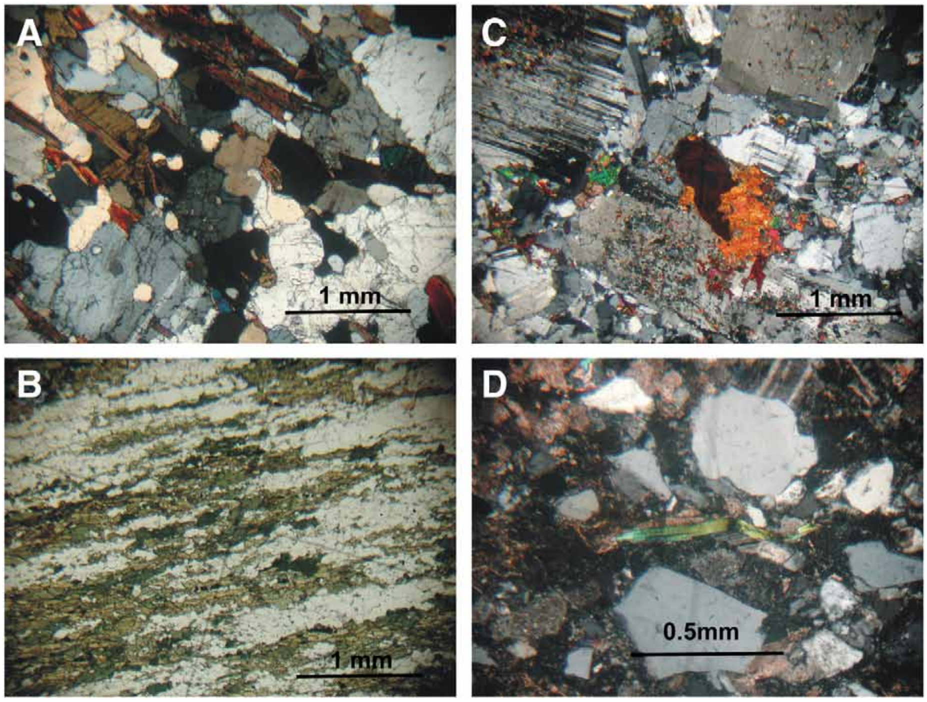

Fig. 13. (A, B, C, D). Photomicrographs of some representative samples recovered by dredge 13; XPL light for A, C, D, PL light for B. See text for lithologic characteristic of each sample.

crystals (up to 7 mm) set in a fine-grained quartz–feldspar association. Magmatic epidote, sphene and opaque minerals occur in subordinated amounts. Observed microstructures suggest a non pervasive medium-*T* deformation (indicated by the development of flame perthites) and a widespread low-*T* deformation within the brittle domain (uneven development of pericline twinning, broken twins, cracks). This sample lacks penetrative ductile foliation, which is characteristic of the majority of the recovered specimens of dredge 13. Micrography of Fig. 13(D) represents a medium-grained sandstone rich in sub-angular to sub-rounded quartz clasts, accompanied by plagioclase and mica particles.

The lithologic association of dredges 4A and 13 is dominated by rocks of granitic composition which indicates a continental/transitional crust provenance. Textural analysis of microstructures suggests at least two groups within these rocks: One displaying significant deformation which overprints and partially masks magmatic textures; the other in which the sub-solid overprint is absent or very minor.

6. Discussion and conclusions

Presented seismic profiles and earthquake data, together with lithologic analyses and combined literature information, show that the central sector of the Scotia–Antarctica plate boundary is presently characterized by an *en-echelon* geometric arrangement, produced by a left-lateral mega shear zone, along with restricted basins, crustal fragments, and deep troughs, coexist.

Three main segments, with different geometry and deep structural characters, have been identified in the analyzed sector of the plate boundary (see Fig. 4). The western segment, oriented WNW, and coinciding with the northern limit of the South Orkney microcontinent, is constituted by a convergent zone, produced by the subduction of the oceanic floor of the Scotia Sea (in correspondence of the Dove Basin) beneath the continental platform. Earthquake data do not show a present-day compressional stress component along this sector of the plate boundary. The convergence, as seen on seismic profiles which document the presence of an accretionary prism, seems to be replaced by a general strike–slip environment along the plate boundary. Focal mechanisms, as the Mw = 7.6 South Orkney Islands earthquake (Plasencia, 2007), show extension along a WNW–ESE fault plane with a strike–slip component.

The central segment, here named Bruce Deep, is composed by two pull-apart sub-basins of different geometry and margin shape, both structurally controlled by left-lateral transtensional lineaments trending from E–W to NE–SW, with throws of the order of thousands of meters. To the south of the Bruce Deep, seismic data show a thrust belt (Jane Thrust Belt), where a series of folding and north-verging thrusts are present. In this structural scenario, Bruce Deep could be interpreted as the deformed fore-deep of the Jane Thrust Belt before the activation of the strike–slip tectonism that generated the present-day pull-apart geometry. The formation of this thrust belt could be explained with the convergence and subsequent subduction of oceanic crust located between the Bruce Bank and the eastern part of the South Orkney microcontinent. The deformation possibly ceased with the collision of the Bruce Bank with the easternmost part of the South Orkney microcontinent.

The eastern segment corresponds to the area located between Discovery Bank to the west and Herdman Bank to the east. This area is characterized by a puzzle of small elevated fragments (here collectively called Irizar Highs) separated by a series of narrow and restricted basins bordered by ENE–WSW trending left-lateral, strike–slip faults. These basins may be formed as a consequence of the N-verging subduction of the Weddell Sea oceanic crust beneath the Discovery Bank, as originally proposed by Galindo-Zaldívar et al. (2002), and successively deformed by the activation of a mostly transcurrent tectonic regime.

The three main segments are separated by NNW–SSE-trending releasing zones which allowed differential motion between blocks pertaining to each segment. In particular, the releasing zone which separates the Bruce Bank–Jane Thrust Belt from the Discovery Bank–Irizar Highs is formed by a system of right-lateral, strike–slip faults which possibly accommodated the different direction of movement of the blocks. This zone would appear inactive because the absence of earthquakes. It separates two segments of the plate boundary characterized by an intense earthquake activity with left-lateral and normal focal mechanisms.

Preliminary analysis of dredged samples collected in the eastern part of the Jane Bank and on one of the elevated blocks of the Irizar Highs (see Fig. 3), indicates the predominance of siliceous-rich rocks (i.e., granites, schists, sandstones) of continental/transitional nature in the investigated area. These rocks probably constituted originally a single tectonic province. The blocks were successively severely stretched, fragmented, and dispersed by tectonic activity that acted along the southern margin of the Scotia Sea. We hypothesize that most of the active faults present along the margin where preferentially located along previous weak zones, where deformation may easily occur.

The reconstruction of the tectonic development of the Scotia–Antarctica plate boundary and its sequential history is very difficult because the lack of precise and univocal temporal constraints about the opening of the basins present along the south Scotia Sea margin. The different blocks, now dispersed along the southern Scotia Sea, suffered the tectonic effects of the ocean basins development, particularly along the edges of adjacent blocks and at the ocean–continental crust transition. These effects are visible on seismic profiles. The uncertainty about the age of the basin opening causes often ambiguous tectonic reconstructions. In the Protector Basin, Hill and Barker (1980) identified linear magnetic anomalies indicating a spreading period between 16 and 13.1 Ma, although a period between 21 and 17 Ma has been proposed by Barker (2001). Instead, Galindo-Zaldívar et al. (2006) assigned, on the basis of magnetic anomaly identifications, a period comprised between 17.4 and 13.8 Ma for the Protector Basin. Eagles et al. (2006), modeling the short magnetic anomaly profiles across the Protector Basin, and applying isostatic correction for its sedimentary fill, proposed a mid to Late Eocene times for the opening (48.5–41 Ma), consistently older than the age proposed by Galindo-Zaldívar et al. (2006). The structural setting and seismic reflection character of oceanic basement of the Dove Basin appear to be similar to those of Protector Basin (Galindo-Zaldívar et al., 2006). The sea-floor in Dove Basin is slightly deeper than in Protector Basin and is consistent with an age range of 40–30 Ma. The Middle Eocene (about 41–34.7 Ma) calculated age of the Dove Basin (Eagles et al., 2006) is significantly older than the age assigned by Galindo-Zaldívar et al. (2006) for the Protector Basin. Finally, very few data are available for the Scan Basin. Bohoyo (2004) hypothesized an age variable from 21 to 14.4 Ma for this basin, based on magnetic data.

Despite these significant uncertainties on the age of opening of the ocean basins, some general considerations can be made. In Fig. 14, a simplified sketch of a possible tectonic development of the Scotia–Antarctica plate boundary between the South Orkney microcontinent and the Herdman Bank is presented. This reconstruction includes all the morpho-structural elements identified from the analysis of seismic data, combined with earthquake data and available information from literature. The present-day central segment of the Scotia–Antarctica plate boundary might be the result of a complex deformational history which comprised: (1) a phase (Lower Miocene) with a north-directed convergence of the Weddell Sea beneath the series of bathymetric highs now distributed along the southern margin of the Scotia Sea; (2) a second phase (about 12 Ma) characterized by the (partial) subduction of the Scotia Sea crust beneath the South Orkney microcontinent, which produced an accretionary prism with N-verging structures. During this phase, a system of dextral transform faults, broadly trending NNE, was active and separated zones with different direction of movement. These faults dismembered and partly deactivated the subduction zone, and facilitated the process of fragmentation and dispersion of the crustal blocks. The southward subduction zone continued toward east in the Bruce Bank area. Here, the S–E migration of the Bruce Bank, related to the opening of the Dove Basin, generated a fore-deep chain system. Compressional structures, folds and N-verging thrust sheets, have been detected along this convergent zone. A NNW-oriented subduction of the Weddell Sea crust persisted in the eastern sector (beneath the Discovery Bank and Herdman Bank); (3) a final phase, characterized by the activation of left-lateral transtensional lineaments, which generated narrow pull-apart basins in the fore-arc sectors of the convergent zones. At present-day, the subduction zones and the dextral transform system seem to be deactivated. Only the subduction zone along the northern margin of the South Orkney microcontinent could be still partially active. A left-lateral transtensional regime controls the Scotia–Antarctica plate boundary, which is actually constituted by a series of kilometric-scale faults with a variable orientation from WNW in the western sector, E–W in the central zone, to N–E in the eastern sector. These faults cut the previous structures and produce pull-apart basins.

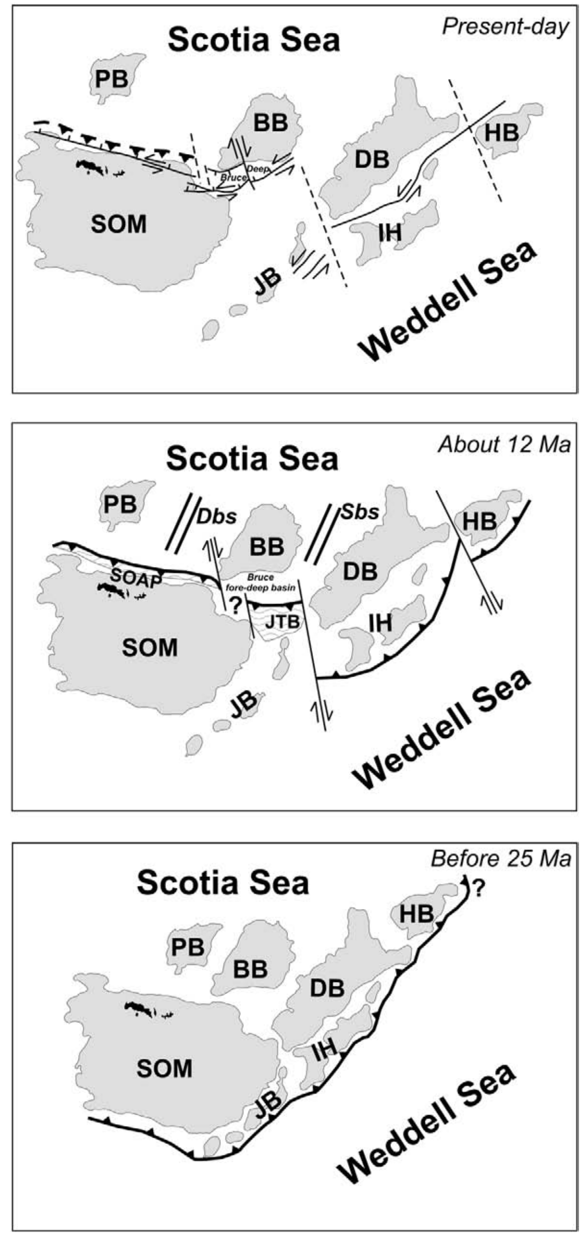

Fig. 14. Three simplified sketches of a possible tectonic evolution of the Scotia–Antarctica plate boundary between the South Orkney microcontinent and the Herdman Bank. Abbreviations are as follows: SOM, South Orkney microcontinent; PB, Pirie Bank; BB, Bruce Bank; JB, Jane Bank; DB, Discovery Bank; IH, Irizar Highs; HB, Herdman Bank; SOAP, South Orkney accretionary prism; JTB, Jane Thrust Belt; DBs, Dove Basin; SBs, Scan Basin.

The differences of this evolutionary model with respect to that presented by Galindo-Zaldívar et al. (2002) concern the identification of some main structures of the area located between the Discovery Bank and the South Orkney microcontinent, which driven the Scotia–Antarctica plate boundary evolution in this sector. A SSE-verging subduction zone is located along the northern margin of the South Orkney microcontinent and to the south of Bruce Bank, where it produced N-verging compressional structures and the formation of the Jane Thrust Belt (both convergent zones are absent in the Galindo-Zaldívar et al. (2002) model), as seen from the analysis of the presented seismic profiles. The dextral, *en-echelon* transform fault system possibly inverted the direction of the subduction: Therefore, the Scotia plate would subduct beneath Antarctic plate, in the western sector, and Weddell Sea would subduct beneath Scotia plate in the eastern sector. This transform system hence separates different geodynamic processes, and represents a new element with respect to the Galindo-Zaldívar et al. (2002) model. At present-day, our model shows that the plate boundary is constituted by mostly left-lateral transtensional faults which cut the previous structures in the western sector, and produces asymmetric pull-apart basins like the Bruce Deep.

Data have shown that the central segment of the Scotia–Antarctica plate boundary is the result of a complex deformational history, which is still difficult to outline because the significant age discrepancies in the tectonic events occurred along the southern margin of the Scotia Sea, which involved the opening of restricted oceanic basins formed between stretched blocks of possible continental/transitional nature.

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