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Propagating rift during the opening of a small oceanic basin: The Protector Basin (Scotia Arc, Antarctica)

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Abstract

The opening of oceanic basins constitutes one of the key features of Plate Tectonics because it determines the rifting and displacement of the continental crustal blocks. Although the mechanisms of development of large oceans are well known, the opening and evolution of small and middle size oceanic basins have not been studied in detail. The Protector Basin, located in the southern Scotia Sea, is a good example of a small oceanic basin developed between two thinned continental blocks, the Pirie Bank and the Terror Rise, poorly studied up to now. A new set of multibeam bathymetry, multichannel seismic reflection, and gravity and magnetic anomaly profiles obtained on the SCAN 2001 cruise led us to determine that the Protector Basin probably opened during the period comprised between C5Dn (17.4 Ma) and C5ACn–C5ABr chrons (13.8 Ma), forming a N–S oriented spreading axis. The end of spreading is slightly younger to the north. The start of spreading is clearly diachronous, with the most complete set of chrons up to C5Dn in the southern profile, C5Cn in the middle section and only up to C5ADn in the northern part of the basin. The spreading axis propagated northwards during the basin development, producing the wedge shape of the basin. In addition, at the NE part of the basin, a reverse fault developed in the border of the Pirie Bank after basin opening accentuates the sharp northern end. Moreover, the northwestern part of the Pirie Bank margin is an extremely stretched continental crust with N–S elongated magnetic anomalies related to incipient oceanic southward propagating spreading axes. The Protector Basin shows the oldest evidence of E–W continental stretching and subsequent oceanic spreading during Middle Miocene, related with the eastward development of the Scotia Arc that continues up to Present. The relative rotation of continental blocks during the development of small sized oceanic basins by continental block drifting favoured the opening of wedge shape basins like the Protector Basin and conjugate propagating rifts.

Keywords: oceanic spreading; seafloor magnetic anomalies; propagating rift; Middle Miocene; Scotia Arc

1. Introduction

The basins floored by oceanic crusts are highly variable in size. Large basins, like the Atlantic or the

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Pacific Oceans, are to date the best studied and occur through the fragmentation and drifting of large continents. The oceanic spreading axes and the subduction zones are the two main structures that control the development of large basins and the drifting of the continents. The progressive cooling of oceanic crust is one of the main mechanisms that led to the development of subduction of old and dense oceanic crust. In small oceanic basin development, the most important structures are those that determine the relative displacement of their margins; this is because there is not enough time for an increase in density of the oceanic crust that might contribute to developing subduction. In back-arc basins, opening is related to the separation of the island arc from the continental margin that determines the oceanic spreading [1], while in pull-apart basins like the Marmara Sea [2] basin opening is a consequence of the relay of transcurrent fault segments. In addition, other more irregular oceanic basins are found between continental blocks in regions of intense fragmentation, like the Caribbean Arc [3].

The mechanisms involved at the end of spreading may be also different in large and small oceanic basins. In large basins, with well developed oceanic crusts, the subduction of the spreading axis below the active continental margin is one of the main mechanisms involved in the spreading end (e.g., Weddell Sea [4]). In small basins, however, the end of the drifting of continental blocks is directly related with the end of spreading, both processes being determined by the regional tectonic context. Spreading axes of large oceanic basins generally end in transcurrent or subduction plate boundaries or in different types of triple junctions [5]. Yet there are few examples where spreading axes end in propagating rifts like the Gulf of Viscay [6–8], which is one of the better known inactive propagating rifts formed during the development of the northern Atlantic ocean; other examples are the opening of the Labrador Sea [9] or the back-arc basin related to the Tonga-Kermadec subduction [10]. In addition, there exist oceanic propagating rifts produced by a change in the spreading features, such as those described in the Galapagos area [11], the Mid-Atlantic ridge [12], the Selkirk palaeomicroplate in the South Pacific [13] or the Pacific–Antarctic ridge [14]. Small microplate development generally is related to fast vertical axis rotations [15]. The studied examples are scarce, and of variable sizes, so the mechanisms and features of propagating rift development and cessation of oceanic spreading may be better characterized by the study of the small oceanic basins.

Good examples of small oceanic basins formed between stretched continental blocks are found in the Scotia Arc (Fig. 1) [16,17] where a complex array of different tectonic plates has developed since the Oligocene. The aim of this contribution is to study the spreading of the Protector Basin in order to contribute to an understanding of the processes of oceanic basin development by the drifting of continental blocks. This basin may offer a good example of a propagating rift that is small in size. Finally, the data presented in this contribution may provide new constraints of a poorly known basin for reconstructions of the development of the Scotia Arc.

1.1. Geological setting

The two main plates found at present in the southern Atlantic area are the South American and Antarctic Plates. The Scotia and Sandwich Plates accommodate the sinistral transcurrent motion between these two large plates in the Scotia Sea area [18].

Small oceanic basins are recognized in the region as a result of this evolution, which is related to the dispersion around the Scotia Arc of the continental blocks that formed the connection between South America and the Antarctic Peninsula. In the Antarctic Plate, two of the most important basins are the Powell and Jane Basins. The Powell Basin is an oceanic basin that opened during the Late Oligocene–Early Miocene [19,20] surrounded by continental crust except along the southeastern border, and formed by the eastward migration of the South Orkney Microcontinent from the Antarctic Peninsula [21,22]. The Jane Basin is a back-arc basin related to the subduction of the oceanic crust of the northern Weddell Sea below the border of the South Orkney microcontinent [23,17], which developed in the time period comprised between the anomalies C5Dn (17.6 Ma) and C5ADn (14.4 Ma) [24]. The end of the oceanic spreading and the migration of the plate boundary to the South Scotia Ridge conditioned the incorporation of these structures into the Antarctic Plate.

The Scotia Plate, mainly of oceanic nature, has developed since Oligocene times [25,26], when the continental connection between South America and the Antarctic Peninsula was broken. The continental blocks were thinned and spread widely around the Scotia Plate [26]. While the central and western part of the Scotia Plate has been structured by oceanic spreading at the West Scotia Ridge, the southeastern part is made up of a complex array of small oceanic basins and continental blocks, with different degrees of stretching, formed during the eastward progressive propagation of the Scotia Arc. In the northern part of the South Scotia Ridge and from west to east, the

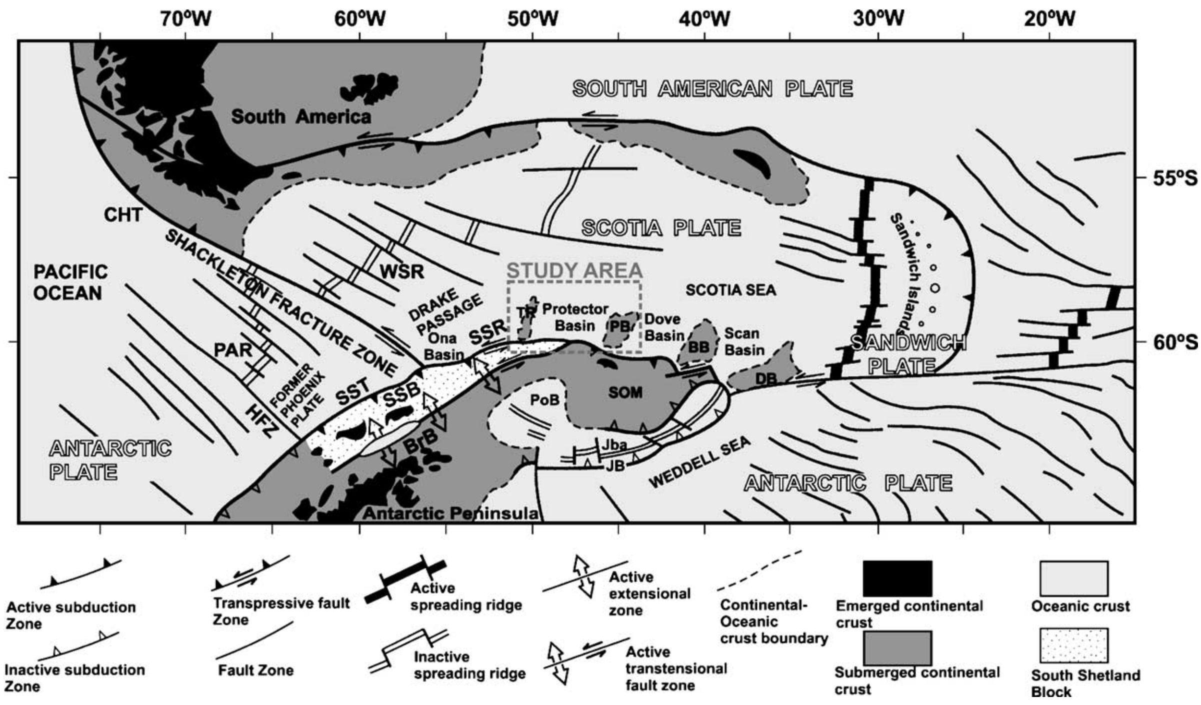

Fig. 1. Tectonic setting of the Protector Basin in the frame of the Scotia Arc. BB, Bruce Bank; BrB, Bransfield Basin; CHT, Chile Trench; DB, Discovery Bank; HFZ, Hero Fracture Zone; JB, Jane Bank; Jba, Jane Basin; PAR, Phoenix–Antarctic Ridge; PB, Pirie Bank; PoB, Powell Basin; SOM, South Orkney Microcontinent; SSB, South Shetland Block; SSR, South Scotia Ridge; SST, South Shetland Trench; TR, Terror Rise.

following tectonic elements can be distinguished: the Ona Basin, the Terror Rise, the Protector Basin, the Pirie Bank, the Dove Basin, the Bruce Bank, the Scan Basin and the Discovery Bank (Fig. 1).

The opening of these basins has not been studied in detail because of a lack of data. In the Protector Basin, Hill and Barker [27] identify linear magnetic anomalies that include the C5Cn and the C5Bn, indicating a period for spreading between 16 and 13.1 Ma, although a period between 21 and 17 Ma has been also proposed [26]. These studies do not pinpoint the end of the oceanic spreading or the full geometry of the anomaly bands, however.

2. Geophysical data and methodology

In order to determine the deep structure of the Protector Basin, we acquired a set of geophysical data–including multichannel seismic, gravity, magnetic and multibeam bathymetry along several transects orthogonal to the basin margins–during the SCAN 2001 cruise aboard the Hespérides research vessel (Fig. 2). The swath bathymetry data were obtained with a SIMRAD EM 12 system and processed with NEPTUNE software.

Three multichannel seismic reflection (MCS) profiles were obtained (SC09 in the south, SC07 in the middle and SC13 in the north, Fig. 2) with a tuned array of five BOLT air guns with a total volume of 22.14 l and a 96 channel streamer with a length of 2.4 km. The shot interval was 50 m. Data were recorded with a GEOMETRIC Strata Visor™ digital system at a sampling record of 2 ms interval and 12 s length. The seismic data were processed with a standard sequence that includes migration using a DISCO/FOCUS system.

Gravity and magnetic data were obtained along the MCS profiles and along profile SC45. Marine gravity data were acquired with a Bell Aerospace TEXTRON BGM-3 marine gravimeter. The Eötvos correction to determine free air anomalies was calculated using Lanzada software (Carbó, pers. comm.) considering ship navigation data. In addition, the bathymetric and free air anomaly data from the [28] database were taken into account. The free air anomalies we obtained and those included in this database are generally similar for the study area, although our data show higher frequency variations.

Total intensity magnetic field data were recorded every 12.5 m with a Geometrics G-876 proton precession magnetometer along the ship track lines. Processing includes elimination of spikes and filtering using a running mean to obtain one value each 1500 m. The magnetic anomalies were calculated using the IGRF

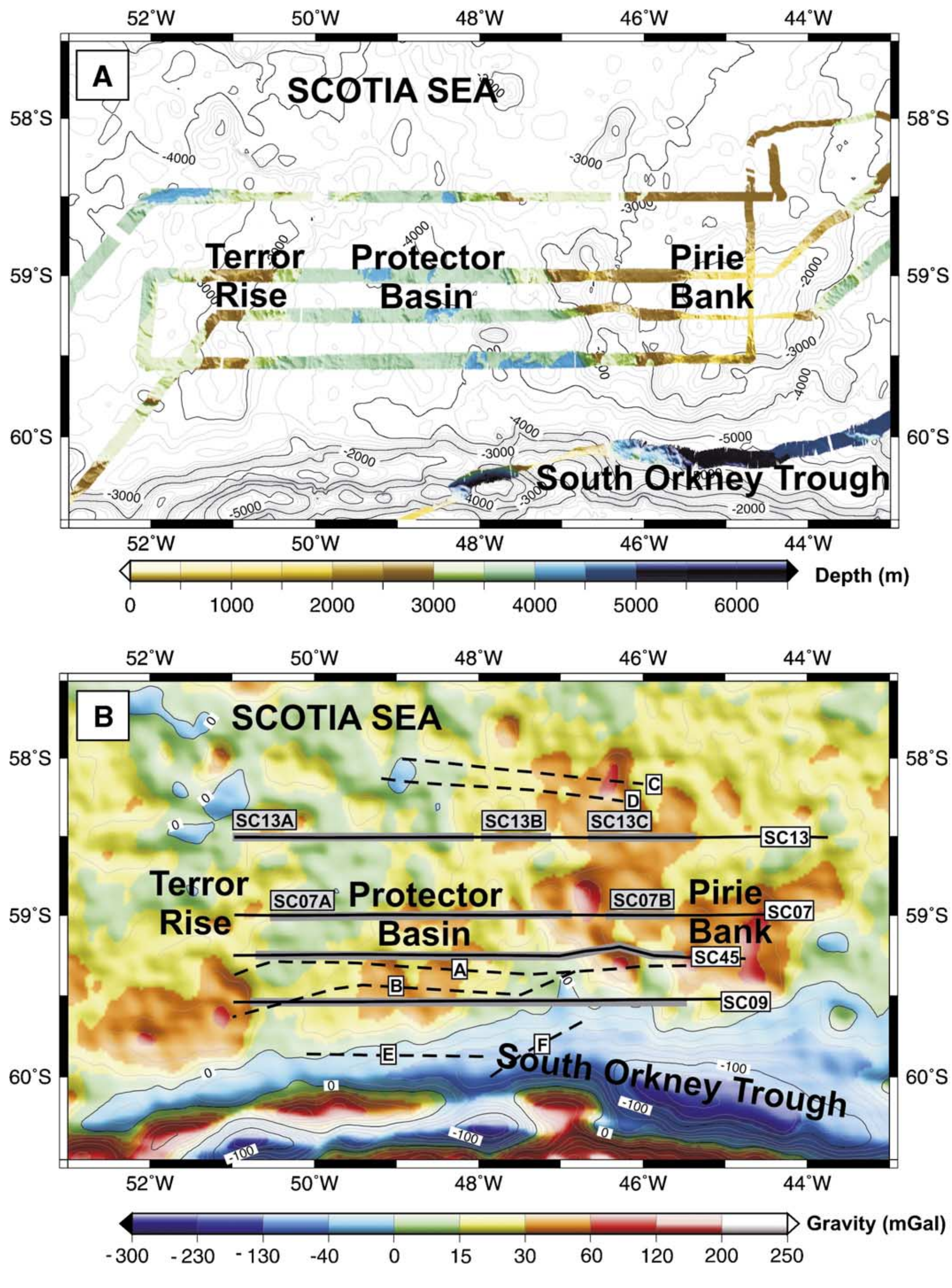

Fig. 2. Protector Basin bathymetry, including multibeam data (A) and free air gravity anomaly map (B) from Sandwell and Smith [28] database. Location of seismic lines of the SCAN2001 cruise and magnetic profiles reported by Hill and Barker [27] (A to F) are included.

2000 [29] and magnetic data recorded at the Spanish magnetic measurement station located on Livingstone Island (South Shetland Islands), for diurnal corrections.

In this contribution, we have also considered magnetic profiles reported by Hill and Barker [27] (Fig. 2). The modelling of seafloor spreading magnetic anomalies took into consideration the Cande and Kent [30] magnetic reversal time scale. In the first step, a plot including the different available E–W oriented profiles was analysed to identify correlation of positive and negative values that evidence the existence of linear magnetic anomalies. Secondly, the

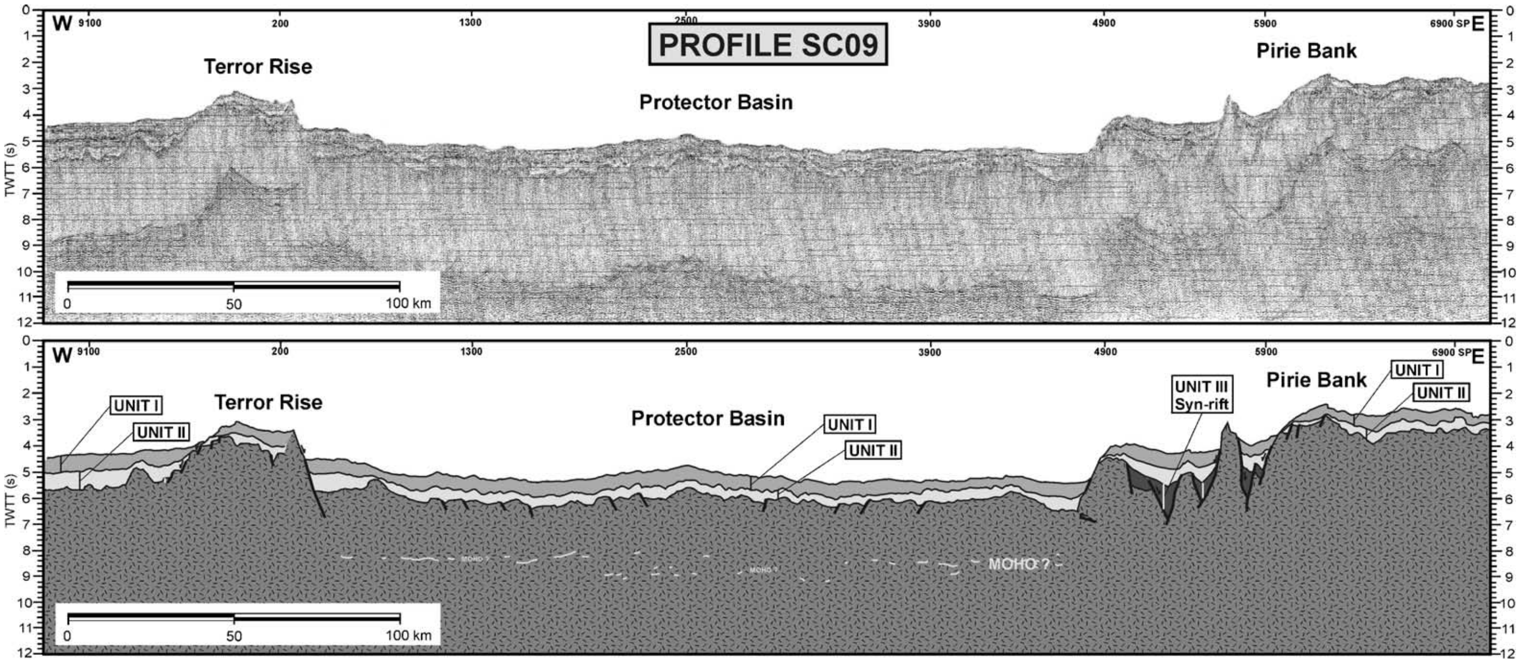

Fig. 3. MCS profile SC09 of the Protector Basin and interpretation. Location in Fig. 2. Only the main sedimentary sequences are distinguished.

measured profiles were compared with the synthetic profiles obtained with the Gravmag v. 1.7 program [31] assuming constant velocities of expansion. The intensity of remanent magnetization was taken as 6 A/m and parameters of magnetized vector were taken according to the Earth dipole magnetic field, with a paleoinclination of $-73°$.

3. Structure of Protector Basin

3.1. Seismic structure and depositional units

The Protector Basin is located near the southern boundary of the Scotia Plate (Fig. 1). Bathymetric data and free air anomaly maps (Fig. 2) indicate that the basin has a triangular shape pointing to the north. In the southern sector, its width is around 250 km and it narrows northwards until disappearing into the abyssal zones of the Scotia Sea. This geometry is a consequence of its progressive opening along a N–S oriented spreading axis located in the middle of the basin. From a morphotectonic point of view, the oceanic area of the Protector Basin is bordered by the western and eastern margins that correspond respectively to the Terror Rise and the Pirie Bank highs; and to the south, the South Scotia Ridge, where the present-day boundary between the Scotia and Antarctic Plates, with related seismicity, is located [18,32].

The MCS data, together with gravity data, help to constrain the geometry of continental and oceanic blocks. Fig. 3 shows that the central part of the Protector Basin is occupied by an oceanic crustal domain of approximately 4000 m in depth (Fig. 2) that deepens slightly southwards. The thickness of the sedimentary cover is irregular, mainly controlled by basement morphology. Maximum thickness appears close to the margins and decreases toward the central ridge, characterized by a single high whose basement crops out in the northern area (Fig. 4). Up to five sedimentary sequences have been distinguished in the

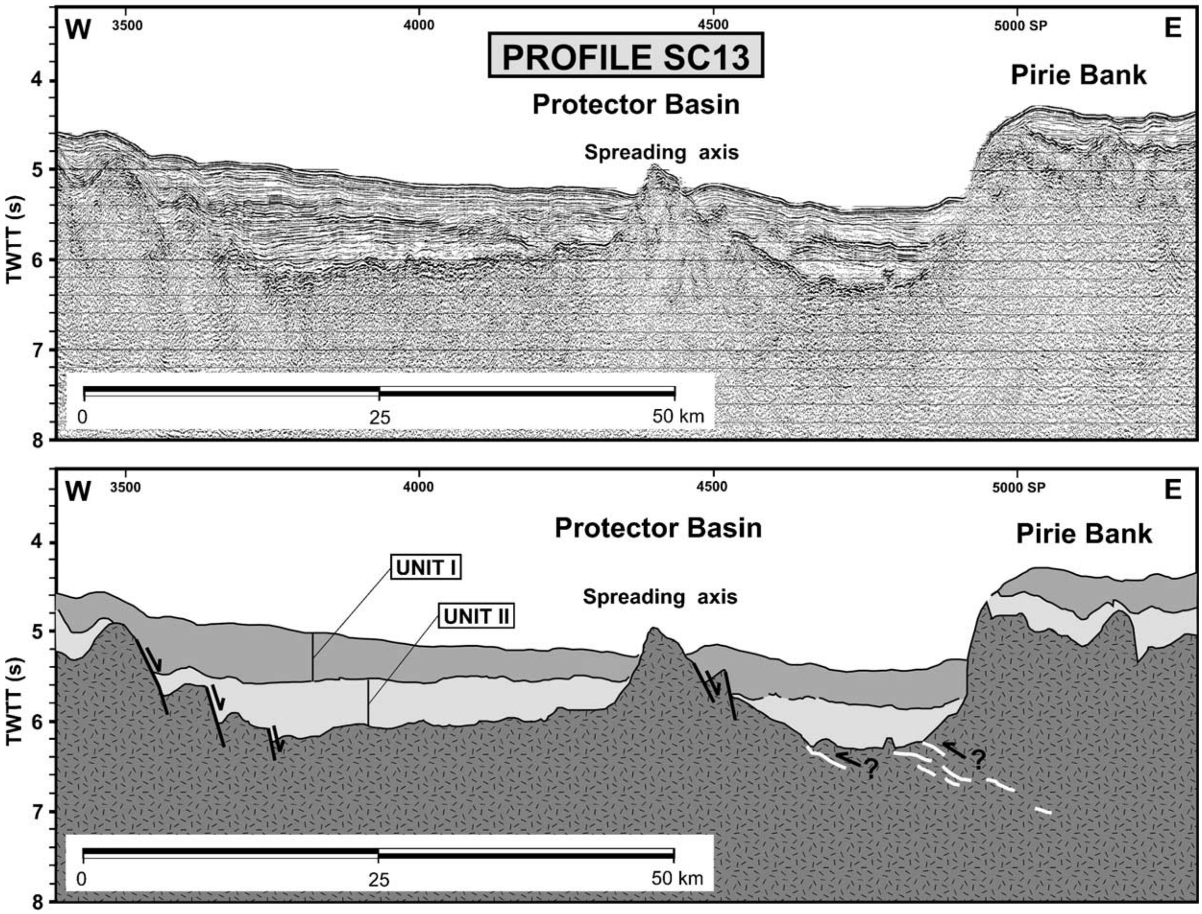

Fig. 4. Detail of MCS profile 13 of Protector Basin and interpretation. Location in Fig. 2. Only the main sedimentary sequences are distinguished.

oceanic crust of this basin [33,34], which may be grouped into two major seismic units separated by a marked reflector.

The top of the basement has an irregular morphology characteristic of an igneous nature, occasionally controlled by the development of normal faults with short slips (Figs. 3 and 4). The physiography shows a central N–S oriented ridge with flanks generally deepening toward the margins and usually in a progressive manner, according to the basement tilting. The basin shape in relation to the central ridge is roughly symmetrical in the southern profiles (profile SC09, Fig. 3) and asymmetrical northwards (profile SC13, Fig. 4), where the eastern flank is shorter and deeper, probably as a consequence of the activity of a reverse fault dipping eastward that separates the oceanic crust of Protector Basin from the thinned continental crust of the Pirie Bank. In some sectors (e.g. profile SC09, Fig. 3), a discontinuous band of reflectors (between 8 and 9 s TWT)–possibly related to the Moho–is recognized.

The Terror Rise is a minor bathymetric high that constitutes the western margin of the Protector basin, with depths of more than 2250 m. It has a NNE–SSW elongation (Fig. 2) and an asymmetrical profile. It is affected by normal faults that sink this continental block progressively into the western Scotia Sea, while the eastern boundary is sharp, controlled by a major extensional fault (Fig. 3). Several small perched basins are developed in the Terror Rise, bounded by normal faults that mainly affect the lowermost part of the sedimentary fill. The morphotectonic features indicate that the Terror Rise may constitute an extremely thinned continental crustal block.

The Pirie Bank, located at the eastern margin of the Protector Basin, corresponds to a complex continental high of about 2000 m in depth (Fig. 3). Its structure is characterized by the development of a set of basins bounded by major normal faults. In the western sector there are asymmetric small perched basins associated with normal faults dipping generally towards the oceanic domain of the Protector Basin. These small basins are half grabens. The central part of this bank is characterized by the development of basins bounded by normal faults that are wider northwards, in a region of highly stretched continental or even oceanic crust. The sedimentary cover is controlled by this structure with a maximum thickness of 2 s (TWT) in small asymmetric basins. Three main seismic units have been differentiated in the Pirie Bank. The normal faults mainly deform the lower sedimentary sequences, which may be interpreted as syn-rift deposits (Fig. 3).

3.2. Gravity models

The analysis of free air anomaly data from the region of study reveals the nature of the crustal elements and the variability of the crustal thickness. The free air anomaly map from the Sandwell and Smith database [28] (Fig. 2) shows low values (−20 to 40 mGal) in the triangular area corresponding to the Protector Basin oceanic crust, with relative minor positive anomalies in the central part, where the spreading axis is covered by sediments. The Terror Rise and the Pirie Bank are characterized by relative positive anomalies that are more intense in the case of the southern part of the Pirie Bank (30 to 130 mGal). The western margin of the Pirie Bank features a progressive and irregular westward decrease in the free air gravity values, pointing to an intermediate crust. The Protector Basin is bounded to the south by a band of negative anomaly values related to the South Orkney Trench, reaching up to −160 mGal, alternating with a chain of positive values corresponding to the continental blocks of the South Scotia Ridge.

Gravity models were determined on the basis of the free air anomaly obtained from the marine data. Along the study profiles, these anomalies are generally positive, ranging from −10 to 70 mGal (Fig. 5). The 2D gravity models (Fig. 5) were obtained considering the geometry for the sea bottom, basement and the Moho discontinuity, locally observed in oceanic crust through MCS profiles. In addition, an initial continental or oceanic attribution of the crust deduced from the seismic data was considered and checked during gravity modelling. The standard densities for the different types of rocks were taken into account [35] and sometimes modified in order to fit the models as well as possible. Although calculated and measured gravity values show a good fit, extreme anomaly values cannot be modelled adequately, probably due to the short spatial limitation of the geometry of the surface structures near the spreading axis, not considered in 2D modelling.

The central part of the basin is occupied by oceanic crust (2.95 g/cm^3) surrounded by the continental crustal blocks of Pirie Bank and Terror Rise. While in the central and southern profiles (SC09 and SC07, Fig. 5) a standard density (2.67 g/cm^3) is considered for the continental crust, in the northern profile (SC13, Fig. 5) a better fit is obtained regarding a higher density (2.75 g/cm^3) that may represent very thin continental or intermediate crust. The western basin margin is determined by the presence of a main sharp scarp, but the eastern continental basin margin, which corresponds to the Pirie Bank, is more irregular and includes several

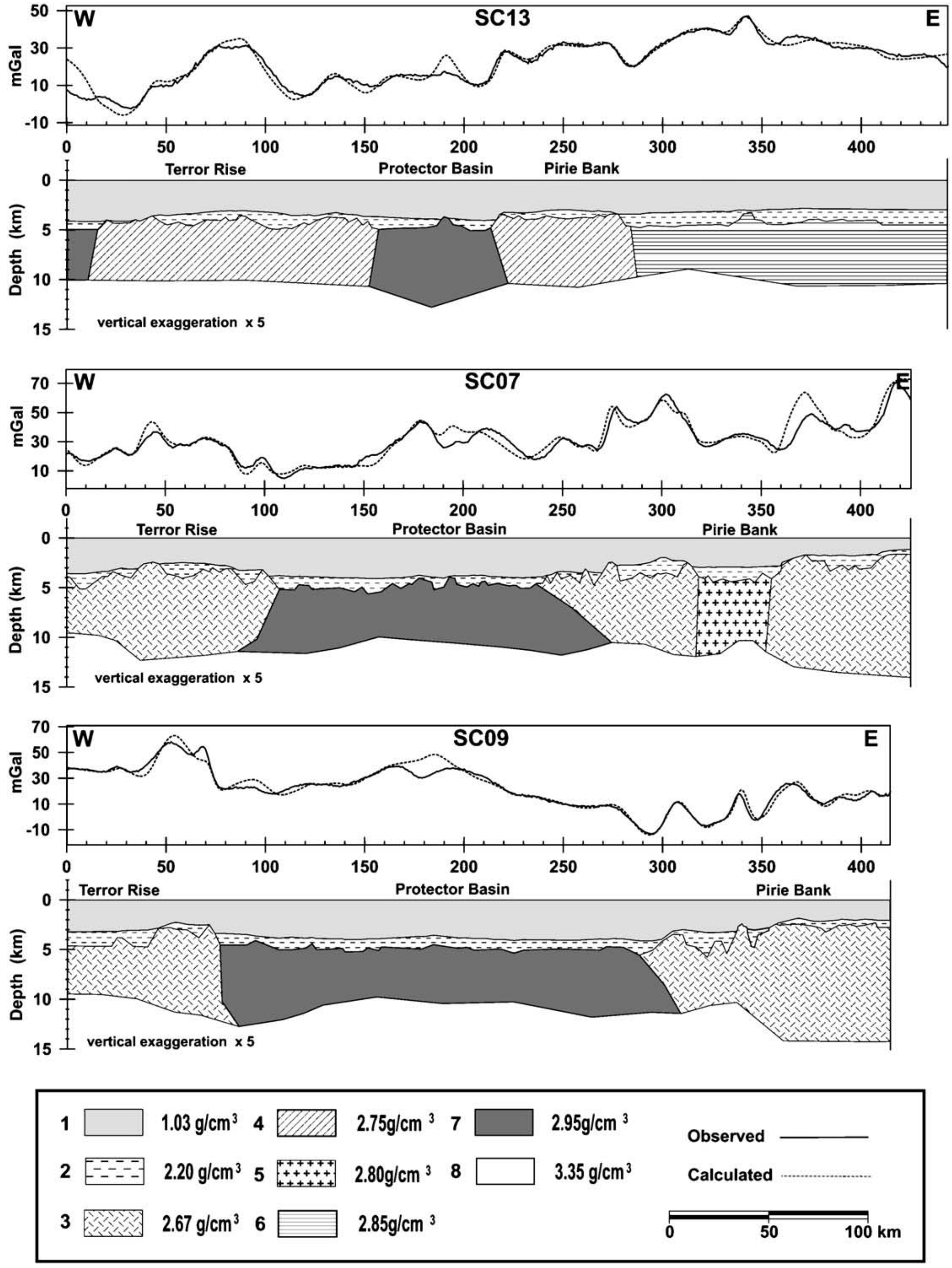

Fig. 5. Gravity models crossing the Protector Basin based on the geometry of MCS profiles. (1) Sea water, (2) sediments, (3) standard continental crust, (4) thinned continental crust, (5, 6) probable intermediate or oceanic crust, (7) oceanic crust and (8) mantle.

minor depressions, filled with sediments and highs that probably developed during the passive margin rifting. The best fit for gravity anomalies in the modelled profiles is obtained when an increase in densities with respect to the standard continental crust (2.67 g/cm^3) is considered for some intermediate blocks (2.80 g/cm^3 to

2.85 g/cm^3) from the southern to the northern profiles, indicating the presence of intermediate to oceanic crust in the thinned northern margin of the Pirie Bank. The northernmost profile (SC13, Figs. 2, 4 and 5) shows a bathymetric step, whereas the eastward dipping reflectors observed in the MCS profile (Fig. 4) may correspond to a reverse fault of continental crust on oceanic crust that is also considered in the gravity model (Fig. 5). In the central and southern profiles, the best fit between model and measured gravity anomalies is obtained when the continent/oceanic crustal boundary dips towards the continental Pirie Bank.

The Moho position determined from MCS data in some profiles is extended by gravity modelling along all the profiles. Moho depths are generally between 10 and 13 km, both in oceanic crust and in very stretched continental or intermediate crust. Only in the central and southern part of Pirie Bank, does Moho reach the deepest values of the region–14 km–in a sector of thinned continental crust.

4. Age and spreading of the oceanic crust

The age of the oceanic crust is established by the analysis of linear magnetic anomalies. The magnetic profiles collected in the Protector Basin and surrounding areas are shown in Fig. 6. Magnetic anomalies are characterized by amplitudes of up to 400 nT and are well correlated between profiles indicating good north–south trends. The magnetic anomaly pattern shows an obvious symmetry from the centre of the basin.

An unambiguous correlation with the linear magnetic time scale is not possible because of the very limited length of the magnetic anomaly sequences in this small basin and the absence of direct ages from samples of oceanic crust by dredging and drilling. Within the period 0–50 Ma, however, three simple and acceptable possibilities have been considered, taking into account the previous published profiles [27,36] (Fig. 6). Model 1 (chrons C5ABr–C5AC to C5D, 13.8–17.4 Ma) and model 2 (chrons C5D to C6AA, 17.6–22 Ma) are according Barker [26]. In addition, we include model 3 (chrons C6 to C6Cn.2n, 20.1–23.8 Ma) as another possible sequence of chrons.

Synthetic anomaly profiles with a constant total opening velocity (6 cm/yr, model 1; 6.6 cm/yr, model 2; and 8 cm/yr, model 3) were computed using the magnetic reversal time scale of Cande and Kent [30]. A magnetized body of 0.5 km thickness is considered below the sea floor, with a depth of 4 km for the basement of oceanic crust at the dead spreading axis. According to Hill and Barker [27], the thickness of the

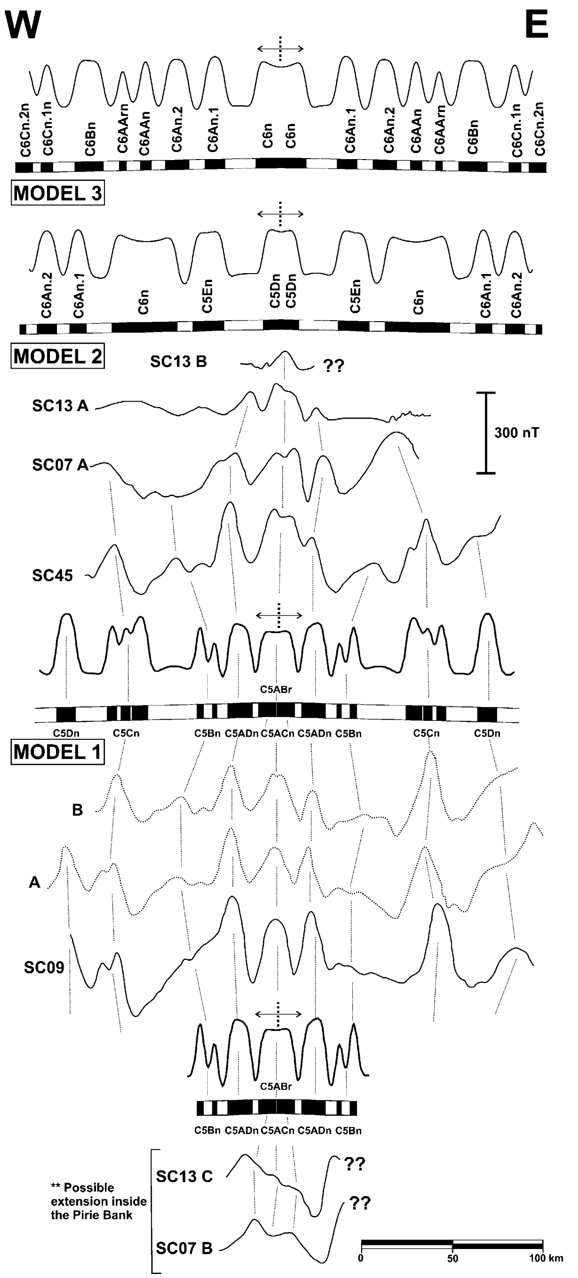

Fig. 6. Correlation of seafloor total field magnetic anomalies on profiles crossing the Protector Basin and northwestern Pirie Bank. Comparison with a constant velocity opening models based on Cande and Kent [30] magnetic reversal time scale. Model 1, chrons C5AC–C5ABr to C5D, 13.8–17.4 Ma, opening velocity of 6 cm/yr; model 2 chrons C5D to C6AA, 17.6–22 Ma, 6.6 cm/yr; model 3, chrons C6 to C6Cn.2n, 20.1–23.8 Ma. Location of profiles in Fig. 2.

magnetized body increases with the square root of age. The observed anomalies along the basin (Fig. 6) are quite similar to those of the synthetic profiles although model 1 seems to represent the best fit and we concentrate our study on it. Anomaly peaks are generally well correlated along the basin, although only the most recent anomalies are recognized to the north and anomaly C5B is only well developed in the central part of the basin. In addition, we observed several anomalies in the NE margin of the Pirie Bank (profile fragments SC13B, SC13C and SC07B, Figs. 2 and 6) in sectors of intermediate or oceanic crusts.

In the southern part of the Protector Basin (profile SC09, Fig. 6), linear magnetic anomalies C5AC to C5D (beginning) are identified; in the central part of the basin (profile SC07A, Fig. 6), magnetic anomalies C5AC to C5C (beginning) can be seen; and in the northern part (profile SC13A, Fig. 6), anomalies C5AC–C5AD are recognizable. North of 58°30′S, in the northern end of the Protector Basin, the character of magnetic anomalies progressively changes. The anomaly related to the axis of spreading shows, in the central and northern profiles (e.g. profiles SC07A and SC13A, Fig. 6), a small local minimum superimposed on a large maximum owing to the presence of a narrow negative polarity body that is also considered in the model. This negative polarity body is associated with the chron C5ABr and points to a slightly more recent age than the one proposed by Hill and Barker [27]. The interpretation of magnetic anomalies allows us to present a new scheme of chron distribution in the Protector Basin and in the northern Pirie Bank margin (Fig. 7).

Two more areas of linear magnetic anomalies are found to the east of the Protector Basin, along the northern margin of the Pirie Bank (Figs. 6 and 7). The length of sequences in these areas is less than those of the Protector Basin, and they do not allow us to present an unambiguous correlation with the linear magnetic anomaly time scale. Anomalies have amplitudes up to 250 nT and are generally elongated from north to south. Tentatively, if we consider that these anomalies developed during the same spreading period as the Protector Basin, it is possible to attribute anomaly C5AC to two segments of the eastern part of the profile SC13 (profile segments SC13B and SC13C, Figs. 6 and 7). An anomaly is also recognized on the eastern part of profile SC07 (profile segment SC07B, Figs. 6 and 7), though it is narrow. Far to the south, these anomalies disappear towards the Pirie Bank.

The mean total opening velocity during the development of Protector Basin is near 6 cm/yr, slightly higher in the central and southern parts (profiles SC09 and SC07A) than in the northern SC13A profile.

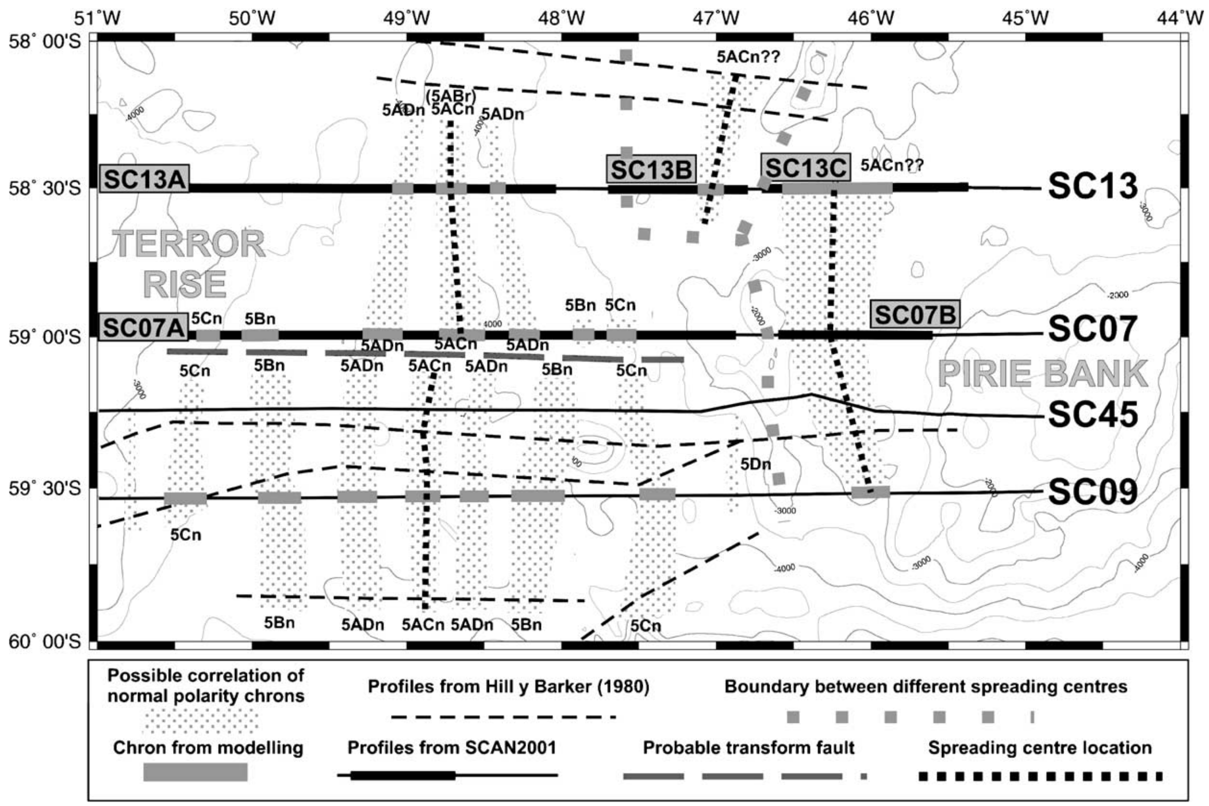

Fig. 7. Magnetic anomaly bands on bathymetric map of Protector Basin and northwestern Pirie Bank.

In detail, however, spreading velocities may show low variability, confirmed by the small divergence of distances along the profiles in between different magnetic anomalies (Fig. 6).

The correlation between adjacent profiles of the magnetic anomaly bands (Fig. 7) illustrates the oceanic crust spreading. The central and southern sectors of the basin are characterized by subparallel magnetic anomaly bands, symmetric with respect to the central ridge that progressively ends northwards toward the continental margins. In between profiles SC45 and SC07A (Fig. 7), a possible E–W oriented transform fault is identified. Towards the north, the magnetic anomaly bands are narrower and show a wedge shape. In addition, along the northern border of the Pirie Bank, two main linear magnetic anomaly bands decreasing in width southwards are identified (Fig. 7).

5. Discussion

The development of small oceanic basins has different constraints than the larger ones. While in large oceanic basins subduction zones may develop (Pacific Ocean) or may not form (Atlantic Ocean), small oceanic basins generally do not have these associated structures, probably as an influence of the relatively low density of their oceanic crusts. While the basins formed in pull apart or in back-arc settings are in general elongated, the small basins formed by the drifting of small and thinned fragments of continental crust are irregular, and their features have been poorly studied to date. The Protector Basin, located in between the western margin of the Pirie Bank and the eastern margin of the Terror Rise, may illustrate the development of small basins by block rifting and drifting. This basin has a triangular shape pointing to the north and is bounded southwards by the continental blocks related to the Scotia–Antarctic Plate boundary along the South Scotia Ridge.

The oceanic nature of the Protector Basin floor is supported by the seismic facies observed in the MCS profiles and by the presence of linear seafloor spreading magnetic anomalies. The Pirie Bank and the Terror Rise are probably formed by thinned continental crust, as suggested by the relatively shallow bathymetry of the sea areas with respect to the abyssal plain of the Protector Basin. The more chaotic and less reflective character of the top of the acoustic basement and the relatively low density obtained in the gravity models also support this hypothesis. In any case, the northern part of the Pirie Bank and even the Terror Rise would represent extremely thinned continental crusts as a consequence of the overprinting of the opening of the Drake Passage and the Protector Basin.

The Protector Basin grows as a consequence of the continental stretching and subsequent oceanic spreading during Middle Miocene times in relation to the development of the southern branch of the Scotia Arc. This process may be a consequence of an eastward flow of the Pacific mantle through the Scotia Arc [37]. While the contact with the Terror Rise is sharp and probably determined by a normal fault, the contact with the Pirie Bank is irregular, characterized by several small perched basins where syn-rift deposits are well recognized below a post-rift sedimentary sequence. To the north, these small basins become larger and have associated linear magnetic anomalies indicating that an intermediate or even an oceanic crust is developed. The asymmetry of the margins and of the surrounding continental banks suggests that the extension along the basin was asymmetric, and related to a low angle fault dipping towards the Terror Rise, similar to those proposed for continental stretching [38]. This asymmetry may similar to the one proposed for the development of large basins.

The data recently acquired during the SCAN 2001 cruise are consistent with the spreading ages proposed by Hill and Barker [27] and allow us to specify their variability along the basin. The Protector Basin opened as a consequence of a northward propagating rift. A set of seafloor magnetic anomalies ranging from chrons C5ACn to C5Dn (14 to 17.4 Ma) has been clearly identified in the basin. Moreover, in some profiles of the central and northern part of the basin, a younger chron (C5ABr, 13.8 Ma) has influenced the anomaly profile on the ridge. The oldest bands of magnetic anomalies progressively end northwards, from the C5Dn in the southern sector, to C5Bn in the central part and up to C5ADn in the northern part (Fig. 7).

The data previously presented suggest the tectonic development of the Protector Basin sketched in Fig. 8. An initial stage of rifting (Fig. 8A) on previously thinned continental crust of the southern part of the Drake Passage is followed by a second stage (Fig. 8B) that implies relative block rotation and opening and spreading of the oceanic crust. The spreading started in the southern part of the basin and extended towards the northern sector. The northwards propagation of the spreading axis continued for 3.6 ma (time space between chrons C5AD and C5D) for about 113 km (distance between profiles SC07A and SC13A) with a average velocity of 3 cm/yr–that is, about the average of half spreading rate–and produced the triangular shape of the basin. These relatively high spreading

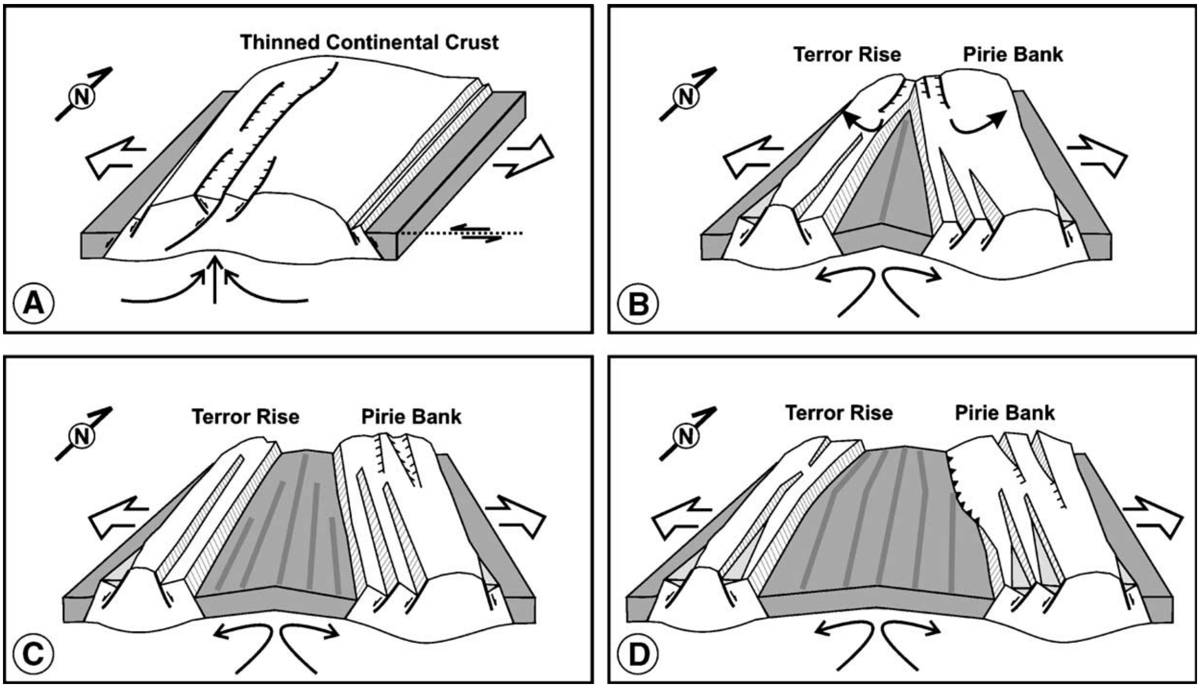

Fig. 8. Tectonic sketch of development of Protector Basin. White, continental crust; grey, oceanic crust.

rates developed a spreading axis characterized by a single ridge. The next stage (Fig. 8C) implies E–W extension and drifting predominant over rotation, as is signaled by the approximately parallel recentmost magnetic anomaly bands in the southern part of the basin, whose small irregularities indicate E–W stretching. This trend of extension is also confirmed by the E–W orientation of the transform fault obtained in between SC07A and SC45 profiles from the interpretation of the magnetic anomaly data.

In a late stage of development, the southwards propagation of thinning or spreading axes along the northern passive margin of the Pirie Bank, conjugated to the Protector Basin, possibly produced rotation of an intermediate block (Fig. 8D). This setting may give rise in the northern part of the basin to northwards convergent magnetic anomalies ranging from C5ADn up to C5ACn. If we apply the same spreading model as applied for Protector Basin in the north Pirie Bank (profile SC13), it is possible to attribute the spreading to chrons C5ABr–C5ACr (Fig. 6). To the south, when approaching the Pirie Bank, spreading becomes more and more narrow and, at 59°30′S (profile SC 07B), it practically disappears (Fig. 7). Bathymetry (Fig. 2) also shows the progressive narrowing of sea floor in the southern direction. Another area of possible spreading lies near 47°W, 58°30′S. In this area, chrons C5ACn and C5ACr can be estimated if we apply the same spreading model as for Protector Basin. These spreading axes produce E–W extension in the region as a whole. Available magnetic data do not contradict the presence of a northern transform fault as indicated by Hill and Barker [27].

The end of the oceanic spreading may not only be a consequence of the switching of the extension eastwards of the Scotia Sea by the development of the Scotia Arc, but also of a compressional deformation that produces reverse faulting at the northeastern border of the Protector Basin at the contact with the Pirie Bank margin (profile SC13, Fig. 4). This fault accentuates the sharp northern end of the basin and its triangular shape. The age of this fault would be shortly after the spreading because apparently no sediments filling the basin are involved (Fig. 4). While in large plates with old oceanic crust, as in the Pacific Plate, the development of young oceanic crust along the ridges may coexist with the presence of subduction of old and dense oceanic crust, this mechanism does not develop in small oceanic basins, where the ridge is frozen before true subduction develops.

Protector Basin is driven by forces at the margins of the basin. However, there appear to be differences from the Schouten model [15], where edge-driven kinematics also results in rift propagation, with Euler poles near the edges, resulting in rapid variations in spreading rates along the propagating ridge axes and simple rotation of the microplate. In the Protector, Basin the spreading rates do not appear to vary as quickly as predicted by the edge-driven model and, although there is a “v”-shaped opening of the basin, there is no overall rotation. This may be a consequence of the combined oceanic and continental terrains involved in the Protector Basin kinematics, resulting in deformation that is partitioned between seafloor spreading and continental extension.

The Scotia Plate, considered thus far as mainly oceanic in nature, is formed by a complex set of oceanic crusts and thin continental blocks. Other similar basins developed in this area, such as the Dove Basin located between Pirie Bank and Bruce Bank, and the Scan Basin, located in between the Bruce and Discovery banks. These basins are poorly known up to date. The development of the Protector Basin is simultaneous with the activity of the West Scotia Ridge spreading axis, with a NE–SW orientation, from anomaly C10 (28.7 Ma, [25]) up to anomaly C3A (6.5 Ma, [39]), and represents a variation of the spreading direction from NW–SE up to E–W, necessary for the eastward development of the tectonic arc. The E–W oceanic spreading in the Protector Basin, which ends about 14 Ma (chron C5ACn) ago in this area, continues up to present in the Scotia–Sandwich spreading axis.

In the Antarctic Plate, the Powell Basin was also developed by a mechanism of continental fragmentation caused by eastward drifting of the South Orkney microcontinent [21,22] from 26 to 17.6 Ma [19] or during the period 29.7 to 22.1 Ma [20]. Later the Jane Basin develops (17.6 to 14.4 Ma, [24]), during a period roughly similar to the one proposed in this contribution for the Protector Basin. However, the mechanisms of development of the two basins, separated by the South Scotia Ridge, are different: Jane Basin is interpreted as a back-arc basin associated to the SE border of the South Orkney microcontinent [24], whereas in this contribution we support that the Protector Basin develops as a consequence of continental block fragmentation and drifting related to the development of the southern branch of the Scotia Arc. Yet the simultaneous opening of the two basins may be related with the final stage of subduction of the western part of the Weddell Sea oceanic crust and a subsequent reorganization of the major plate setting.

6. Conclusions

The Protector Basin is an asymmetrical rifted basin probably formed by the activity of a westward dipping low angle fault. The Terror Rise and the Pirie Bank correspond respectively to the upper and lower blocks of this extensional system.

The Protector Basin spreading is related to a north propagating rift. The interpretation of magnetic anomalies indicates that the oceanic spreading was active during a period of about 3.6 ma comprised between chrons C5ACn and C5Dn (14–17.6 Ma). Although in all the profiles the end of spreading corresponds to the same chron (C5ACn, in transition to C5ABr, 13.8 Ma), the set of chrons is more complete to the south, ranging from C5ADn in the northern part of the basin up to C5Dn in the southern part. This geometry is a consequence of the northward propagation of the spreading axis during the basin development at a rate of approximately 3 cm/yr, equivalent to the average half opening rate (6 cm/yr of total opening) in the area. In addition, two other minor spreading axes, located in the northern margin of Pirie Bank, extended to the south and existed during a short time period of about 0.5 Ma in the latest stages. The development of these two last spreading axes probably produces block rotations and accentuates the triangular shape of the anomalies in the northern part of the Protector Basin. On a whole, the spreading system indicates regional E–W stretching.

After the end of the oceanic spreading, the spreading axis freezes and the ridge begins to be covered by sediments. The development of a reverse fault located at the northeastern border of the basin, in contact with the Pirie Bank margin, indicates an inversion in the tectonic regime that accentuates the sharp northern end of the basin.

The Protector Basin represents the oldest evidence up to date of the E–W oriented extension into the Scotia Arc, which switched eastward up to the present-day active Scotia–Sandwich spreading axis. The geophysical data presented here evidence the extreme fragmentation and stretching of the continental crust, which for small oceans should not be considered rigid blocks of constant shape during reconstructions. In addition, the new data presented here may help to constrain the tectonic development of the Scotia Arc, although more data in similar basins located north of the South Scotia Ridge are needed for this purpose. The opening of the Drake Passage and the dispersion of its crustal elements are determinant in the development of one of the most important oceanic gateways around the Antarctica, with a global climatic influence.

The continental rifting in small oceanic basins may develop just as it does in large basins, through the activity of crustal detachments that produce asymmetric continental margins. However, the development of small oceanic basins by continental block drifting entails differential features with respect to other oceanic basins, such as the presence of well developed propagating rift with accentuated triangular shapes, implying large rotation of small continental blocks and the development of relays of conjugate spreading axes. In addition, the presence of fossil spreading axes, generally preserved below the sediments, is a common feature because in these basins the cessation of oceanic spreading is related to the end of block drifting and the frozen spreading axis is not destroyed by subduction.

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