The Scan Basin evolution: Oceanographic consequences of the deep connection between the Weddell and Scotia Seas (Antarctica)

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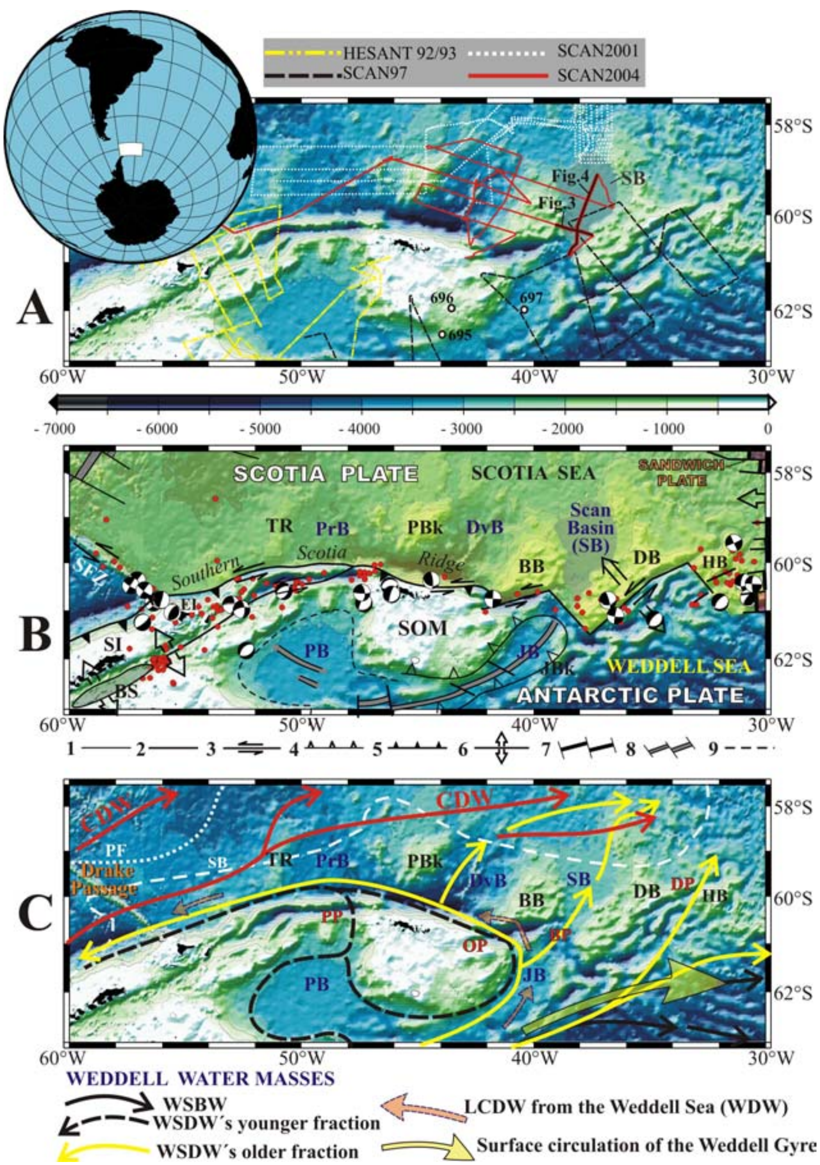
Summary The Scan Basin is a small oceanic basin located in the southern central Scotia Sea, north of the Bruce Passage (BP) which represents the main gateway between the Weddell Sea and the Scotia Sea. A seismic stratigraphic analysis has been carried out on multichannel seismic reflection profiles to determine the Miocene to present evolution of the basin. Five seismic units are identified. The oldest unit (Sc5) was deposited during seafloor spreading in the Scan Basin. The upper four units represent the post-spreading deposits and show three major evolutionary stages: A) pre-BP opening (unit Sc-4); B) BP opening (units Sc3 and Sc2) and C) post-BP opening (unit Sc1). Stage B occurred once the BP was deep enough to allow Weddell Sea Deep Water (WSDW) into the Scotia Sea. This led to the development of large, northwards-migrating contourite drifts. Stage C developed during the present-day sinistral transcurrent compressive regime.



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Introduction

Several independent small basins bounded by extended continental blocks are recognised in the southern Scotia Sea and northern Weddell Sea, near the Scotia-Antarctic plate boundary (Fig. 1). All these basins have developed in response to sea-floor spreading in the Scotia Sea and subduction of the Weddell Sea and Southern Atlantic below several fragments of an eastward- and southward-migrating trench (Maldonado et al., 2006). The main

Figure 1. Location of the Scan Basin. A) Position of seismic profiles collected in the area. B) Geological setting. 1: transform fault; 2: active transcurrent fault; 3: inactive subduction zone, 4: active subduction zone; 5: active extensional zone; 6: active transtensional zone; 7: active spreading centre; 8: inactive; spreading centre; 9: continental-oceanic crust boundary. BB: Bruce Bank; DB: Discovery Bank; DvB: Dove Basin; HB: Herdman Bank; JB: Jane Basin; JBk: Jane Bank; PB: Powell Basin; PBk: Pirie Bank; PrB: Protector Basin; SB: Scan Basin; SOM: South Orkney Microcontinent; TR: Terror Rise; C) Regional deep-water masses circulation. BP = Bruce Passage; DP = Discovery Passage; OP = Orkney Passage; PP = Philip Passage.

aim of this work is to elucidate the Miocene to present evolution of the Scan Basin, located between Bruce Bank (BB) to the west and Discovery Bank (DB) to the east and northeast of Bruce Passage (BP), which provides the main connection between the Weddell and Scotia Seas through Jane Basin (JB) (Fig. 1B). To the south, a complex tectonic structure comprising highs and troughs constitutes the plate boundary, and separates the Scan Basin, through the BP, from the NE prolongation of both the South Orkney Microcontinent (SOM) and JB. To the north, the Scan Basin is connected to the abyssal plain of the central Scotia Sea. Tectonic deformation of that plate boundary is concentrated along the South Scotia Ridge (SSR), formed by a complex array of continental blocks that show evidence of tectonic activity related to the present-day sinistral transcurrent motion (Bohoyo et al., 2007).

The present study is based on new geophysical data collected during the SCAN2004 cruise onboard R/V *Hesperides* (Figure. 1A). We have focused on interpretation of multichannel seismic reflection (MCS) profiles, in particular two sections, one orthogonal to the Scan Basin margins and one parallel to the eastern margin.

Oceanographic framework

Among the deep-water masses in the Weddell and Scotia Seas region, two distinct components can be distinguished (Naveira-Garabato et al., 2002) (Fig.1C):

- The Circumpolar Deep Water (CDW) flows mostly to the E with the ACC. It is internally sub-divided into Upper (UCDW) and Lower (LCDW) components. The LCDW is the densest component, derived mainly from North Atlantic Deep Water (NADW) intruding into the ACC in the Atlantic sector.
- The deepest water mass is the Antarctic Bottom Water (AABW), which is composed of the Weddell Sea Bottom Water (WSBW) and the Weddell Sea Deep Water (WSDW). The Warm Deep Water (WDW) flowing above the WSDW is a branch of the LCDW in the Weddell Sea. WSBW is the deepest water mass and is bathymetrically constrained to circulate within the Weddell Gyre. The WSDW is not a uniform water mass, and can be sub-divided into younger and older fractions. The WSDW's older fraction flows below 1600 m, and is divided into two different main cores. One core is channelled through JB and overflows into the Scotia Sea beyond the SOM mainly through Orkney Passage (OP), BP and Discovery Passage (DP) (Fig 2). The other core moves (as does the WSBW), around the South Sandwich Trench towards the north. The WSDW spills over the SSR and spreads westward, reaching Drake Passage and filling the bottom of the South Shetland Trench.

This modern oceanographic regime came into existence following: (a) establishment of a deep water pathway in Drake Passage when the Scotia Sea started to develop; (b) the opening of gaps between the continental and arc fragments to the east in the Scotia Sea to allow a complete, full-ocean-depth ACC to develop; and (c) the opening of gaps in the SSR to allow WSDW (and WDW) to flow from the Weddell Gyre into the Scotia Sea, and then to flow westwards. According to Maldonado et al. (2003), initial incursions of the WSDW into the Scotia Sea were possible from the Middle Miocene.

Morpho-structural and seismic stratigraphic analysis

The Scan Basin is a small, oceanic basin with a generally NE trend and opening to the north, showing a triangular shape. It ranges in width from about 40 km in the south to 150 km in the north, and is about 250 km in length (Figs 1B & 2). The morphology and orientation of the basin suggests that ENE–WSW oriented oceanic spreading or continental crustal stretching caused the separation of BB and DB. A WNW–ESE oriented basement high is located in the eastern part of BP, at the southernmost end of the Scan Basin and

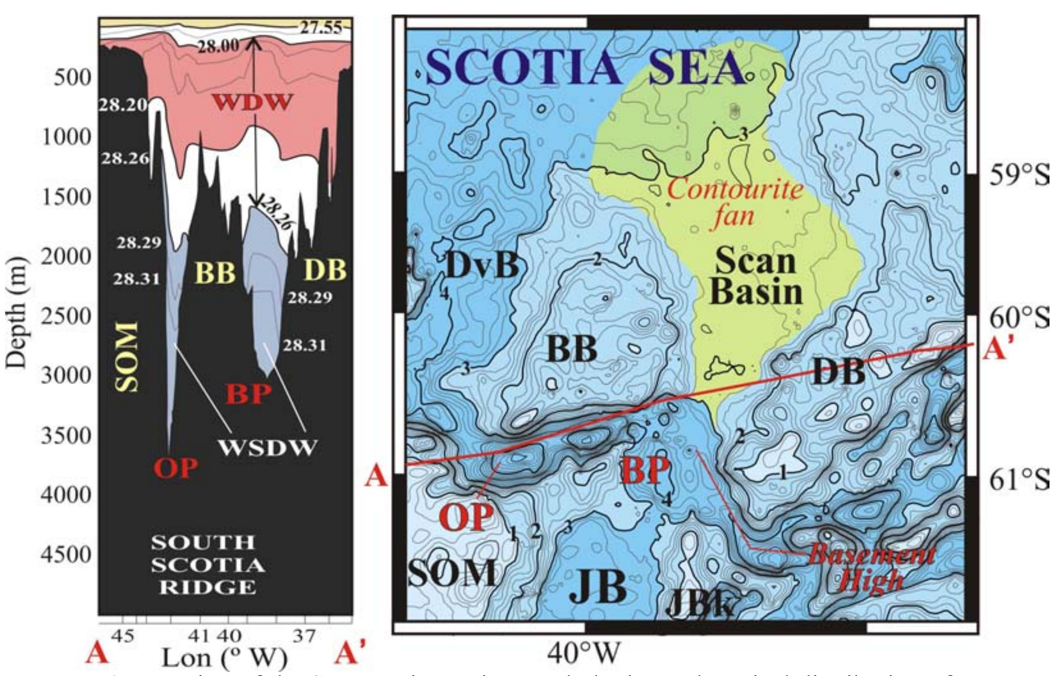

Figure 2. Location of the Scan Basin. Main morphologies and vertical distribution of water masses with density contours are showed (Legend shown in Figure1).

northernmost part of JB. This basement structure is approximately 1000 m high, 30 km wide and 45 km in length (Fig. 2 & 3). The sedimentary record is deformed over the basement high, reaching a total of ~1500 ms in thickness but thinning northwards to ~1200 ms (twt). Seismic stratigraphic analysis has permitted the recognition of five seismic units, Sc5 to Sc1, characterising four evolutionary stages of the Basin (Figs 3 & 4). The basement was not identified in the southern sector, where internal reflections could be attributed to a thinned continental crust. Nevertheless, the oceanic basement is clearly identified at variable depths of 5-6 s (twt) in the northern sector.

In the southern sector, a thick deposit (unit Sc5) characterises the syn-rift stage (Fig. 3). This unit is identified over the eastern flank of BB, where it is ~800 ms thick and shows high-amplitude internal reflections tilted toward the E and with high lateral continuity. The internal configuration changes eastward to massive, chaotic seismic facies. Four major seismic units constitute the post-drift sedimentary record (units Sc4 to Sc1). These seismic units abut westward against BB in the southern sector, sealing syn-rift deposits. Nevertheless, in the northern sector they can be correlated with the Dove Basin (DvB) over BB. Eastwards, these deposits occur on DB where they are deformed and tilted to the west. Units Sc4 to Sc1 characterise the following three evolutionary stages (Fig. 3 & 4):

a) Pre- BP opening stage (unit Sc-4)

This unit shows a patchy distribution above the older unit Sc5 in the south and above oceanic basement to the north. It is ~400 ms thick on average, but it may reach up to 1 s thick above the eastern flank of DB or it may pinch out laterally. Internal reflections display high amplitude and lateral continuity, showing a southward progradational trend.

b) BP opening stage (units Sc3 and Sc2)

The onset of this stage is recorded by a widespread, high-amplitude discontinuity (Reflector **c**), that can be traced at basin scale. Units Sc3 and Sc2 display similar seismic facies, but are separated by Reflector **b**; they characterising a large confined drift. Although sheet-like morphologies are most common in both seismic units, they locally show mounded geometries. Seismic units Sc3 and Sc2 prograde northward in the southernmost sector, and internal reflections display high to very high amplitudes and low lateral continuity. Depocenters in units Sc3 and Sc2 occur close to DB and form an asymmetrical basin, where Reflectors **c** and **b** are marked by paleo-valleys positioned at the base and oriented parallel to the DB (eastern part of Scan Basin). Unit Sc3 shows two internal subunits (b and a) that downlap onto Reflector **c**. These subunits have a combined thickness of ~400 ms in the southern sector but thin considerably to the north. The upper boundary (Reflector **b**) is an erosive unconformity with low to moderate amplitude. The younger unit Sc2 is up to 600 ms thick in the southern sector, and thins northward, where it is ~400 ms thick on average. Unit Sc2 shows downlap terminations over the Reflector **b**, and displays mounded and sheet-like external forms. Superimposed sedimentary waves are recognized locally.

c) Post- BP opening stage (unit Sc1)

The youngest seismic unit is composed of several subunits. The lower discontinuity (Reflector **a**) shows high amplitude and high lateral continuity, constituting a significant change in the sedimentary evolution of the basin. This

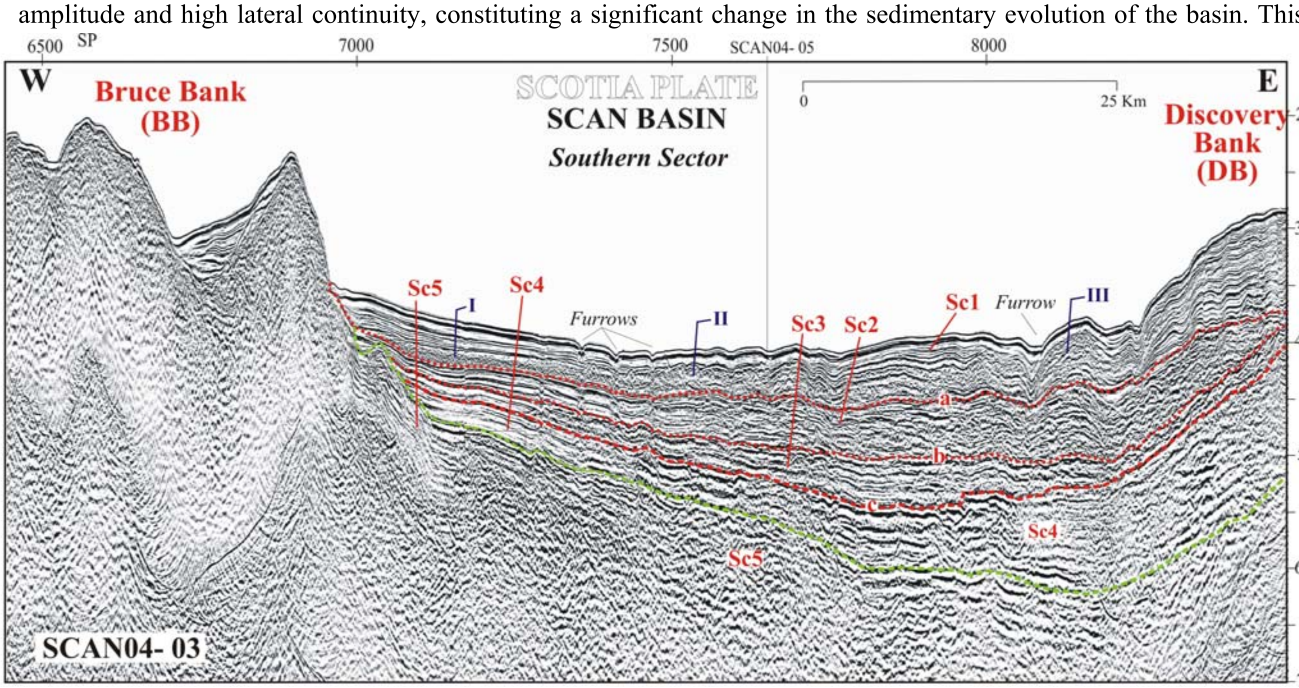

Figure 3. Seismic profile Scan04-05 collected across the Scan Basin. Seismic units (Sc5 to Sc1) are illustrated. Location shown in Figure 1A.

boundary is interpreted as an erosive surface which controls a paleo-valley situated at the base of unit Sc1 and parallel to the BB (western part of Scan Basin). Above Reflector **a** (and before Unit Sc1), four lobate subunits (IV, III, II & I in Figs 3 & 4) are locally identified which are characterized by chaotic to massive seismic facies. The distribution of the subunits shows a progressive northward displacement from oldest to youngest. Above these subunits, a thick homogeneous unit (Unit Sc1) with wide distribution and reflective acoustic response is present. Above the basement high in the southernmost sector this unit is quite thin (~100 ms); it then reaches ~400 ms thickness in the southern sector and is 600 ms thick in the northernmost sector. This unit is characterized by thin, well-stratified, sub-parallel reflectors with very good lateral continuity. It progrades northwards and downlaps onto the basal discontinuity. Low-amplitude sediment waves are identified locally. Unit Sc1 is interpreted as a massive contourite fan. Three internal subunits (c, b and a) can be identified within Sc1, as well as many furrows, especially in the southern sector of the basin.

Discussion and conclusion: Scan Basin evolution and its oceanographic consequences

The NNE margin of the SOM, with its WNW–ESE orientation, is characterised by convergence that produces the subduction of the Scotia Plate below the Antarctic Plate, as proposed by Busetti et al. (2000). Between the SOM and BB, an E–W oriented depression with associated seismic activity and strike-slip earthquake focal mechanisms points to a purely sinistral regime on E–W oriented faults (Bohoyo et al., 2007).

The four aforementioned evolutionary stages within the Scan Basin should be placed in the context of basin evolution and the connection between the Weddell Sea and Scotia Sea through the BP. The basement age of the Scan Basin is difficult to determine, but, taking in consideration the regional tectonic context (Galindo-Zaldívar et al., 2006; Bohoyo et al., 2007), the age of opening of the Scan Basin should be coeval with the age of opening of the Protector and Dove Basins, which took place between 14 and 12 Ma (Middle Miocene), later than JB, which was had opened by 14.4 Ma (Bohoyo et al., 2002). Unit Sc-4 was probably deposited once the Scan Basin and JB were already opened but prior to any deep connection between them. This unit is most probably Middle Miocene in age. In any case, by the Early Miocene, a deep water pathway had certainly been established through the Drake Passage, allowing vigorous ACC circulation. Paleobathymetric analysis shows that at 20 Ma the deep basins of the southern hemisphere were well connected (Lawver and Gahagan, 2003). The southwards progradation of the deposits was induced by the effect of the circulation of one southern core of the CDW within the Scan Basin.

Reflector **c** correlates with the beginning of the opening of BP, initiated once this passage was opened (or deep enough) for deep water circulation. The existence of different units (Sc3, Sc2 and Sc1) suggests that the connection took place in different steps, which produced the stacking of large, northwards-migrating drifts as a consequence of the WSDW incursion into the Scotia Sea, but being restricted first to the interior of the Scan Basin (unit Sc3). Sykes et al., (1998) suggested that by 15 Ma, due to waning proto-AABW production, bottom current activity due to AABW was mainly restricted to water depths greater than ~5500 m, and therefore the branch of dense WSDW flowing to the Pacific margin may have been relatively weak during the Middle–Late Miocene, which could explain why unit Sc3 thins out northwards. Paleo-valleys related to Reflectors **c** and **b**, allow us to infer that during the deposition of units Sc3 and Sc2, the main core of the WSDW was located in the eastern part of the Scan Basin (right downstream), at the base of the DB.

The post-BP opening stage represents the last major evolutionary stage of Scan Basin, starting with Reflector **a**. The deposition of the four lobate chaotic subunits (VI, III, II & I) represents an important event related to the present compressive regime in the Scan Basin. This compressive regime probably produced: (a) the deformation and tilting of the units generated in the previous stages; (b) the basement high located beneath the eastern part of BP, which may be a pop-up structure due to a local compressive regime as proposed by Bohoyo et al. (2007) in their tectonic model; (c) the lateral migration in position of the main core of the WSDW, which has been confined from this time until the present

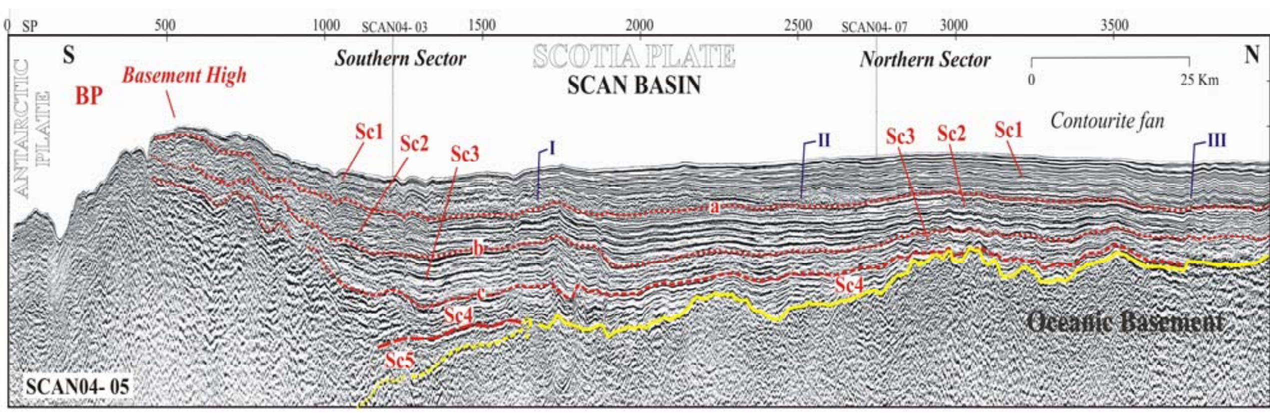

Figure 4. Seismic profile Scan04-05 collected along the Scan Basin. Seismic units (Sc5 to Sc1) and basement are illustrated. Location shown in Figure 1A.

day to the western part of the basin (left downstream) at the base of the BB. This lateral change in the position of the main core can be related to formation of the basement high in the BP, thereby constraining the principal core to the western margin of this high. The present-day sinistral transcurrent regime, with local compression, was established once (a) all basins located in the southern Scotia Sea had completely opened (10–12 Ma, Galindo-Zaldívar et al., 2006), (b) the onset of oceanic spreading in the East Scotia Ridge (C5C?- 16.4 Ma, Larter et al., 2003) took place, and (c) spreading in the West Scotia Ridge (C4- 6 Ma, Maldonado et al., 2000) had ceased.

A massive northwards-migrating contourite fan was deposited coevally with the compressive regime. Internal facies and common erosive features suggest an intensification of the WSDW energy in comparison with older units. Therefore these deposits could be related to the later, waxing phase of AABW after the latest Miocene-early Pliocene, which permitted the reconnection of the deep basins, thereby activating a strong thermohaline circulation (Sykes et al., 1998).

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