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The global relevance of the Scotia Arc: an introduction

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Abstract

The Scotia Arc, situated between South America and Antarctica, is one of the Earth's most important ocean gateways and former land bridges. Understanding its structure and development is critical for the knowledge of tectonic, paleoenvironmental and biological processes in the southern oceans and Antarctica. It extends from the Drake Passage in the west, where the Shackleton Fracture Zone forms a prominent, but discontinuous, bathymetric ridge between the southern South American continent and the northern tip of the Antarctic Peninsula to the active intra-oceanic volcanic arc forming the South Sandwich Island in the east. The tectonic arc comprises the NSR to the north and to the south the South Scotia Ridge, both transcurrent plate margins that respectively include the South Georgia and South Orkney microcontinents. The Scotia and Sandwich tectonic plates form the major basin within these margins. As the basins opened, formation of first shallow sea ways and then deep ocean connections controlled the initiation and development of the Antarctic Circumpolar Current, which is widely thought to have been important in providing the climatic conditions for formation of the polar ice-sheets. The evolution of the Scotia Arc is therefore of global palaeoclimatic significance. The Scotia Arc has been the focus of increasing international research interest. Many recent studies have stressed the links and interactions between the solid Earth, oceanographic, palaeoenvironmental and biological processes in the area.

This special issue presents new works that summarize significant recent research results and synthesize the current state of knowledge for the Scotia Arc.

Keywords: Scotia Arc, Scotia Sea, Drake Passage, continental break-up, back-arc basins, ocean spreading, land-bridge, depositional processes, geological hazards, Southern Ocean paleoceanography, paleobiology, global changes

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1. Importance of the Scotia Arc

The Scotia Arc (Figs. 1, 2), situated between the southeastern Pacific and the southwestern Atlantic oceans, is one of Earth's major ocean gateways and is critical for understanding behavior of the Antarctic Circumpolar Current (ACC) and its influence on the development of global climate, the evolution and stability of Antarctic ice-sheets and Southern Hemisphere biodiversity (Kennett, 1977; Barker and Burrell, 1977; Maldonado et al., 2003; Livermore et al., 2004; Scher and Martin, 2006). It is also important for understanding the processes and consequences of Gondwana break-up, current and past Southern Hemisphere plate motions, ocean basin tectonics and development of subduction zones (Barker, 2001; Leat et al., 2004; Dalziel et al., 2013a, 2013b). The Scotia Arc influences the exchanges between the Pacific and Atlantic oceans: deep mantle flow, oceanographic water masses, and migrations of biota (Alvarez, 1982; Pearce et al., 2001; Russo and Silver, 1994; Maldonado et al., 2006; Lagabrielle et al., 2009; Eagles and Jokat, 2014; Martos et al., 2014a, and references therein). This arc embraces the Scotia Sea, an ocean basin located between South America and the Antarctic Peninsula that connects the Pacific and Atlantic oceans (Figs. 1, 2). Drake Passage, located between the southern tip of South America and the Antarctic Peninsula (Figs. 2, 3), and the Scotia Sea were formed by the tectonic dispersion of the continental blocks that until the early Cenozoic constituted a continental bridge between South America and the Antarctic Peninsula (Lawver and Gahagan, 2003; Livermore et al., 2007).

Some aspects of the tectonic and environmental framework of the Scotia Arc are now relatively well established, including the onshore magmatic and structural development and most of the history of sea floor spreading along the West and East Scotia Ridges, although many others are the subject of on-going debate. There have been significant new discoveries leading to improved understanding of the Scotia Arc over the past two decades. Nevertheless, much of the marine record in this dominantly submarine region, including the tectonic development of the key Central Scotia Sea, the age and significance of small oceanic basins in the southern Scotia Sea, the relationship of onshore to offshore paleoenviromental records, the paleoceanographic evolution, and the development of marine biota, among others, are still poorly known or actively debated. Glaciogenic erosion and sedimentation controlled by advances and retreats of ice sheets have modified the continental shelves and slopes, while interaction of powerful bottom currents with sediments has produced large scale contouritic sediment drifts (Howe et al., 1998; Maldonado et al., 2003; Hillenbrand et al., 2008; Milliken et al., 2009; Simms et al., 2011; Nitsche et al., 2013). The role of the region as a land bridge for terrestrial biota before final formation of an ocean gateway is also a topic of considerable interest. The Scotia Arc is therefore an exceptional region for multidisciplinary environmental science where major questions about the evolution of the Earth System can be investigated.

As a consequence, an integrated view of the geodynamic evolution of the Scotia Arc and of its influence on global evolution including climate and biota is important and constitutes the goal of this Special Issue. Contributions in this special issue were presented at a multidisciplinary, international 3-day meeting on the evolution of the Scotia Arc held at the Andalucía Institute of Earth Sciences (Spanish Research Council (CSIC)/University of Granada (UGR)), Spain, during May 2013 (Maldonado et al., 2013). This Symposium 'The Scotia Arc: Geodynamic Evolution and Global Implications' was held to celebrate the major multidisciplinary contributions of Peter F. Barker to our understanding of the Scotia Arc. Previous volumes on the region, in addition to the work of Barker et al. (1991), include a Special Publication of the Geological Society of London concentrating on the Geophysics and Tectonics of the Weddell Sea, to the south of the Scotia Arc (Storey et al., 1996), and many books and special journal issues concerned with the geology and geophysics of Antarctica, most recently Hambrey et al. (2013) and Harley et al. (2013). This is the first special issue of a journal to focus on the geology and geophysics of the Scotia Arc.

2. Geodynamic and paleoceanographic setting

The Scotia Arc is one of the three main tectonic arcs that intersect the otherwise passive margins of the Atlantic Ocean, the others being the Gibraltar and Caribbean arcs (Fig. 1). All these arcs were important oceanographic and biological ocean gateways during their development. Their history also involved past and present land bridges.

Tectonic arcs of this type are a result of relative motion of their major bounding plates and may incorporate continental fragments in dominantly oceanic domains, such as in the Scotia Arc (BAS, 1985; Smith and Sandwell, 1997; Sandwell and Smith, 2009). The Gibraltar Arc is a tight orogenic arc and, together with its extensional hinterland, the Alboran Sea, is located between two colliding continents (Doblas et al., 2007; Platt et al., 2013). This arc straddles the convergent boundary between Africa and Iberia and is associated with the development of an accretionary prism in the Gulf of Cádiz which is overriding the central eastern Atlantic Plate (Maldonado et al., 1999; Medialdea et al., 2004; Zitellini et al., 2009; Duarte et al., 2013). The Gibraltar Arc occupies the location of the Mesozoic Atlantic-Tethys connection during the Mesozoic and early Cenozoic and of Atlantic–Mediterranean oceanographic interactions during the late Cenozoic (Maldonado and Nelson, 1999; Vergés and Fernández, 2012.). The Caribbean Arc, in the central western Atlantic Ocean represents the subduction of the western central Atlantic oceanic crust beneath the Caribbean Plate and has been active since the Eocene (DeMets et al., 1990; Pindell and Kennan, 2009; Evain et al., 2013). The development of the Isthmus of Panama closed the oceanographic connection between the Pacific and the Atlantic oceans during the Pliocene and subsequently all oceanographic connections between these two oceans became restricted to the Drake Passage in the Scotia Arc (Lawver and Gahagan, 2003; Coates et al., 2013).

The Scotia Arc is an intra-oceanic tectonic feature that comprises the curvilinear array of islands, shallow and emergent continental blocks and submarine ridges that joins southern South America to the Antarctic Peninsula, via the North Scotia Ridge (NSR), South Georgia, South Sandwich Islands, South Orkney Block and South Scotia Ridge (SSR). The northern and southern boundaries are mainly composed of continental fragments of the former continental bridge, whereas the eastern boundary is an active intra-oceanic arc and the western boundary is a transform fault that was active during the opening of the West Scotia Sea (Figs. 2, 3). The arc encloses the Scotia Sea which is composed of amalgamated oceanic crust terrains that developed during relative motion of the bounding South American and Antarctic plates (BAS, 1985; Cunningham et al., 1995). Several migrating Cenozoic oceanic spreading centers comprise the oceanic crust of the Scotia Sea (Fig. 2).

Two tectonic plates form the ocean floor of the Scotia Sea, the Scotia Plate in the west, and the Sandwich Plate in the east (Fig. 3). The boundaries of the Scotia Plate are defined by earthquake sources (Pelayo and Wiens, 1989; Thomas et al., 2003, Smalley et al., 2007). The north and south margins of the Scotia Plate are transcurrent boundaries following respectively the North and South Scotia ridges. To the west, the Shackleton Fracture Zone (SFZ), an intraoceanic ridge that protrudes several hundreds to thousands of meters above the surrounding oceanic floor, forms the boundary between the Scotia Plate and ocean crust of the Antarctic Plate mainly comprising the former Phoenix Plate (Maldonado et al. 2000; Livermore et al., 2004). To the east, the Scotia Plate is separated from the smaller Sandwich Plate by the active East Scotia Ridge spreading center (Larter et al., 2003; Leat etal., 2014). Active westward subduction of the South American Plate beneath the Sandwich Plate is associated with the active, mainly submarine South Sandwich volcanic arc (Leat et al., 2010, 2013, 2014; Nicholson and Georgen, 2013). Kinematic reconstructions of South America-Antarctica motions during the Cenozoic are based on the analysis of seafloor magnetic anomalies in the Scotia Sea and surrounding oceanic areas, and on the relative motions of South America, Africa and the Antarctic Peninsula (Vérard et al., 2012; Dalziel et al., 2013a,b; Eagles and Jokat, 2014). These studies depict a progressive opening of the Scotia Sea through continental stretching and oceanic spreading. The initial stages of spreading of the Scotia Sea were characterized by extension within several small oceanic basins, particularly in the southern region (Maldonado et al., 1998, 2006; Eagles et al., 2006; Galindo-Zaldívar et al., 2006). The basins developed as a result of subduction of the Weddell Sea and the southwestern South American Plate below several fragments of an eastward and northward migrating trench (Barker, 2001). The age and origin of some regions of the ocean floor remain a subject of debate, such as the enigmatic Central Scotia Sea (Eagles, 2010b; Dalziel et al., 2013b).

The Drake Passage is situated between the southern tip of South America and the Antarctic Peninsula (Figs. 2, 3). Opening of the gateway has influenced the oceanographic flows between the Pacific and Atlantic oceans and, hence, as has been widely speculated, the climatic evolution of the Southern Ocean and Antarctica and global climate change in general (Kennett 1977, Barker, 2001; Livermore et at., 2005, 2007, Dalziel et al., 2013b; Martos et al., 2013, among others). This gateway is also very important for mantle dynamics since, together with the Caribbean Arc, it is the main potential gateway for the asthenopheric flow between the shrinking Pacific and the expanding Atlantic oceans (Alvarez ,1982; Russo and Silver, 1994; Pearce et al., 2001; Leat et al., 2004; Haase et al., 2011; Dalziel et al., 2013a; Lynner and Long, 2013; Martos et al., 2014a).

At present, the Drake Passage is the oceanic gateway that exerts the largest influence on the circulation of the main water masses in the Southern Ocean (Fig. 2). The Circum-Antarctic Low Pressure Belt activates a westward atmospheric current along the continental margin, called the Sub-polar Current or East Wind Drift (Le Roux, 2012). The ACC flows clockwise around Antarctica north of the Circum-Antarctic Low Pressure Belt (Fig. 2). The ACC controls the transport of heat, salt, and nutrients in the Southern Ocean and is the principal contributor to the boundary currents of the South Atlantic, South Pacific and Indian oceans (Nowlin and Klinck, 1986; Foldvik and Gammelsrød, 1988; Naveira-Garavato et al., 2002). The ACC also plays an important role in maintaining the thermal isolation of the continent. Where the ACC is impeded by the NSR it splits into a shallow, warm branch flowing to the north and a deeper, cold branch moving farther to the east which then turns northwards to form the Falkland-Malvinas Current that in turn flows along the Atlantic coast up to the estuary of the Río de la Plata (Piola and Matano, 2001). The Circumpolar Deep Water (CDW) constitutes the deeper components of the ACC (Fig. 2). Another important deep-water mass flow below the CDW, across the southern Drake Passage, is the westward directed Weddell Sea Deep Water (WSDW), derived from the Weddell Gyre (WG) which crosses passages in the SSR into the Scotia Sea (Orsi et al., 1999; Naveira-Garabato et al., 2002; Palmer et al., 2012).

The morphological influence exerted by the developing SFZ upon bottom-current circulation has been considered by several studies; these propose that until the Miocene deep-water flows were inhibited through the Drake Passage by overlapping continental slivers and other bathymetric highs along the SFZ or by relict fragments of the volcanic arc in the Central Scotia Sea (Barker, 2001; Dalziel et al., 2013b). Other studies propose, in contrast, that the SFZ is a rather recent feature that acted as a barrier only after 17 Ma (Livermore et al., 2004). The uplift of the barrier induced the northward displacement of the bottom water masses since the Miocene (Hernández-Molina et al., 2006; Hillenbrand et al., 2008; Martos et al., 2013).

3. Outline of studies in this issue

This issue is organized into five topical groups of papers that discuss: the break-up of the South America-Antarctic Bridge (Section 3.1); crustal structure (Section 3.2); magmatism and tectonic development (Section 3.3); gateways, sedimentation and paleoceanography (Section 3.4) and effects of the final break-up of Gondwanaland on biota (Section 3.5).

3.1. The break-up of the South America-Antarctic Bridge

A model of oceanic development by ridge jumping for the initial opening of the Scotia Sea is proposed by **Maldonado et al.** (this issue) from an extensive geophysical data set collected in the Ona Basin, the westernmost ocean basin located in the southern Scotia Sea (Figs. 2, 3). This basin is a small intra-oceanic basin, bounded by the SFZ to the west, the Terror Rise to the east and the South Shetland Islands Block to the south (Fig. 2). Based on the stratigraphy of the depositional units and the magnetic anomalies, a middle Eocene age is postulated for the initiation of oceanic spreading in the eastern Ona Basin, while spreading in the western Ona Basin occurred during the early Oligocene, where oceanic seafloor spreading is associated with the jumping of the ridge. These authors propose shallow gateways between the Pacific and Atlantic oceans during the middle and late Eocene, which initiated the thermal isolation of Antarctica.

The relationship of the Andean Cordillera of Tierra del Fuego to the Antarctic Peninsula and the extent of oroclinal bending, both north and south of Drake Passage have remained enigmatic through many decades of study. **Torres Carbonell et al**. (this issue) attempt to correlate the tectonic history of the Fuegian Andes with that of the Scotia Arc, while acknowledging that uncertainties increase for older times. Pointing out that initial mid- to Late Cretaceous inversion of the Late Jurassic-Early Cretaceous Rocas Verdes marginal basin probably took place within the northern part of an Antarctic Peninsula-Tierra del Fuego land bridge. They suggest that proximity of the pole of rotation of South America with respect to the Antarctic Peninsula resulted in clockwise rotation of the latter. This would have resulted in the eastward directed cuspate land bridge configuration prior to opening of Drake Passage (Barker, 2001), and also the counterclockwise rotation of a “Fuegian backstop” in South America, the initial orogenic wedge resulting from the obduction of the floor of the Rocas Verdes Basin. The authors link seafloor spreading in Drake Passage and the western Scotia Sea to contraction in the thrust-fold belt in the northern Fuegian Andes and consider that major strike-slip deformation in Tierra del Fuego was not initiated prior to the late Miocene.

A new plate kinematic model of plate motions is presented from the early Paleogene to the present for the southeastern Pacific Ocean, close to the west and south of Drake Passage by **Eagles and Scott** (this issue). The Phoenix Plate (Fig. 3) motion is interpreted as having been affected by a northeast-increasing gradient in the slab pull force since chron 18 (39 Ma), during which time newer, less dense lithosphere was largely subducting in the southwest. The model allows comparison with independent interpretations of slab-window migration and associated magmatism, and in turn provides insight into possible causal relationships between subduction kinematics and geologic repercussions on the overriding plate.

3.2.Crustal structure

Bransfield Strait is a tectonically active rift situated between the South Shetland Islands and the Antarctic Peninsula mainland. Deception Island is the emergent part of one of the main volcanoes within this rift and has a history of unrest since its last eruption in 1970. **Catalán et al**. (this issue) present and interpret magnetic data acquired from the volcano during marine surveys over two decades between 1989 and 2008, recently supplemented by an aerial survey using an unmanned aerial vehicle (UAV). Changes in magnetism, particularly during 1989-1999, correlate with seismic activity and ground deformation and record intrusion of magma at shallow levels within the volcano. The magnetic data reveal changes in the internal structure of the volcano on a small spatial scale that are difficult to resolve using other methods.

The summary of the Polish seismic wide-angle refraction expeditions between 1979 and 1991 concentrating on the northern Antarctic Peninsula region is analyzed by **Janik et al.** (this issue). These experiments reveal that the continental shelf of the Antarctic Peninsula has an atypical continental crustal structure, with crustal thicknesses of 36–42 km near the coast that decrease to 25–28 km beneath the outer continental shelf (Fig. 2). The Moho discontinuity in the South Shetlands Island region, in contrast, dips southeastward, from a depth of 10 km beneath the South Shetland Trench to 40 km under the northern tip of the Antarctic Peninsula, where a high-velocity body with P-wave velocities exceeding 7.0 km/s was detected at depths of 6–32 km below the central basin of Bransfield Strait.

New seismic tomographic results for the Scotia Sea region are presented by **Vuan et al.** (this issue).The study incorporates results from earthquakes between 2001 and 2013 into an earlier compilation to provide improved resolution seismic velocity data for crust and upper mantle in the region. The derived seismic velocities confirm the heterogeneous tectonic structure of the Scotia Sea, with high velocity oceanic lithosphere similar to that in the eastern Pacific underlying the West Scotia Sea, and distinct low velocity material underlying the active Bransfield Strait. The large continental fragments and parts of the North and South Scotia ridges form contrasting low crustal velocity features. The distinct structure of the Central Scotia Sea contrasts with that of the oceanic West Scotia Sea.

Martos et al. (this issue) have compiled the most complete and accurate magnetic anomaly map of the Scotia arc to date from marine, airborne and satellite data. Apart from anomalies associated with spreading centers in the southeasternmost Pacific Ocean basin, the Western Scotia Sea and the Eastern Scotia Sea, they identify a linear anomaly beneath the Falkland Trough between the Falkland Plateau and NSR which, they suggest is associated with an E-W elongated “dyke” resulting from crustal thinning. This is an interesting observation and interpretation as the origin of that basin is unknown. There is also a linear E-W anomaly to the south of the NSR, but the most striking anomaly is the so-called Pacific Margin Anomaly (PMA). It runs along the continental margin of the Antarctic Peninsula and is assumed to be caused by the presence of a subduction-related batholith. The PMA is taken by the authors to extend eastward along the SSR, though diminishing in intensity. The authors ascribe this to a change in the angle of plate convergence. There is also a possibility, however, of some diachroneity in the age of the subduction along strike. Subdued anomalies on the southern side of the NSR are suggested to reflect mafic rocks in pull-apart basins, although the one on the southwestern shelf of the South Georgia Microcontinent is probably associated with a continuation of the Patagonian batholith.

3.3. Magmatism and tectonic development

Seismic and magnetic data, geochemistry and Ar-Ar geochronology of dredge samples are used by **Galindo-Zaldívar et al.** (this issue) to interpret the development of the Dove Basin as a back-arc spreading center within the ancestral South Sandwich subduction system (Fig. 3). The Dove Basin, situated adjacent to the SSR between the continent-like Pirie and Bruce banks, is underlain by oceanic crust that formed after east-west rifting apart of the two continental blocks. New Ar-Ar ages from an up-faulted exposure of the most recently-active part of the ocean spreading center are in the range of 20.4 to 22.8 Ma, consistent with their best fit interpretations of magnetic anomalies, indicating that spreading took place between about 24 and 21 Ma (late Oligocene to early Miocene). Compositions of dredged basalts are consistent with a back-arc setting with respect to the ancestral arc situated to the east.

The evolution of the stress field on the southern limb of the Scotia arc is evaluated by **Maestro et al**. (this issue) using more than 6000 measurements of brittle fractures, basaltic dikes and tension gashes collected over 20 years together with information derived from earthquakes. The authors conclude that NW-SE to N-S compressional stress inferred from analysis of this data reflects subduction of the former Phoenix Plate under the Antarctic Plate, and that inferred NE-SW compressional stress is associated with Cenozoic to present-day sinistral transcurrent motion between the Scotia and Antarctic plates. They ascribe NW-SE extension-related structures to development of Cenozoic basins in Bransfield Strait and the southern Scotia Sea due to subduction of the former Phoenix Plate in the west and Weddell Sea floor in the east, and NE-SW and E-W extension to opening of Powell Basin as the South Orkney Microcontinent separated from the Antarctic Peninsula.

There is strong geophysical and geochemical evidence for the existence of an Oligocene-Miocene subduction system with associated volcanic arcs in the southern and central parts of the Scotia Sea associated with subduction of ocean crust beneath what is now the central part of the Scotia Plate (Barker, 1995; Dalziel et al., 2013b). **Pearce et al.** (this issue) reconstruct the evolution of this arc using geochemical data from volcanic arc rocks dredged in the Central Scotia Sea, Discovery and Jane banks and the forearc of the South Sandwich arc (Fig. 3). This Oligocene-Miocene ancestral South Sandwich arc formed a potential barrier to deep ocean and mantle flow across the eastern part of the developing Scotia Sea. Geochemical characteristics of the arc varied in space and time. The oldest, Eocene- Oligocene volcanic arc is most consistent with an Andean-style subduction initiation in the north but a Western Pacific (slab roll-back) style in the south. Some Miocene samples are interpreted as belonging to a tholeiitic arc similar to the present South Sandwich Islands, while those from the Central Scotia Sea indicate a high temperature subduction flux, interpreted to result from collision of the Central Scotia Sea and South Georgia with the Northeast Georgia Rise.

3.4. Gateways, sedimentation and paleoceanography

The structure and sedimentology of the Endurance Basin (Fig. 3), a 3900 m deep elongate depression situated immediately adjacent to the southwestern margin of the South Georgia Microcontinent, is described by **Owen et al.** (this issue). The basin is interpreted as a foreland basin and it is bounded by an array of sinistral strike-slip faults along its northern, continental margin. Sedimentation within the basin is interpreted to be dominated by contourite deposits and mass flow deposits sourced from the coutourites and glaciogenic sources on the continental margin.

The Scan Basin, the easternmost basin north of the SSR and a geologically complex structural depression (Fig. 3), is analyzed on the basis of multichannel seismic reflection profiles by **Perez et al.** (this issue). The seismic data and gravity modeling support the interpretation that the basin is mainly floored by oceanic crust, where it is bounded to the south by the strike-slip boundary between the Scotia and Antarctic plates. The basin developed during the Oligocene to Miocene. Its northern and southern provinces exhibit different tectonic attributes. Their stratigraphic features reveal major paleoceanographic changes influenced by plate tectonic processes and the opening of gateways with the Weddell Sea, which enabled initiation of the overflow of the WSDW. The WSDW forced the northwards migration of the Circumpolar Deep Water and became progressively dominant through time, largely influencing the middle Miocene to present depositional patterns in the Scan Basin.

A variety of impressive sea-floor and sub-surface structures in the Scan Basin (Fig. 2) is revealed from the analysis of an extensive data set of seismic reflection profiles by **Somoza et al.** (this issue). Sea floor and shallow subsurface features as pagoda structures, craters and elongated cone-shape depressions are attributed to gas hydrate-related beds at depth. The authors infer, based on the theoretical modeling of gas hydrate conditions from heat flow values in the Scan Basin that the thickness of the hydrate layer may have increased at least since the early Miocene to present times, due to the progressive decrease in heat flow as the oceanic floor aged.

The analysis of swath-bathymetry and high-resolution seismic data by **Ruano et al.** (this issue) reveals a large number of mass-transport deposits (MTDs) within the Dove and Scan basins, which highlight the importance of seismicity and depositional processes in the growth patterns of these small ocean basins of the southern Scotia Sea (Fig. 3). The active tectonic processes and the associated shallow to intermediate earthquakes seem to be the most influential triggering mechanism for the development of MTD in Dove Basin, although volcanic activity, strong bottom-currents, and higher sedimentation rates are additionally proposed for the generation of MTDs in Scan Basin. The authors suggest that the MTDs are appropriate proxies for paleoearthquake analysis, with important implications for geodynamic and geohazard research.

3.5. Effects of final break-up of Gondwanaland on biota

The separation of South America from the Antarctic Peninsula eventually resulted in the deep gateway joining the Pacific Ocean to the Atlantic Ocean. In doing so, it severed the land bridge between the two continents. **Poulin et al**. (this issue) performed molecular comparisons between South American and Antarctic marine benthic invertebrate taxa. They conclude that genetic continuity was maintained between the two continents, presumably around the submerged ridges forming the Scotia Arc, until the middle Miocene and a late intensification of the ACC at the Miocene-Pliocene boundary. Interestingly the older date is close to the time of inception of the eastern Scotia Sea opening and the development of a major gap in the NSR to the east of the South Georgia Microcontinent (Dalziel et al., 2013b).

On the other hand, stratigraphically calibrated phylogenies, including those of large terrestrial ungulates, indicate to **Reguero et al**. (this issue) through long ghost lineages that the South America-Antarctica land bridge, the so-called “Weddell Isthmus”, was functional until the late Paleocene. This time, ~56-57 Ma, is significantly older than the earliest estimates of a marine connection between the Pacific and Atlantic oceans. The authors speculate that a wide and relatively shallow sea first separated the two continents.

4. Outstanding problems and future research

The relevance of the Scotia Arc in the geodynamic evolution of the Earth and in influencing global paleoenvironmental changes, including biota, oceanography and climate is widely recognized and accepted. Time will show, however, how unique this region of the Earth´s oceans is, and whether this issue has contributed important new discoveries and models for the understanding of such a complex system. The interdisciplinary approach represented by the collection of studies in this issue provide new insight into how the system operates and the degree to which tectonic, paleoceanographic and paleobiologic processes are interconnected. Clearly not all topics are analyzed to the same level in this issue, but all the studies are critical for the better understanding of key issues related to the Scotia Arc.

Among the outstanding problems that need to be resolved through for future research are the timing and mechanisms of the initial stages of opening the Drake Passage. What are the processes that influence the initiation, the jumping and the extinction of the spreading centers implicated in the growth of the Scotia Sea? Is mantle flow influential in this process? The northern, central and southern regions of the Scotia

Sea are depicted as having different structures, but what is the relevance of inherited terrains (Eagles, 2010b) incorporated during the growth of the ocean basin? Recent studies reveal the affinities of the South Georgia Microcontinent with the Fuegian Andes and Tierra del Fuego (Carter et al., 2014; Dalziel, 2014) in contrast to a southern Atlantic origin (Eagles, 2010a), but what are the tectonic mechanisms for the displacement of the South Georgia block from the South American continent?

The migration of the ancestral arc and the evolution of the spreading ridges are of critical importance for the initiation of the thermal isolation of Antarctica and the development of a circum-Antarctic paleoceanographic flow. Were the initial shallow gateways sufficient to allow a paleo ACC? And if so, how influential were they in the growth of the large continental ice-sheets?

The precise reconstruction of the paleogeography and growth patterns of the arc and ocean basins is crucial not only for paleoceanography, but also to understand biological migration and evolution. The biota tell us about continental and marine bridges and opening of gateways, but the tectonics of the region and the correlation of these also contribute to the understanding of biological evolution.

Unfortunately deep boreholes have not been drilled within the Scotia Sea and this should be a prime method for future research to address the outstanding problems posed here. Deep sediment cores will allow the precise dating of the major seismic reflectors identified in the region and to correlate these with relevant tectonic events of the region and in turn, with significant global events (Lindeque et al., 2013). What was more influential for the development of the Antarctic ice-sheets: changes in the global atmospheric composition, the tectonics and thermal isolation of the Antarctic continent by shallow and deep gateways, or a combination of both?

We hope, finally, that the papers collected together in this issue have highlighted some of the outstanding problems about the evolution and relevance of the Scotia Arc and that they will provoke new thoughts and guide future research.

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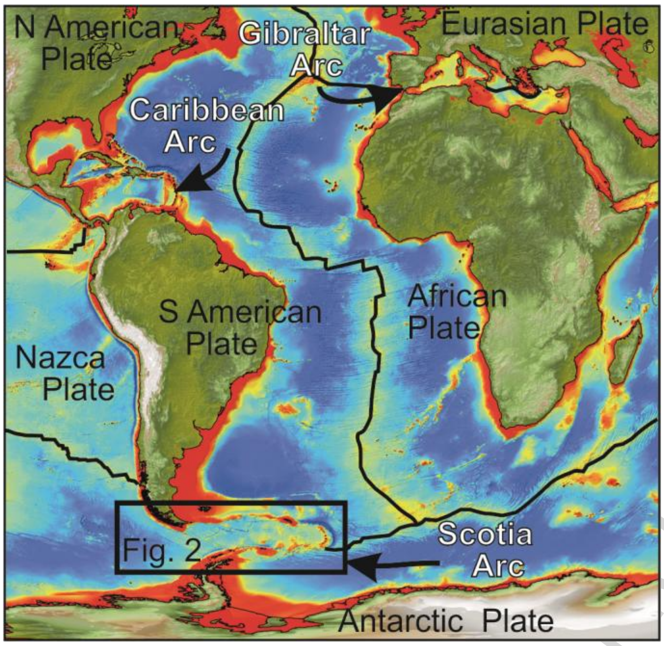
Figure captions

Figure 1. - Sketch bathymetric map of the central and southern Atlantic Ocean showing the location of the three tectonic arcs, Gibraltar, Caribbean and Scotia, within the otherwise passive margins of the ocean, and major tectonic plates and plate margins.

Figure 2. - Simplified map of predicted bathymetry derived from the satellite altimetry and ship soundings of the Scotia Arc region (Smith and Sandwell, 1997) with the general plate tectonic setting of the Scotia Sea and the distribution of main oceanographic flows in the region. Geological elements legend: APR, Antarctic-Phoenix Ridge; BB, Bruce Bank; DB, Discovery Bank; ESR, East Scotia Ridge; HB, Herman Bank; JB, Jane Bank; JBs, Jane Basin; OB, Ona Basin; PB, Powell Basin; PiB, Pirie Bank; SGI, South Georgia Island; SSIB, South Shetland Islands Block; SFZ, Shackleton Fracture Zone; SOM, South Orkney Microcontinent; TR, Terror Rise; TdF, Tierra del Fuego; WSR, West Scotia Ridge. Oceanographic currents legend: ACC, Antarctic Circumpolar Current; CDW, Circumpolar Deep Water; WG, Weddell Gyre; WSDW, Weddell Sea Deep Water. (Modified from Maldonado et al., this issue).

Figure 3. - Tectonic setting of the Scotia Arc. Legend: 1, Inactive transform fault; 2, active transcurrent fault; 3, relict subduction zone; 4, active subduction zone; 5, active spreading ridge; 6, relict spreading ridge; 7, active extensional zone; 8, continent-ocean crust boundary. APR, Antarctic-Phoenix Ridge; BB, Bruce Bank; BkP, Barker Plateau; CSS, Central Scotia Sea; DB, Discovery Bank; DvB, Dove Basin; EB, Endurance Basin; ESR, East Scotia Ridge; ESS, East Scotia Sea; HB, Herman Bank; JB, Jane Basin; JBk, Jane Bank; OB, Ona Basin; PB, Powell Basin; PBk, Protector Bank; PrB, Protector Basin; SB, Scan Basin; SGM, South Georgia Microcontinent; SOM, South Orkney Microcontinent; SSIB, South Shetland Islands Block; TdF, Tierra de Fuego; TR, Terror Rise; WSR, West Scotia Ridge; WSS, West Scotia Sea. (Modified from Maldonado et al., 2006).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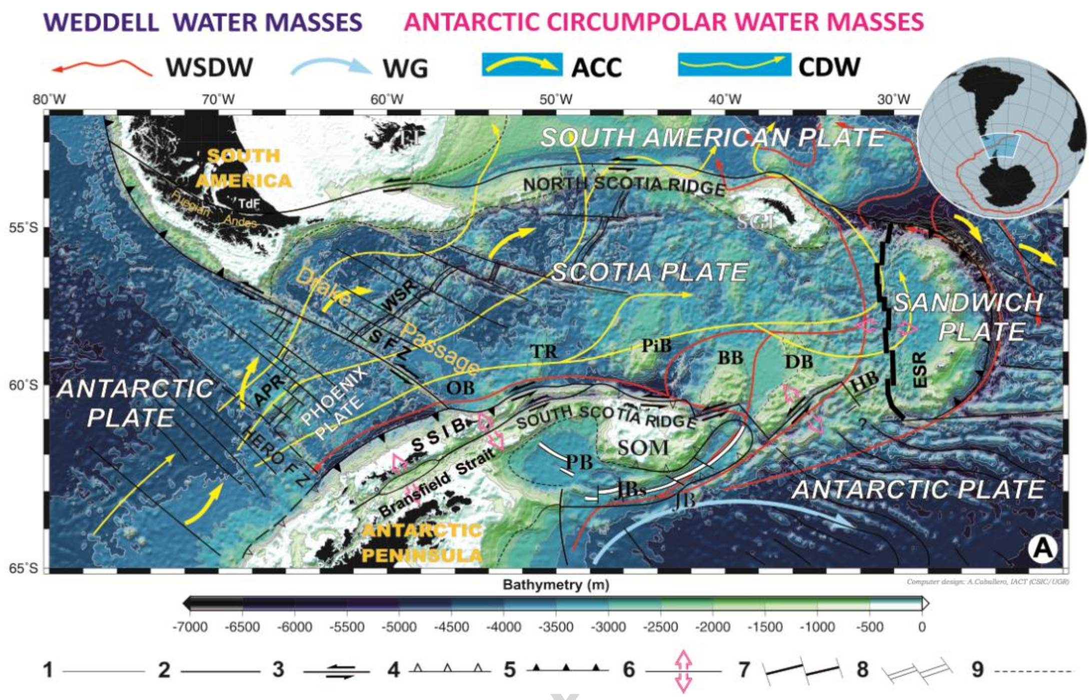
Nazca Plate
Fig. 2
Scotia Arc
Antarctic Plate

Figure 1


WEDDELL WATER MASSES
ANTARCTIC CIRCUMPOLAR WATER MASSES
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ACC
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80°W
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30°W
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65°S
SOUTH AMERICA
TdF
Fuegian Andes
SOUTH AMERICAN PLATE
NORTH SCOTIA RIDGE
SGI
SCOTIA PLATE
Drake Passage
WSR
SFZ
SANDWICH PLATE
ESR
TR
PiB
BB
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HB
OB
APR
PHOENIX PLATE
ANTARCTIC PLATE
HERO FZ
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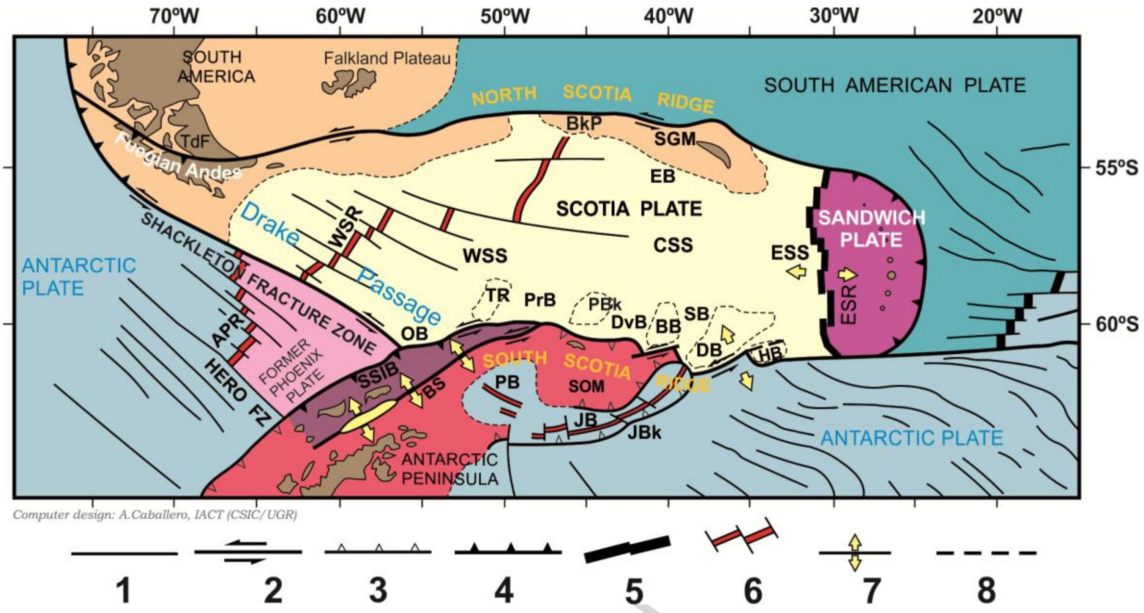
Figure 2



Computer design: A.Caballero, IACT (CSIC/UGR)

Figure 3

HIGHLIGHTS

1. The Scotia Arc: an Earth Sciences laboratory.

2. Opening of Drake Passage and global change: paleoenvironmental evolution.

3. Current state and advances in the knowledge of the Scotia Arc: geodynamic implications.