Gateways and climate: the Drake Passage opening

E. Lodolo[1] and A. Tassone[2]

[1] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS, Trieste, Italy
[2] CONICET, Instituto de Geofisica D. Valencio, Univ. de Buenos Aires, Argentina

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ABSTRACT The Oligocene opening of the Drake Passage between the southern tip of South America and the Antarctic Peninsula, and the subsequent evolution of the Scotia plate, have definitively separated Antarctica from the other continental masses, and have created conditions for the development of the Antarctic Circumpolar Current. This annular water flow has had a profound influence on the global climate system because it has allowed the free transfer of water masses between the Pacific and Atlantic Oceans at mid to high southerly latitudes. The comparative seismic analysis of the passive margins of the western sector of the Scotia plate, represented by the Tierra del Fuego continental margin to the north, and by the Terror Rise to the south, has shown significant morphological and structural similarities between these two margins, supporting the interpretation that they were conjugate before the Drake Passage opened. Moreover, the identification of the oldest magnetic anomalies present at the base of the two margin pairs, corresponding to about 32 million years ago, has allowed the reconstruction, through time, of the relative positions of the two continental margins, and to constrain the events that occurred immediately after the break-up and opening of the Drake Passage. These timings correlate with events seen in the oxygen isotope record from benthic foraminera, and support the view that the Drake Passage opening was the trigger for abrupt Eocene-Oligocene climate deterioration and the growth of extensive ice sheets on the Antarctic continent.

1. Introduction

The present continental-ocean geometry is the result of a long (~200 million years) history of changing spatial configurations. Major changes in plate tectonics, which led to the opening (or closure) of oceanic gateways (Fig. 1), have had a major influence on oceanic circulation, and determined a profound effect on the global paleo-climate. The role of gateways (and barriers) is hence fundamental for recreating the scenario of past climatic histories. Oceans represent one of the most important components of the global climatic system because, with their high thermal capacity (over 1000 times that of the atmosphere), they act as a buffer for the transport of energy from summer to winter hemispheres, and from low to high latitudes.

With these premises, it is clear that the key to understanding the Late Cenozoic climate lies through the knowledge of changes in ocean circulation triggered by tectonic processes such as the opening and closing of oceanic gateways. Moreover, the opening and closing of ocean gateways breaks and creates biological land bridges and sea migration routes.

The Oligocene opening of the Drake Passage represented one of the major Cenozoic tectonic

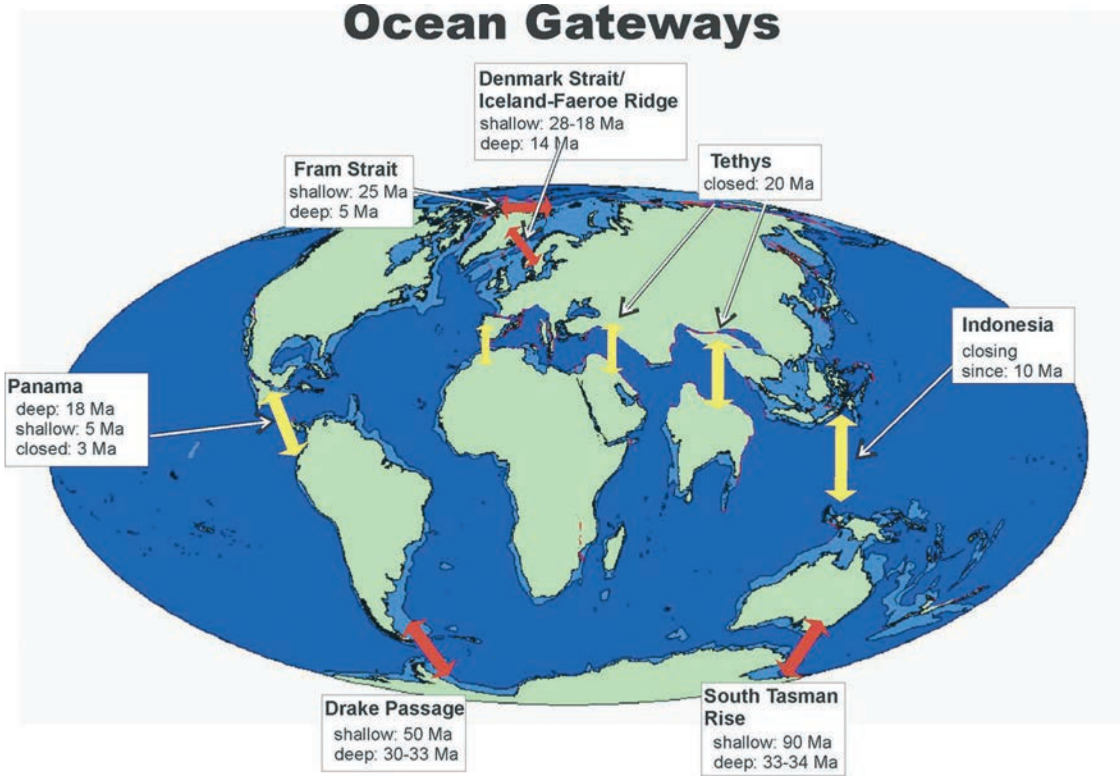

Fig. 1 - Map of the known gateways (and relative ages in Ma) responsible of major changes in ocean circulation (taken from http://platesgates.geo.su.se).

reorganizations occurring in the southern hemisphere. It finally separated the southern part of South America from the Antarctic Peninsula, and allowed the establishment of the Antarctic Circumpolar Current (ACC, Fig. 2), an annular, continuous water current both at the surface and at deep levels, whose development has been implicated in the formation of permanent ice sheets on Antarctica (Kennett, 1977; Zachos *et al*., 2001; Exon *et al*., 2002; Barker and Thomas, 2004; Livermore *et al*., 2005).

The comparative analysis of the conjugate passive margins of the western sector of the Scotia plate, represented by the Tierra del Fuego continental margin to the north, and by the northern flank of the South Scotia Ridge to the south, are crucial for reconstructing, through time, the relative positions of the pair of continental margins, and for constraining the events that occurred immediately after the break-up and opening of the Drake Passage.

2. Western Scotia Sea's tectonic evolution

The opening of the Drake Passage, initiated about 32 million years ago (Ma), represented the last phase of the Gondwana fragmentation. The former Mesozoic continental link connecting southernmost South America and the Antarctic Peninsula was progressively disrupted by ocean

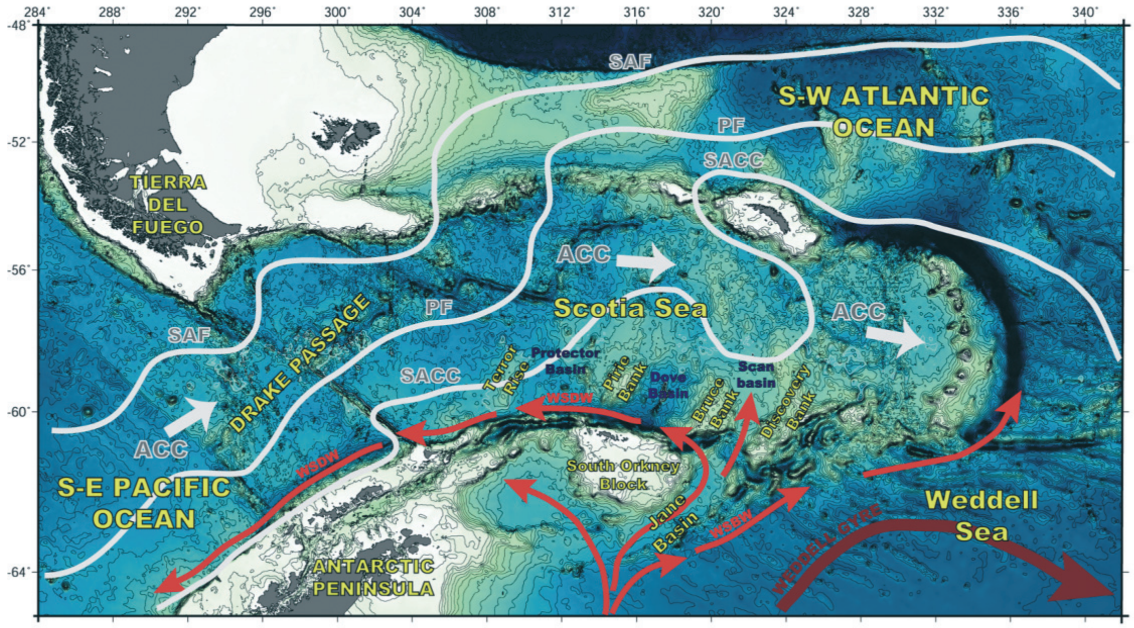

Fig. 2 - General map of the Scotia Sea, with its main geological provinces, and trends of the ocean currents that affect the region. ACC indicates the Antarctic Circumpolar Current, which is composed of a northern front (sub-Antarctic front, SAF), an axial front (polar front, PF), and a southern front (SACC). The currents of the Weddell Sea are represented by the deep current (WSDW), and the bottom current (WSBW), both associated with the Weddell Gyre.

crust accretion between the two major South America and Antarctic landmasses, with the subsequent development of the Scotia plate [see Barker (2001) for a general review of the Scotia Sea evolution]. The northern and southern boundaries of the western sector of the Scotia plate are defined by the North Scotia Ridge and the South Scotia Ridge, respectively, while the topographic relief associated to the NW–SE-trending Shackleton Fracture Zone represents the western boundary of the Scotia plate. The South Scotia Ridge is constituted by elongated continental banks (from west to east: Terror, Pirie, Bruce, and Discovery banks) which were affected by severe tectonic deformation and stretching. Between those fragments, several basins floored by oceanic crust developed (from west to east: Protector, Dove and Scan basins), some of them probably formed during, and possibly after, the western Scotia Sea spreading. The blocks that were once part of the continental link, are now distributed along the Scotia plate periphery, and their original position has been partially reconstructed on the basis of petrologic affinities, the paleo-magnetic signature, fitting geometries of margins, and magnetic anomaly identifications (Fig. 3).

A significant number of reconstructions for the Scotia plate have been proposed [Maldonado *et al*. (2000); Barker (2001); Eagles *et al*. (2005); Lodolo *et al*. (2006); among the most recent], mostly based on magnetic anomaly identifications and modeled flow lines. Here, a tectonic evolution of the western Scotia Sea from about 32 Ma up to 3.2 Ma is summarized (Fig. 4). It emphasizes the important role played by strike-slip tectonics since the early development of the Scotia plate.

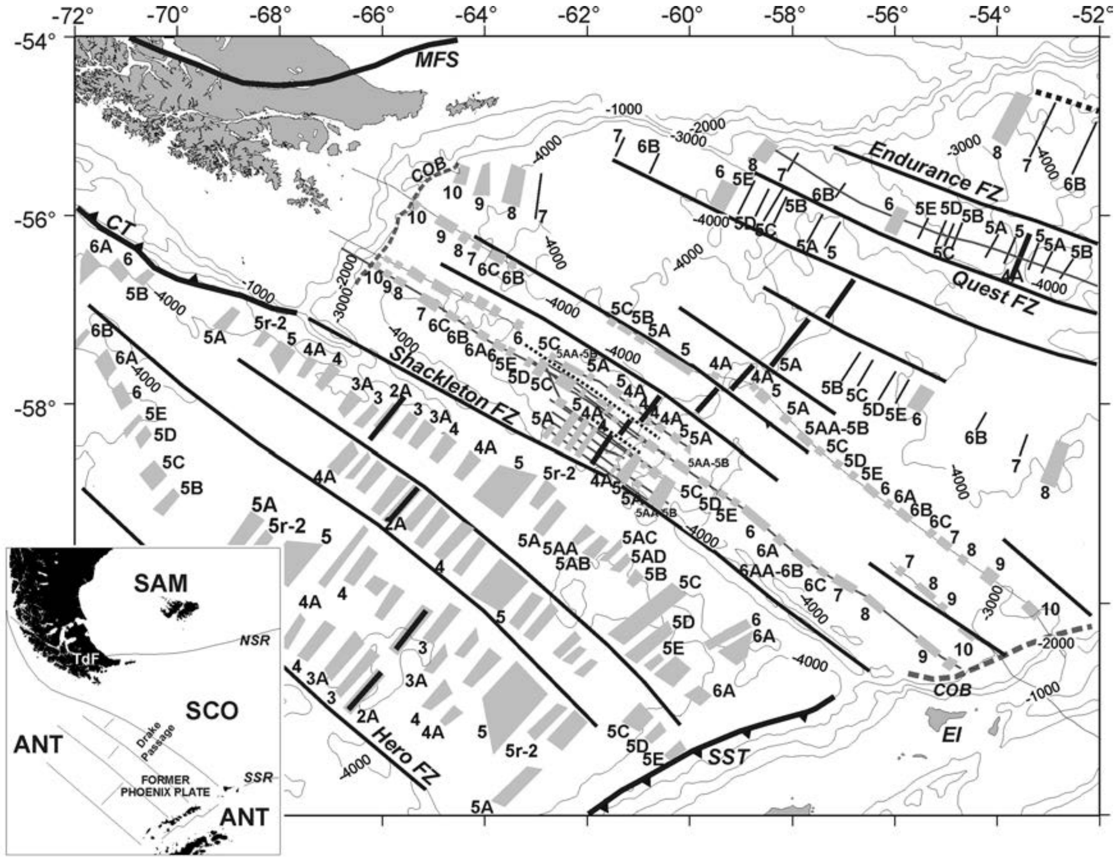

Fig. 3 - Magnetic Chron distribution for the western Scotia Sea and southwestern Pacific Ocean, obtained from all identified magnetic anomalies in the region (Barker and Burrell, 1977; Tectonic Map of the Scotia Arc, 1985; Livermore *et al.,* 1994; Lodolo *et al.,* 1997; Maldonado *et al.,* 2000; Schreider *et al.,* 2003). Simplified bathymetry from satellite-derived data (Sandwell and Smith, 1997). Box in the left-bottom corner shows a simplified plate tectonic sketch for the region. SAM, South America plate; ANT, Antarctic plate; SCO, Scotia plate; NSR, North Scotia Ridge; SSR, South Scotia Ridge; CT, Chile Trench; SST, South Shetland Trench; EI, Elephant Island; MFS, Magallanes-Fagnano transform system (Lodolo *et al.,* 2003); TdF, Tierra del Fuego Island; COB, Continent-ocean boundary [modified from Geletti *et al.* (2005)].

When sea-floor spreading in the western Scotia Sea initiated at ~32 Ma, the Shackleton Fracture Zone separated two spreading systems: the Phoenix Ridge system to the west and the Western Scotia Ridge system to the east. During the time span ~32-6 Ma, an E-W left-lateral, and a N-S divergent motion between South America and Antarctica was accommodated by the now extinct spreading centres of the Western Scotia Sea, and by intense faulting, stretching, and tectonic rotation within the South Scotia Ridge blocks. While the Western Scotia Ridge was active, the oceanic crust of the South Scotia plate occupied the SE flank of the ridge, and the plate boundary between Antarctica and the South Scotia plate was located within the modern South Scotia Ridge. When the spreading along the Western Scotia Ridge system ceased at about 6 Ma, the South Scotia plate and the South America plate became a single plate. At this time, the

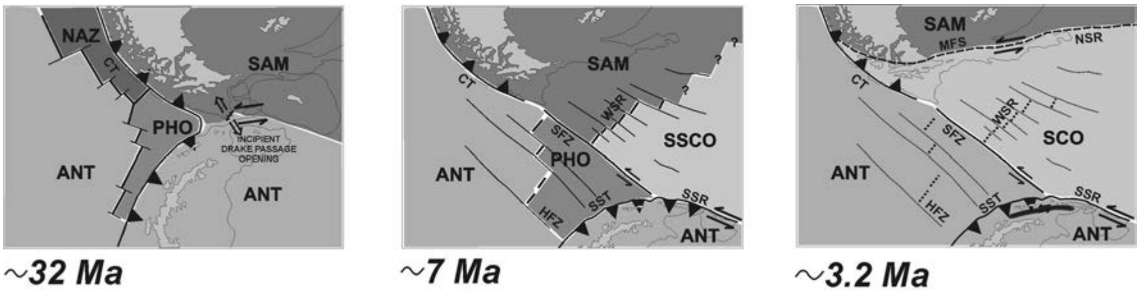

Fig. 4 - Sketches of three tectonic stages of evolution of the western Scotia Sea and surrounding regions, at ~32 Ma, ~7 Ma, and at ~3.2 Ma. NAZ, Nazca plate; PHO, Phoenix plate; SAM, South America plate; ANT, Antarctic plate; SCO, Scotia plate; SSCO, South Scotia plate; NSR, North Scotia Ridge; SSR, South Scotia Ridge; SFZ, Shackleton Fracture Zone; HFZ, Hero Fracture Zone; WSR, Western Scotia Ridge system; SST, South Shetland Trench; MFS, Magallanes-Fagnano transform system [modified from Lodolo *et al.* (2006)].

Magallanes-Fagnano transform system started to develop (Lodolo *et al*., 2003), and this fault became the western segment of the South America-Scotia plate boundary. Between 6 and 3.2 Ma, the Shackleton Fracture Zone separated the still active Phoenix Ridge system (separating the Phoenix and Antarctic plates), and the extinct Western Scotia Ridge system. When spreading at the Phoenix Ridge system stopped at about 3.2 Ma, the Phoenix and Antarctic plates became a single plate (Antarctic plate). Between 3.2 Ma to the present time, the Shackleton Fracture Zone separated the Antarctic plate from the Scotia plate, and the Scotia plate moved between two left-lateral, dominantly strike-slip fault zones on the South Scotia Ridge-the Shackleton Fracture Zone and the North Scotia Ridge-Magallanes-Fagnano transform system (Thomas *et al*., 2003).

2.1. Western Scotia Sea conjugate margins and temporal uncertainties in the Drake Passage early opening

The precise age of the initial rifting between the southern South America and the Antarctic Peninsula is still uncertain, due to the controversial signature of the oldest magnetic anomalies adjacent to the Tierra del Fuego and Western South Scotia Ridge margins. This, in turn, complicates the analysis of the temporal relationships between tectonic events and paleo-oceanographic consequences. The comparison between the two margins, once adjacent before the Drake Passage opened, shows that they are remarkably different in both their morphology and structure (Lodolo *et al*., 2006). The crustal fragments that originally formed the continental connection between the two landmasses were stretched, thinned, and finally dispersed around the Scotia Sea.

In the frame of the International Polar Year (IPY), a geophysical and geological survey was carried out onboard the Spanish R/V Hesperides during January-February 2008 in the Drake Passage, to better constrain the age and mechanism of its early development, and analyze the geometries of the conjugate margins of the south-western Scotia Sea. Data acquired include parametric and multibeam mapping, multichannel seismic, gravity, and magnetic profiles (Fig. 5). Two profiles were recorded along the spreading corridors of the southern half of the Western Scotia Ridge axis, crossing the oldest oceanic crust, the Terror Rise up to the oceanic Protector Basin. Both seismic data show similar features and put in evidence the continental nature of the

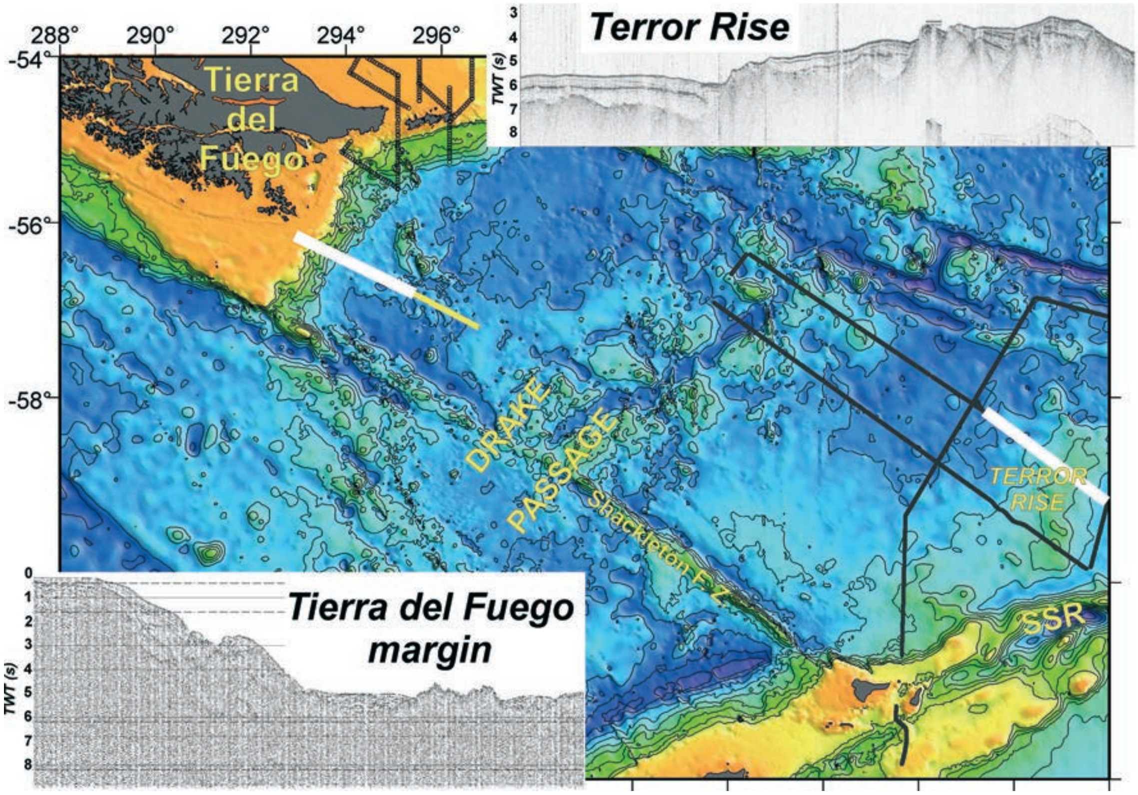

Fig. 5 - Map of data acquired by the R/V Hesperides during the IPY cruise in the Drake Passage region (black lines). Segments indicated with small circles are the seismic profiles acquired in 1998 in the frame of the TESAC project. Yellow line indicates the profile acquired by the R/V OGS-Explora during the 1994-95 Antarctic cruise. Thick white segments refer to two representative seismic profiles crossing the Tierra del Fuego margin (data courtesy from IGM Bologna), and the Terror Rise (data courtesy from J. Galindo-Zaldívar), supposed to be conjugate before the Drake Passage opening. SSR= South Scotia Ridge.

Terror Rise. It represents a NNE-SSW elongated ridge whose top lies at about a 2000 m water depth between abyssal plains of more than 3000 m deep. It is surrounded by asymmetrical slopes with NW smooth and SE sharp margins. The Bouguer anomaly minima values point to its thinned continental nature. Several half-graben bounded by north-westward dipping faults and with sedimentary wedges of more than 1 km thick, thickening towards SE, suggest that the initial phase of rifting was followed by an oceanic spreading axis located north-westwards. These structures undoubtedly show that the Terror Rise is the remnant part of the stretched Antarctic passive margin during the Drake Passage opening. In its initial phase of evolution, the Protector Basin was not yet opened and this passive margin probably was adjacent to the western flank of the Pirie Bank, which is now located east of the Protector Basin where overprinted deformations are found on its eastern margin (Galindo-Zaldívar *et al*., 2006). Half-graben basins of similar features have been described off the Tierra del Fuego continental margin (see Figs. 2 to 5 in Lodolo *et al*., 2006), testifying that the Terror Rise and possibly other continental blocks now dispersed along the south-western Scotia Sea margin, represent the conjugate margin of the

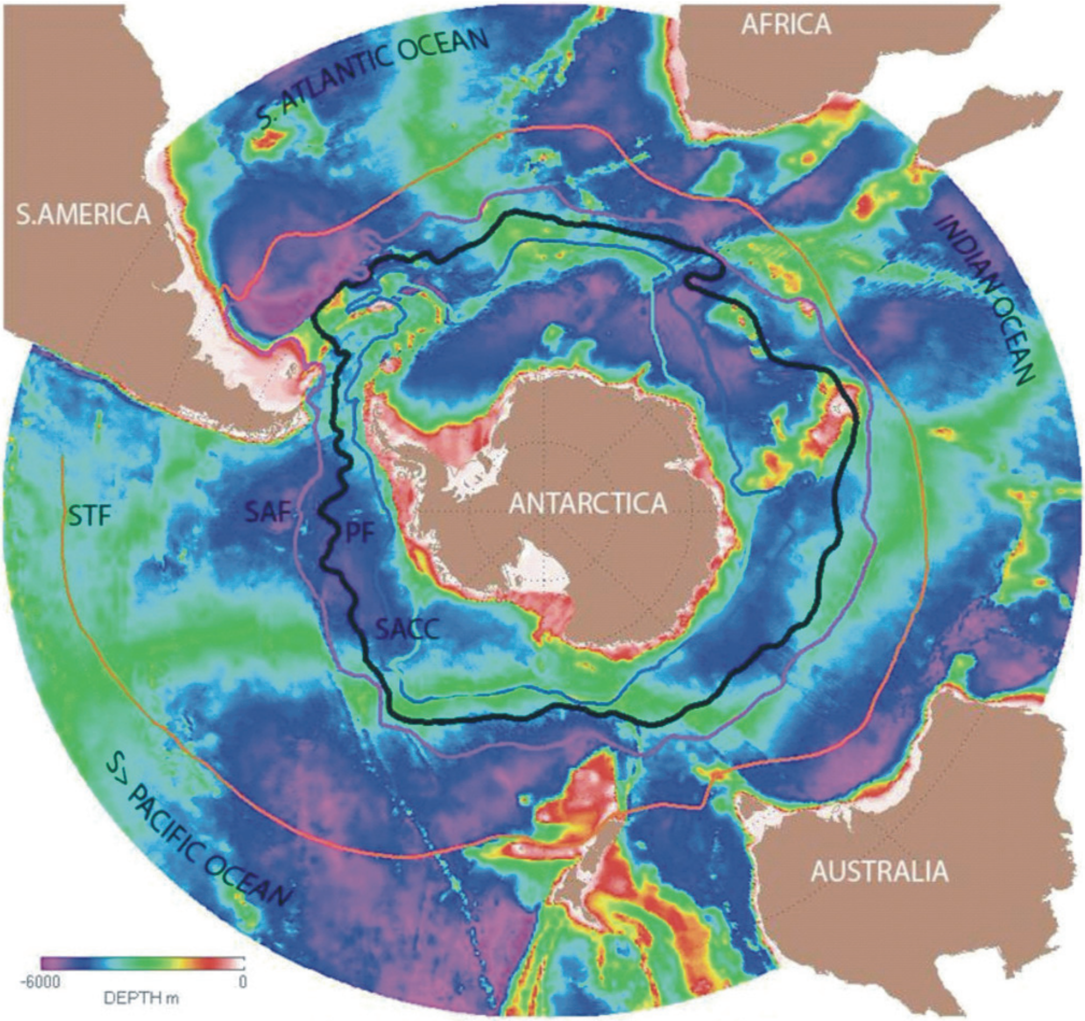

Fig. 6 - Paths and fronts of the ACC, as inferred from data collected in several oceanographic campaigns. PF is the polar front of the ACC, where much of the water transport is carried; SAF is the sub-antarctic front; SACC is the southernmost front of the ACC. The front further north is the sub-tropical front (STF), whose path is not continuous [modified from Orsi *et al*. (1995)].

southernmost part of South America.

3. The Antarctic Circumpolar Current

The opening of the Drake Passage determined the conditions for the establishment of a deep oceanic circulation around Antarctica (the ACC) which in turn influenced dramatically the climatic evolution of the southern hemisphere. The ACC is the dominant circulation feature of the southern oceans (Fig. 6) and connects the Atlantic, Pacific and Indian Ocean basins, and as such serves as a principal pathway of exchange between these basins. The ACC is considered to be largely or entirely wind-driven, and is strongly constrained by landform and bathymetric features.

The westerly wind system that drives this current reaches its maximum velocity at the latitude of Tierra del Fuego. The prominent relief of the Shackelton Fracture Zone would have prevented a deep-water pathway until about 22 Ma (Barker and Burrell, 1977). A possible further delay in the deep ACC development to the east would also have been caused by the presence of continental fragments and subduction-related volcanoes around the Scotia Sea.

The ACC consists of a number of fronts. The northern boundary of the ACC is defined by the sub-tropical front. This marks the boundary between warm, salty sub-tropical waters and fresher, cooler sub-polar waters. Moving southwards, we find the sub-antarctic front, along which much of the ACC transport is carried, which is defined as the latitude with a sub-surface salinity minimum. Still further south lays the Polar front, which is marked by a transition to very cold, relatively fresh, Antarctic surface water at the surface. Further south still is the Southern Boundary front, which is determined as the point where very dense abyssal waters reach to well within a few hundred meters from the surface. The bulk of the transport is carried in the middle two fronts. The total transport of the ACC at the Drake Passage is estimated to be around 135 times the transport of all the world's rivers combined.

The Weddell Sea Deep Water is the other important water circulation present in the southern Scotia Sea; it is also a wind-driven water mass. It originates as a consequence of the production of dense, cold and salty bottom-waters in the southern Weddell Sea (Foldvik and Gammelsrod, 1988). The Weddell Sea Deep Water escapes from the north-western Weddell Sea through gaps in the South Scotia Ridge, and flows into the Scotia Sea with a dominant westward component (Nowlin and Zenk, 1988; Pudsey and Howe, 1998; Maldonado *et al*., 2006).

4. The record of the sedimentary sequences

The analysis of sedimentary covers, and in particular the gaps between the stratigraphic sequences, provides important information about environmental changes that may occur on a regional scale. In the case of deep-sea environments, such as the Scotia Sea, these discontinuities represent areas of erosion or non-deposition. The processes that produce such discontinuities are mainly related to the action of bottom currents. These gaps may have a very broad extent, which occupy the entire sedimentary basin, and may even be linked between different basins.

An extremely noteworthy regional discontinuity has been identified within the Scotia and Weddell basins, whose tentative age is Middle Miocene (Maldonado *et al*., 2006). It developed once the basins were fully established and connected one to the other. This discontinuity recorded the instauration of a new oceanographic scenario, where a more vigorous intermediate and deep circulation model was established, similar (in general terms) to the present-day conditions. This paleo-oceanography was facilitated by the tectonic connection between the Scotia and Weddell Seas across the South Scotia Ridge. Above that discontinuity a reorganization of bottom flows took place, probably due to a changing scenario of gateways that resulted from the end of both spreading in Jane Basin and subduction of the northern Weddell Sea beneath to Jane Bank.

The dynamics of the bottom currents is not only recognizable from their effects on erosion, but also from the generation of depositional bodies, collectively known as sediment drifts. The analysis of their morphological characteristics, their geometry, and their internal structure, allow us to reconstruct the processes which produce them. In the case of polar and sub-polar environments, their presence is determined by the interaction of two distinct processes: the bottom currents, prevalent in the interglacial periods, which distribute the finest fractions of the sediment, and the action of gravity, that prevails in the glacial periods, which creates instability on the slope and the continental shelf with deposition of sediment drifts. Huge sedimentary deposits, in some cases thicker than 1 km, have been identified and analyzed in the central and southern Scotia Sea, where the ACC which flows eastwards and the deep Weddell current which flows northwards are present.

5. Gateways and climate

An important factor that has allowed us to reconstruct the trend in global temperatures during geological history is the value of the ratio of two oxygen isotopes, oxygen-16 (^{16}O) and oxygen-18 (^{18}O). This ratio is determined on calcium carbonate from shells of microfossils (mostly benthic foraminifera) that accumulated on the sea-floor. The ratio depends on two factors: (1) the temperature, and (2) the isotopic composition of the sea water from which the organism secreted its shell. Evaporation and condensation are the two processes that most influence the ratio of heavy oxygen to light oxygen in the oceans. Here, we recall the main aspects of the relationships between this ratio and paleo-temperatures. Shells secreted from colder water contain more ^{18}O relative to ^{16}O than do shells secreted from warmer water. The isotopic composition of the oceans has proved to be related to the storage of water in large ice sheets on land. Because molecules of ^{18}O evaporate less readily and condense more readily, an air mass with oceanic water vapor becomes depleted in the heavier isotope (^{18}O) as the air mass is cooled and loses water by precipitation. When moisture condenses and falls as snow, its isotopic composition is also dependent on the temperature of the air. Snow falling on a large ice sheet becomes isotopically lighter (i.e., has less ^{18}O) as one goes higher on the glacier surface, where it is both colder and farther from the moisture source. As a result, large ice sheets store water that is relatively light (has more ^{16}O), and so during a major glaciation the ocean waters become relatively heavier (contain more ^{18}O) than during interglacial times when there is less global ice. Accordingly, the shells of marine organisms that formed during a glaciation contain more ^{18}O than those that formed during an interglaciation. Although the exact relationship is not known, about 70% of the isotopic change in shell carbonate is the result of changes in the isotopic composition of the sea water. Because the latter is directly related to the volume of ice on land, the marine oxygen isotope record is primarily a record of past glaciations on the continents. Water that is 10° to 15°C cooler than the present represents a glaciation. Precipitation and therefore glacial ice contain water with a low ^{18}O content. Since large amounts of ^{16}O water are being stored as glacial ice, the ^{18}O content of oceanic water is high. Water up to 5°C warmer than today, represents an interglacial period, when the ^{18}O content is lower.

The data made it possible to reconstruct a series of glacial and interglacial periods during the geological history (Fig. 7) indicating that the climate has varied cyclically, with large cycles and harmonics, or smaller cycles, superimposed on the large ones (Zachos *et al.*, 2001). For the most recent geological past, an invaluable archive comes from ice cores taken from Antarctica (Vostok and Dome-C sites) and in Greenland. From the analysis of tiny particles of air trapped in ice, it was possible to reconstruct the pattern of temperatures of up to 900,000 years ago (EPICA,

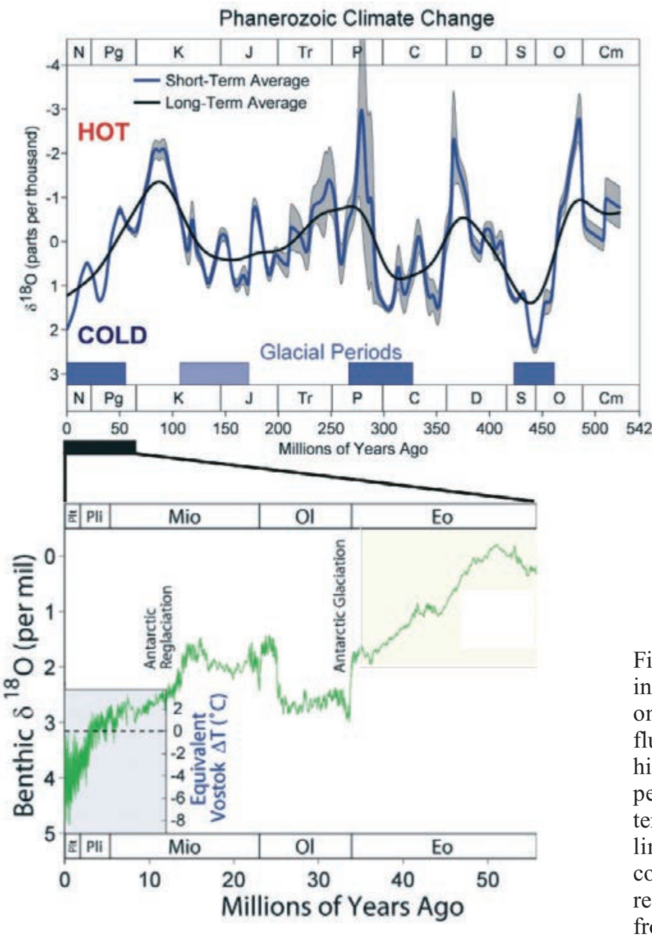

Fig. 7 - Ratio of ^{18}O and ^{16}O, associated to changes in temperature, vs. geological time scale. Figure on top shows that there have been major fluctuations in temperature during the geological history of our planet, with glacial and interglacial periods. Figure below shows the details of temperatures starting from the Paleocene-Eocene limit; data for the last 900,000 years were compared with those obtained from ice cores recovered in the Vostok Antarctic site (modified from various authors).

2004). Data for the Cenozoic period clearly show a gradual reduction in global temperature from about 50 Ma, followed by a sharp, further cooling to about 33-34 Ma (Eocene-Oligocene limit), and a prolonged cold period to around 26 Ma, during which large ice caps in East Antarctica developed. The opening of gateways in the southern hemisphere, such as the Drake Passage (about 35 Ma) and the South Tasman Rise [about 33 Ma, Exon *et al*. (2002)] coincide approximately with the Eocene-Oligocene limit. These gateways have allowed the establishment of a complete annular deep water flow around Antarctica, and have reduced the transport of more temperate water masses to the south, as well as contributing significantly to the cooling of the continent.

Despite these temporal coincidences, there is still a wide debate about the role that southern gateways have played in the Cenozoic climatic changes, and there is still much skepticism about these interpretations. Alternative hypotheses, based primarily on mathematical models and simulations, argue that the primary cause of cooling is linked to a sharp decrease in carbon dioxide content in atmosphere (DeConto and Pollard, 2003), and that the opening of gateways has played a rather marginal role in the gradual cooling of the southern hemisphere.

6. Conclusions

The Scotia Sea is located in a highly critical position with respect to global climatic systems. The opening of the Drake Passage during the Cenozoic permitted the formation of a completely globe-encircling circumpolar current. The westerly wind system that drives this current reaches its maximum velocity at the latitude of Tierra del Fuego and the North Scotia Ridge. The morphological and structural comparison of the conjugate continental margins, i.e., the Tierra del Fuego continental margin and the Terror Rise, once adjacent before the Drake Passage opened, and the identification of the oldest magnetic anomalies at the base of the continental slopes, has constrained the events that occurred immediately after break-up, and the successive tectonic development. The opening of this gateway had profound consequences on water circulation, as testified by the presence of widespread bottom-current-related deposits that contain important paleo-oceanographic records. The opening of the oceanic gateway between the South America and the Antarctic continents is often cited as a critical factor in the initiation of the Earth's most recent glaciation.

Studies of the relationship of climate and tectonics in the region between the southernmost Andes and the Antarctic Peninsula have a major potential for modeling past climate changes, and for making critical contributions to the understanding of the Earth's system processes.

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Corresponding author: Emanuele Lodolo
Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
Borgo Grotta Gigante 42/C, 34010 Sgonico (Trieste), Italy
phone: +39 040 2140359; fax: +39 040 327307; e-mail: elodolo@ogs.trieste.it