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The tectonic history of Drake Passage and its possible impacts on global climate

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ABSTRACT

This study provides an integrated review of plate tectonic models of the evolution of the Antarctica–Patagonia connection compared to geological records collected on land in Patagonia and Tierra del Fuego, and offshore along the northern edge of the Scotia Sea. A temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego is constructed with additional data compiled from entire Patagonia and the Austral Basin. This review provides robust correlations of seaways and tectonic events along the Scotia and South America plates and indicates that the opening of the Drake Passage was not steady state since ca. 30 Ma. Rather the regions forming the present-day northern limit of this gateway experienced important paleogeographic changes, from deep marine basins to shallow ridges and emerged regions during the late Oligocene and early–middle Miocene time. Our compilation of geological data shows that emergence along the North Scotia Ridge and Tierra del Fuego was achieved at 23–22 Ma, and has been followed by elimination of the Patagoniano Sea in Patagonia, starting at 22–23 Ma and achieved at 20 Ma. This transition towards more continental sedimentation in southern South America is correlated with more shallow marine conditions in the Austral Basin. This succession of events had a strong influence on the general geometry of the Drake Passage, corresponding to a constriction of its northern limit, starting in the window 29–22 Ma and achieved at 21 Ma. This period of active deformation in southern South America also corresponds to a period of the global climate having two anomalies well known from the isotopic records: the Late Oligocene Warming, around 26 Ma and the Mid-Miocene Climatic Optimum which ended between 15 and 14 Ma. The possible effects of the post-Oligocene tectonic evolution of the Drake Passage region on general oceanic circulation are discussed. Causes for the synchronicity between tectonic events and these global warming events are examined.

1. Introduction

The timing of events controlling the width and depth of the connections between the Pacific and the Atlantic oceans at Drake Passage is important because early gateway opening and, in some cases, further constriction may have had a profound effect on global circulation and climate during the entire Cenozoic. In recent years, general studies have depicted the progressive opening of the Tasman–Antarctic gateway and the Drake Passage, between Antarctica and Southern South America, due to increased seafloor spreading around the Antarctica plate during the Cenozoic (Lawver and Gahagan, 2003; Barker and Thomas, 2004; Brown et al., 2006). These works point to the possible link between global climate cooling in the Eocene and the onset of free transfer of oceanic water masses south of South America due the establishment of the Antarctic Circumpolar Current (ACC). In the same time, the kinematic history of the South America–Antarctica connection at the Drake Passage during the Cenozoic has been reconstructed with details from the analysis of seafloor magnetic anomalies in the Scotia Sea and adjoining oceanic areas (Fig. 1) (e.g. Eagles, 2003; Livermore et al., 2005; Eagles et al., 2005; Livermore et al., 2007). These studies account for a progressive opening of the Drake Passage since ca. 50 Ma, through continental stretching and oceanic spreading (Eagles et al., 2006).

However, geological records collected on land in Patagonia and Tierra del Fuego, and offshore along the northern edge of the Scotia Sea, indicate that the opening of the Drake Passage was not monotonic. Rather, the regions forming the present-day northern limit of this gateway experienced important paleogeographic changes, from deep marine basins to shallow ridges and emerged countries during the late Oligocene and early–middle Miocene. These information suggest that between ca. 29–22 Ma and 14 Ma, a period of constriction followed the early stages of opening of the Drake Passage. This period of active deformation in southern South America also corresponds to anomalies of the global climate, well known from the

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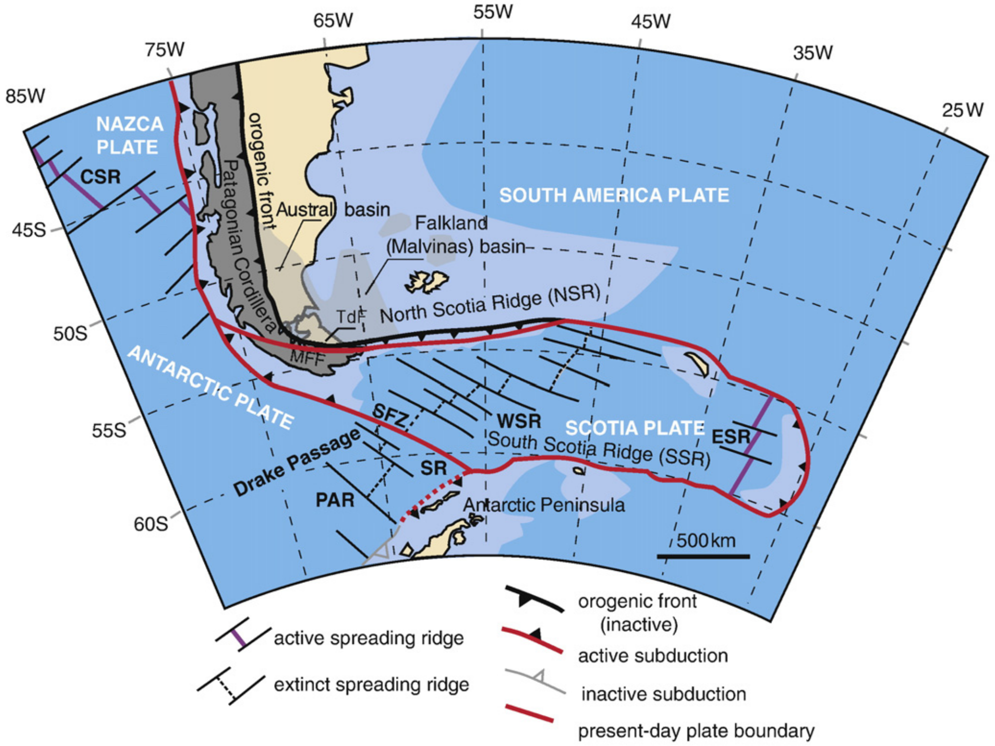


Fig. 1. Present-day setting of the Antarctica–South America connection and tectonic environment of the Drake Passage. TdF: Tierra del Fuego; CSR: Chile Spreading Ridge (active); WSR: West Scotia Ridge (extinct spreading center); ESR: East Scotia Ridge (active spreading center); PAR: Phoenix–Antarctic Ridge (extinct spreading center); SFZ: Shackleton fracture zone (active transpressive); SR: Shackleton Ridge (uplift from compressional deformation of oceanic crust after 8 Ma); NSR: North Scotia Ridge (tectonic front of the Cenozoic transpressive belt, northern edge of Scotia Plate); MFF: Magnano–Fagnano Fault (active transform boundary between Scotia and South America plates in Tierra del Fuego).

isotopic records: the Late Oligocene Warming, around 26 Ma, and the Mid-Miocene Climatic Optimum which ended between 15 and 14 Ma (Zachos et al., 2001, 2008).

By now, no studies have concentrated on the post-Oligocene tectonic evolution of the Drake Passage region and its possible consequences on general oceanic circulation and global climate. In this paper we present for the first time an integrated review of plate kinematic constraints and geological records from Southern South America and from the Scotia Sea region during the Cenozoic. We first propose a review of plate tectonic models of the evolution of the Antarctica–Patagonia connection. Second, we draw a temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego with additional data compiled from entire Patagonia and the Austral Basin. We thus provide robust correlations of seaways and tectonic events across the entire Drake Passage region which document a temporary constriction of the Drake Passage between ca. 29–22 Ma and 14 Ma. Finally we explore some possible explanations of the synchronicity between this tectonic event and the Late Oligocene Warming, taking into account additional constraints deduced from Atlantic paleoceanographic records.

2. Evolution of the Antarctica–Patagonia connection: plate tectonic models

2.1. Timing of opening of the Drake Passage region

Rifting south of Australia began to open the Tasman Gateway for marine circulation between Australia and Antarctica in the 40–30 Ma period (Lawver and Gahagan, 2003; Brown et al., 2006). The final event critical to the establishment of the ACC is generally thought to be the full opening of the Drake Passage (Kennet, 1977; Barker and Burrell, 1977; Barker, 1982, 2001; Barker and Thomas, 2004). There are paleontological evidences on land for a complete opening of the Drake Passage and ACC circulation around 23 Ma (Beu et al., 1997), and numerous records from the ODP and DSDP sites testify the establishment of the ACC following the late Oligocene opening of the Drake Passage and deepening in the Tasman Gateway region (e.g. Rack, 1991; Pfuhl and McCave, 2005). Seismic investigations along the South Scotia Arc provide evidence of intense bottom currents linked to early ACC flows over a 21–17 Ma old oceanic crust (Maldonado et al., 2003). However, estimates for the oldest oceanic crust in the Drake Passage area range from 34 to 29 Ma, and onset of spreading near the Eocene/Oligocene boundary is a genuine possibility (Livermore et al., 2005; Eagles et al., 2005).

For the advocates of the « early Drake Passage opening », the onset of the period of extension in this region is estimated to have occurred around 50±3 Ma through crustal stretching before true seafloor spreading between the tips of South America and Antarctica (Livermore et al., 2005; Eagles et al., 2006; Livermore et al., 2007). For Lawver and Gahagan (2003), the Drake Passage was open to deep circulation around 32 Ma, but motions of micro-continental fragments between Antarctica and Tierra del Fuego are poorly constrained and early opening of a deep seaway in the Drake Passage before 30 Ma is not certain. According to Brown et al. (2006) extensional tectonic between 43 and 32 Ma in the Drake Passage area led to depths >2000 m in this gateway. Changes in deep-water circulation at about 32.8 Ma in the Agulhas Basin is suggested from a measured shift in clay mineralogy, permanent change in the geochemical character of the terrigeneous sediment fraction, and hiatus in the sedimentation at 33–32 Ma (ODP Site 1090, Latimer and Fillipelli, 2002). These changes are interpreted as the consequence of an early opening of Drake Passage flows to deep ACC. More recently, Scher and Martin (2006) found that the influx of shallow Pacific waters into the Southern Atlantic started at 41 Ma, based on Nd isotopic data from fossil fish teeth in drill cores. They conclude that the Drake Passage opened before the Tasman Gateway, implying late Eocene inception of circum-Antarctic pathway, a result supporting the Eagles et al. (2006) assumption of an early opening of the Drake Passage. Micropaleontological analysis of a core from Bruce Bank in the Scotia Sea (Fig. 2) shows that it was lying between 800 m and 2000 m depth around 45 Ma, and that subsidence was active at that time in this region, confirming the early opening of the Drake Passage at least to depths greater than 800 m (Eagles et al., 2006).

2.2. Plate kinematics of the West Scotia Sea

In this section, we describe the plate tectonic framework of the Drake Passage region. We show how oceanic spreading in the center of the Scotia Sea triggered uplift and shortening along the northern edge of the proto-Scotia plate, driving in turn possible changes in the geometry of the Drake Passage region.

The Scotia Sea consists of three relatively large ocean basins, subsided continental blocks at Pirie Bank and Bruce Bank, and smaller and less well known basins including the Protector Basin and Dowe Basin (Fig. 2). The largest basin, the West Scotia Sea, was created at the now extinct West Scotia Ridge. The Central Scotia Sea is more enigmatic, it can be an old oceanic area trapped from older ocean or a younger feature created during the Cenozoic spreading in the Scotia Sea (Eagles et al., 2006). The East Scotia Sea was created at the still

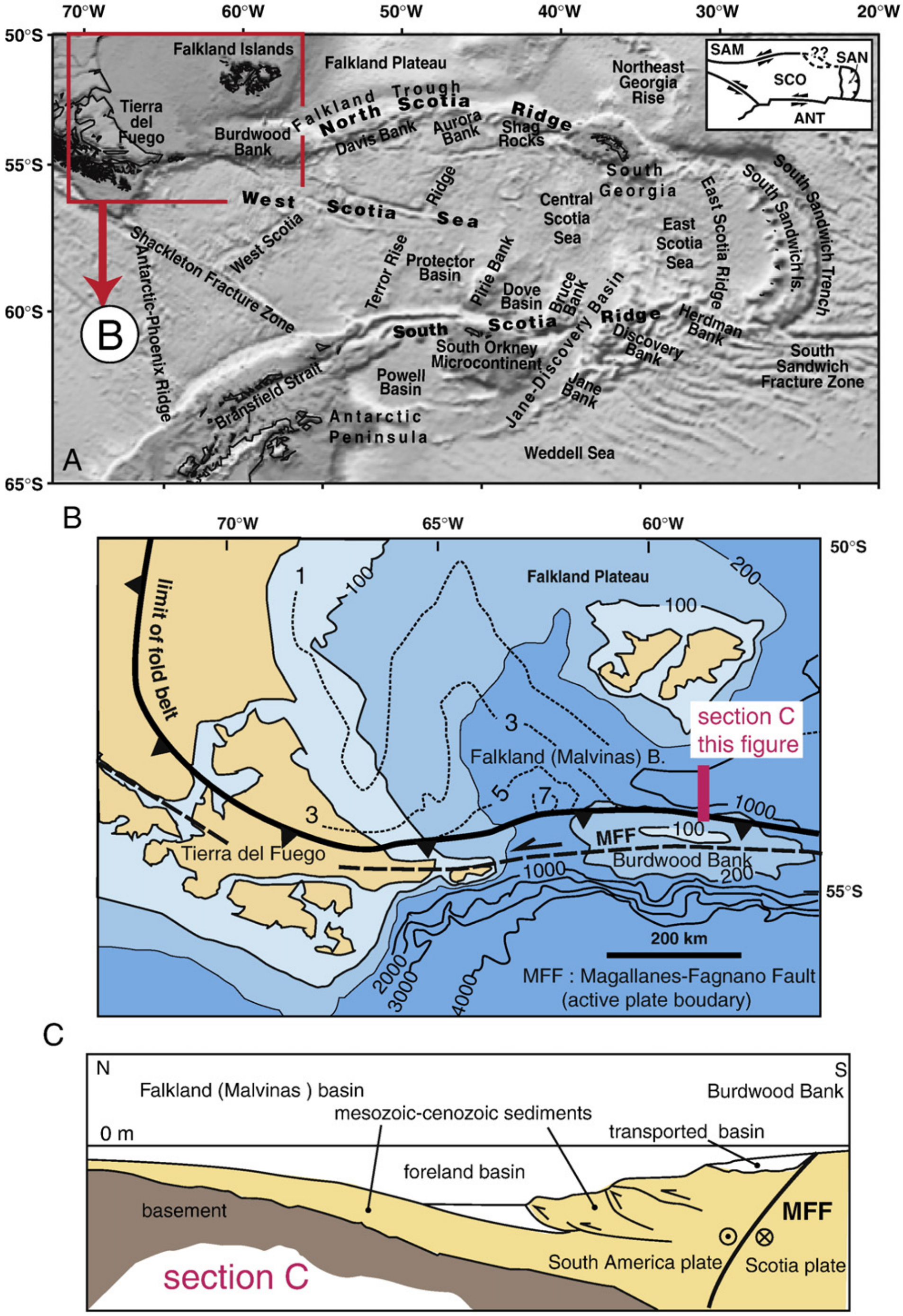


Fig. 2. A. Drake Passage physiography with names of the main features described in text. B. detailed physiography of the Tierra del Fuego and Burdwood Bank region. Thin black lines are isobaths (in m), thin dotted lines are isopachs of the post-Jurassic sediments (in km). C. Simplified N–S cross-section between the summit of the Burdwood Bank and the Falkland (Malvinas) Islands showing that this area results from the closure of a sedimentary basin during the Cenozoic (simplified after Platt and Philip, 1995; Ramos, 1996).

active East Scotia Ridge, an N–S trending back-arc spreading center opening in response to the subduction of the South America Plate at the South Sandwich trench. A chain of islands and submarine highs, termed the Scotia arc, encircles the Scotia Sea. The northern arm of the arc, the North Scotia Ridge, is the offshore continuation of the orogenic system exposed at Tierra del Fuego including a northward verging fold and thrust belt of Mesozoic–Cenozoic sediments and the continuation of the Magallanes–Fagnano active, strike-slip sinistral fault. The Falkland trough represents the Cenozoic foreland basin of the North Scotia Ridge transpressional belt. The southern arm of the Scotia arc corresponds to the South Scotia Ridge (SSR) made up of remnants of arc crust formed over the South Sandwich subduction zone and its predecessors. To the west, the Scotia Sea is delineated by the NW–SE trending Shackleton Fracture Zone (SFZ). West of the SFZ, an extinct spreading ridge composed of three segments, the Antarctic–Phoenix Ridge, is connected to the SFZ. It was active between 15 Ma and 8–3 Ma (Livermore et al., 2000; Eagles, 2003). The current Scotia Plate is defined by the following boundaries: the North Scotia Ridge, the East Scotia Ridge, the SSR and the SFZ (Figs. 1 and 2).

Joint inversion of seafloor isochrons and continuous flow lines derived from satellite gravity anomalies in the Weddell Sea combined with spreading records in the Scotia Sea provide an updated model of the relative South America–Antarctica plates motion (Livermore et al., 2005). The onset of the period of extension in the Drake Passage region is estimated to have occurred around 50 ± 3 Ma through crustal extension followed by seafloor spreading at the West Scotia Ridge (Livermore et al., 2005). Three phases have been recognized. Phase I lasts from 66 to 46 Ma and corresponds to a period of extremely slow separation in a N–S direction giving rise to minimal motion between Tierra del Fuego and the Antarctica Peninsula. Phase II occurs between C21 and C6 (46–20 Ma) and corresponds to an abrupt change in direction from N–S to WNW–ESE, together with an increase in divergence rate up to 24 km/Ma. This phase is thought to be related to the initiation of the subduction of the oceanic seafloor of southern South America beneath the eastern side of the Antarctica Peninsula. Slab retreat was accompanied by the stretching of the continental bridge near the tips of Tierra del Fuego and the Antarctica Peninsula. Eagles et al. (2006) proposed that disruption of this continental link led to the formation and migration of continental micro-blocks, the Terror Rise, Pirie Bank, and Bruce Bank, separated by actively opening small oceanic basins, the Protector Basin and the Dove Basin (Fig. 2). The relative motion of the continental microblocks is an important topic regarding the proto-Drake Passage geometry. Indeed, according to plate reconstructions (Barker, 2001; Lawver and Gahagan, 2003; Eagles et al., 2005; Brown et al., 2006), they remained a long time within the passage before rotating and moving southeastward. At 32 Ma, these micro-blocks form an N–S barrier, forcing the proto-ACC to flow over Patagonia and Tierra del Fuego. The ages of the Protector and Dove Basins are not well constrained. Eagles et al. (2006) propose onset of seafloor spreading in the Dove Basin during the period 41–34.7 Ma, moving to Protector Basin during 34–30 Ma and to the West Scotia Ridge. Phase III starts at chron C6 (20 Ma) with a change to E–W motion leading to a major reorganization of the spreading within the Scotia Sea and initiation of spreading at the East Scotia Ridge.

Spreading along the West Scotia Ridge separated Tierra del Fuego from its conjugate, the Terror Rise by more than 500 km of oceanic crust. Anomaly C10 has been recognized offshore Tierra del Fuego and near Terror Rise, and oldest estimates for the very first spreading stages range between 34 and 29 Ma, but anomalies older than C8 are incoherent and lack conjugates (Eagles et al., 2005; Livermore et al., 2005). Joint inversion of seafloor isochrons and satellite-derived flow lines from the flanks of the extinct West Scotia Ridge constrain opening along this axis between C8 and C3A (26.5 Ma to 6.6–5.9 Ma) (Eagles et al., 2005). In a first stage, from 26.5 Ma to 20.13/16.73 Ma, the West Scotia Ridge opens at a rate of 24 to 26 km/Ma. In a second stage, from 20.13/16.73 Ma (C6/C5C) to the extinction of the West Scotia Ridge at 6.6–5.9 Ma (C3A), spreading rate slows down to 10–12 km/Ma, with an important drop at 16 Ma (Chron C5c), while spreading along the East Scotia Ridge starts, thus accommodating the slab roll-back and trench retreat due to the eastward migration of the South Sandwich subduction zone.

According to Eagles et al. (2005), there are very few possible closed plate circuits that account for the geophysical data set in the Scotia region. The models involve two small plates, the Magallanes and Central Scotia plates, now welded to form the Scotia Sea (Fig. 3). The Magallanes plate was delineated by the West Scotia Ridge, the North Scotia Ridge and the SFZ. In one end-member model, considering that the Magallanes plate was not fixed to South America Plate, there is a 200 km WSW relative motion between Magallanes and South America plates, roughly parallel to the plate boundary, between C8 and C6 (26.5–20.13 Ma). This motion implies therefore strike-slip with a possible shortening component along the North Scotia Ridge (Fig. 3). It is followed by 150 km shortening in the NE direction in the period C6/C5C-C3A (20.13/16.73 to 6 Ma). Hence, it is important to point out that all reconstructions predict Miocene and even earlier convergence along the North Scotia Ridge and in Tierra del Fuego. This is consistent with geological data obtained in the southernmost Andes and along the North Scotia Ridge sedimentary prism and fits remarkably with the description of subsidence followed by closure of marine basins in Tierra del Fuego within the period 37 to 14 Ma, as shown in the following section.

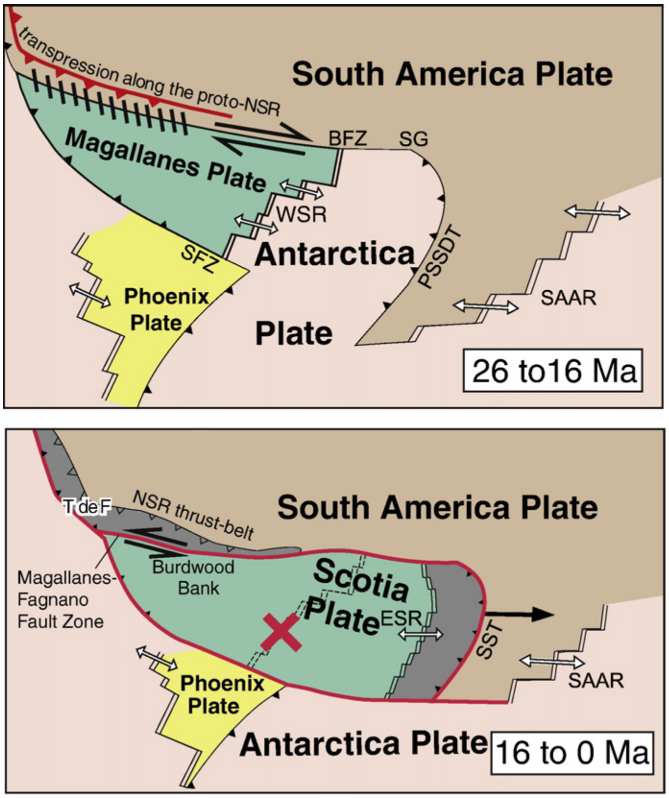


Fig. 3. Cartoons showing the plate tectonic evolution of the Scotia Sea based on models by Eagles et al. (2005) involving early strike-slip motion along the Magallanes Fault (MF), between the Magallanes and South America plates, as soon as spreading commences along the West Scotia Ridge (West Scotia Ridge). This scenario allows transpressional tectonics along the North Scotia Rigde (NSR) starting around 29–28 Ma and closure of seaways in the Tierra del Fuego region achieved at 22 Ma, reducing for some Myrs the volume of the Drake Passage. Lower model represents the current Scotia plate geometry with the extinct West Scotia Ridge (WSR) and sinistral motion along the Magallanes–Magnano fault. Abbreviations are as follows: BFZ, Burdwood Fracture Zone; ESR, East Scotia Ridge; PSSDT, proto-South Sandwich-Discovery Trench, SAAR, South American–Antarctic Ridge; SG, South Georgia; SST, South Sandwich Trench.

3. Geological records from the North Scotia Ridge, Tierra del Fuego and Patagonia: evidence for closure of seaways in the Oligocene

In this section we focus on the geological records obtained offshore along the North Scotia Ridge, and on land in Tierra del Fuego and Patagonia showing that these regions have experienced important paleographic changes, from deep marine basins to shallow ridges and emerged regions, due to shortening and uplift in a strike-slip tectonic regime. These events occurred as a consequence of active spreading along the West Scotia Ridge. We draw a temporal framework for the sedimentary and tectonic events of the North Scotia Ridge and Tierra del Fuego with additional data compiled from entire Patagonia and Austral Basin in order to provide robust correlations of seaways and tectonic events across the entire Drake Passage region during the crucial Eocene to Miocene period.

3.1. Uplift history of the North Scotia Ridge

Southern Andean tectonics has been active since at least 50 Ma, modifying drastically the shape of the tip of the South American continent. The question of the amount of shortening along the North Scotia Ridge during the Eocene is rarely addressed except in few plate tectonic reconstructions at a regional scale, as reported in the section above (Eagles et al., 2005). All published reconstructions are based on present-day continent contours, which do not correspond to the Cenozoic geometry of marine and terrestrial areas, especially in the Tierra del Fuego region and along the North Scotia Ridge. Therefore, attempts to reconstruct the geometry of the Drake Passage region must integrate the timing of the Andean tectonics and the subsequent changes of marine basins and coastlines in relation with continent deformation in the northern edge of the Scotia Sea.

Tierra del Fuego is the very small emerged part of an important E–W orogenic system that develops all along the northern Scotia plate, forming the boundary of the Scotia Sea with the South Malvinas (Falkland) Basin (Ramos, 1996). This boundary corresponds to the North Scotia Ridge, consisting of a series of shallow banks (Burdwood, Davis and Aurora Banks, and Shag rocks). The Burdwood Bank is a prominent feature, as large as entire Tierra del Fuego. Its southern flank is oriented E–W. Along with the Davis Bank, it forces the present-day ACC to flow in an E–W direction over more than 800 km. The North Scotia Ridge ends at the South Georgia island which displays rocks like those of Mesozoic South America (Fig. 2).

The North Scotia Ridge is a major E–W directed recent compressional boundary, orthogonal to the Patagonian Andes. It is well imaged by seismic lines in the Burdwood Bank region showing that the South Falkland Basin is over-ridden from the south by a prograding thrust pile with blind and emergent thrusts (Platt and Philip, 1995; Ramos, 1996; Bry et al., 2004). Therefore, the Malvinas (Falkland) Trough must be regarded as a Cenozoic foreland basin due to this compressive system (Bry et al., 2004). The Paleocene–Pliocene sedimentary succession of the Malvinas basin displays an overall foredeep-style strata pattern. The full development of the foredeep, north of the North Scotia Ridge, occurred during the middle Eocene–Oligocene, but a transtensional episode during the Early Paleogene is inferred (Galeazzi, 1996, 1998). The summit of the Burdwood Bank is only 200–100 m below sea-level, but during the Paleocene–Eocene, a trough trending N70 was present south of 54°S, at the emplacement of the Bank (Galeazzi, 1998). As synthetized in Fig. 5, uplift occurred during a compressional stage accompanied by the development of north verging thrusts and related strike slip faults. Constraints from seismic lines indicate that inversion of the southern edge of the Malvinas Basin by progressive thrusting occurred during the late Eocene–early Miocene (Galeazzi, 1998). Similar records are obtained farther East along the North Scotia Ridge (Platt and Philip, 1995; Bry et al., 2004).

3.2. From subsidence to uplift and emergence in Tierra del Fuego

Since Tierra del Fuego is located at the tip of the Patagonian fold and thrust belt, its tectonic evolution is a key-factor controlling the changes in the Drake Passage physiography. The southernmost Andes of Tierra del Fuego run E–W (Figs. 3 and 5) and are composed of an internal domain with basement-involved contractional deformation and a thin-skinned external domain. This domain is made up of folded and imbricated marine sequences of Cretaceous to Neogene age showing numerous evidences of syntectonic sedimentation, deposited within environments ranging from deep open marine to a more shallow platform. Variations in thickness of the marine sequence indicate progressive cratonward (northward) propagation of marine depocenters during the late Cretaceous–Paleogene. These formations are important records of the presence of a seaway in this region.

The tectonic evolution of the Fuegian region has been described by Kraemer (2003) who proposed an average of 80 km of shortening during the Neogene. More recently, Ghiglione and Ramos (2005) found that faulting of the Fuegian orogenic wedge occurred in three main episodes. The two first episodes led to a rapid uplift of basement rocks (Rocas Verdes and Cordillera Darwin domains) and occurred between the late Cretaceous and the Middle Eocene at 61–55 Ma, and at 49–34 Ma (Rio Bueno thrusting event), that is before the first magnetic anomalies in the Drake passage. After these two events, post tectonic uplift was very slow and restricted in these domains. The third tectonic event occurred from the Late Oligocene to the Quaternary (29 Ma to Present) with a peak of transpressional deformation in the 24–16 Ma period, well constrained at the locality of Punta Gruesa. Propagation of the Fuegian wedge apparently slowed down after the Rio Bueno thrusting event. After that episode, the deformation is wrench-related and thrusting is associated with dominant strike-slip faulting linked to displacement along the Magallanes–Fagnano sinistral fault corresponding to motion along the northern boundary of the Scotia plate (Menichetti and Tassone, 2007).

Stratigraphy of the upper Cretaceous–Paleocene beds from Tierra del Fuego includes deep marine turbidites, sandy mudstones followed by fan delta conglomerates indicating permanent marine conditions, with progressive uplift during the Paleocene (Olivero et al., 2003). Marine sediments deposited during the Eocene–Oligocene to Early Miocene are exposed north and south of the Punta Gruesa lineament marking the northern limit of the deformed part of Tierra del Fuego (Fig. 4).

(1) South of Punta Gruesa, the succession is divided into well dated formations (Olivero and Malumian, 1999; Olivero et al., 2003; Malumian and Olivero, 2005; Malumian and Olivero, 2006; Olivero and Malumian, 2008) (Fig. 5).

- *The Cerro Colorado formation* (37–34 Ma) is a major transgressive sequence, more than 800 m thick, that recorded tectonic instabilities. It is composed of mudstones and sandstones with benthic foraminifera assemblage reflecting cooling waters. It overlies the Punta Torcida and Leticia Formations, of late-middle Eocene age, deposited in more shallow environments (shelf to estuarine settings). Therefore, this succession has recorded an important subsidence phase around 37 Ma.
- The following marine formations (*Ballena, Punta Gruesa, Desdemona, Cabo Pena Formations,* Olivero and Malumian, 2008) rest on a subtle parallel unconformity over the upper Eocene sediments of the Cerro Colorado Formation. The basal stratigraphic section of Lower Oligocene age consists of folded conglomerates, sandstones and silt-claystones which bear foraminiferal assemblage indicating deep marine environments and active bottom currents (Malumian and Olivero, 2005). In the upper section, of late Oligocene age, there is a brutal change of

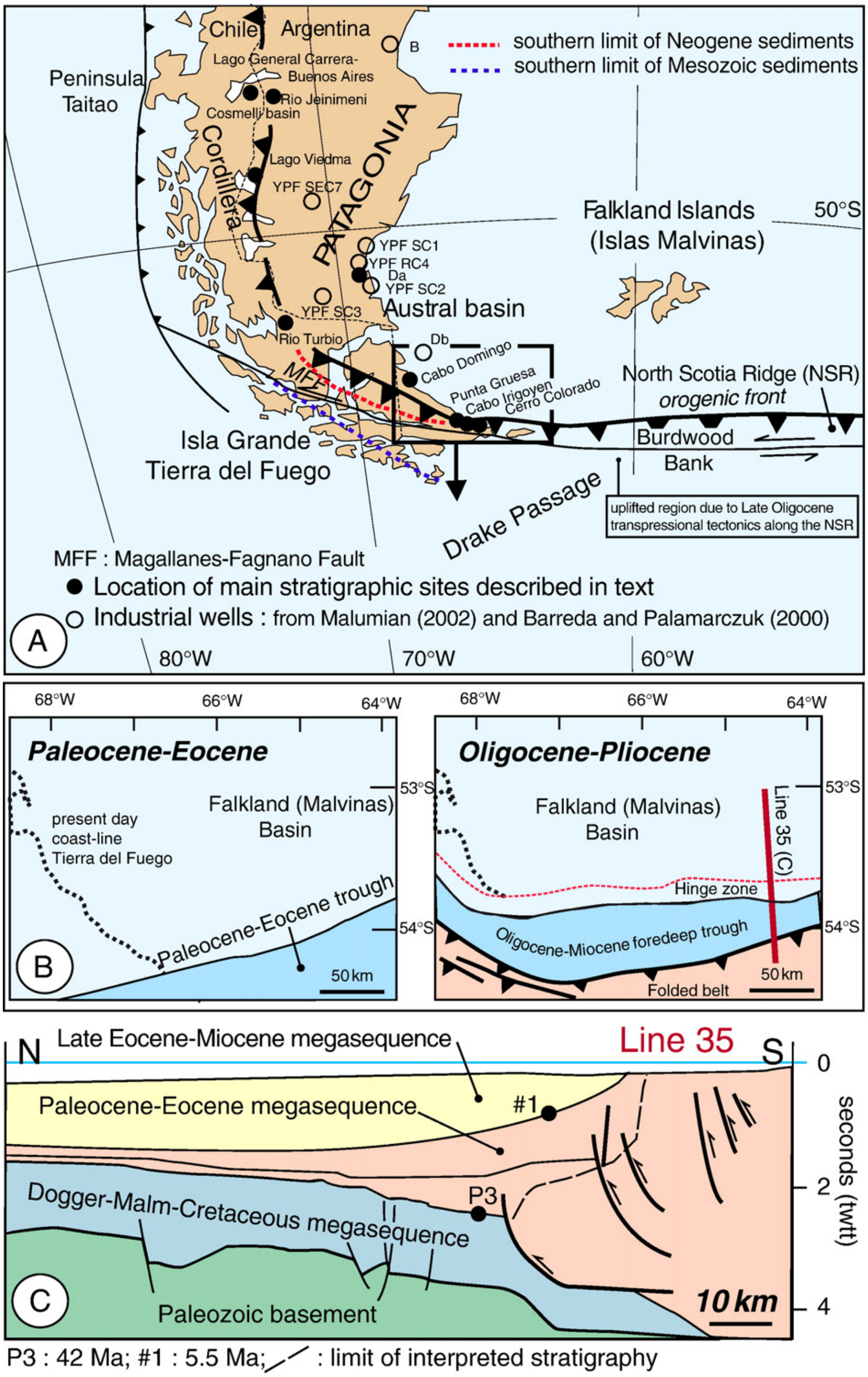


Fig. 4. Map of southern South America showing key-localities used for the synthesis of stratigraphic and tectonic records discussed in text. Simplified stratigraphic sections at each locality and related paleoenvironments depicting the Eocene–Miocene geological evolution of Patagonia are presented in Fig. 6. The tectonic front in Tierra del Fuego and in the main Cordillera is also shown. Shortening along this boundary triggered closure of deep marine basins in Tierra del Fuego leading to temporary decrease in volume of the Drake Passage.

conditions towards shallower environments between 29 and 24 Ma (Malumian and Olivero, 2005).

- *The Maria Luisa and Irigoyen Formations* are shallow water clastic sediments of Late Miocene to Pliocene age deposited after a more than 10 Myr long hiatus (11–3 Ma).

Finally, this record reflects deep marine conditions below the lysocline from 37 to 29–24 Ma and shows that a tectonic phase around 29–24 Ma started closing the deep marine seaways, leading progressively to emersion. Shallow marine and estuarine conditions are back in the region after 11 Ma, indicating renewed subsidence or higher sea level.

(2) North of the Punta Gruesa Fault, in the region of Cabo Domingo (Fig. 4), the marine sediments of Cabo Domingo group include:

- The *Cerro Colorado Formation* (36–34 Ma) (Fig. 5) consisting of mudstones and sandstones of late Eocene age with a maximum thickness of 900 m at the depocenter (Malumian and Olivero, 2006).). These sediments were deposited in a few Myr only, during the maximum deepening of the basin. They have recorded a rapid

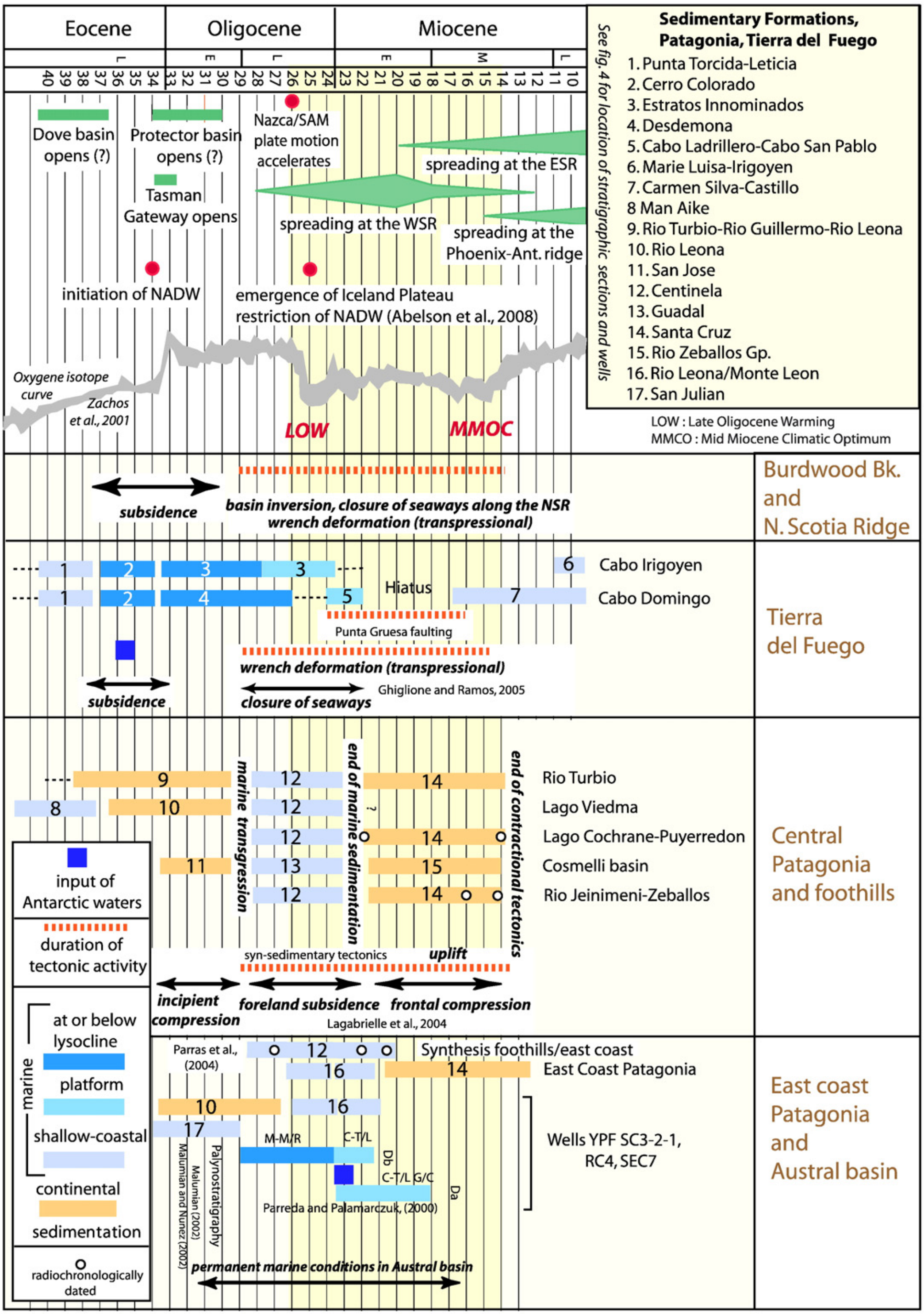


Fig. 5. Table of the main stratigraphic and tectonic events that affected southern South America during a key-period of the evolution of the Drake Passage region, between 40 and 10 Ma. Simplified stratigraphic columns with indication of paleoenvironments are plotted against the d^{18}O curve of benthic foraminiferas by Zachos et al. (2001). Numbers refer to formations listed in upper cartoon and described in text. Main events related to oceanic spreading in the Scotia Sea and in the northern hemisphere are reported.

temperature change at 36 Ma as shown by the presence of Antarctica fauna, confirming early opening of the Drake Passage region that allowed entrance of Antarctic corrosive waters.

- The *Tchat-Chi Formation*, develops laterally toward the NW. It consists of conglomerates from fan delta deposits, indicating localized tectonic activity around 32–34 Ma.
- The *Desdemona Formation*, is a 250 m thick succession of deep marine silt-claystones, deposited near or at the lysocline, containing benthic foraminiferas and carbonaceous beds. This includes claystones and sandstones of the *Estancia Maria Cristina beds* of earliest Oligocene (34–30 Ma) and claystones of *Puesto Herminita beds* of Oligocene age (30–26.5 Ma). These beds mark a change

toward external platform conditions. They contain numerous evidences of gravity induced instabilities and clastic dykes, which indicate active tectonics.

- The *Cabo Ladrillero and Cabo San Pablo Formations*, are 24–22 Ma old. They consist of glauconia-bearing sandstones deposited in deep platform environment, with cold waters and frequent gravity slidings, passing to shallow external platform environment. These formations and the *Puesto Herminita* beds have recorded the closure of the basin, between 26 Ma and 24 Ma, that was completed at 22 Ma. This event is followed by a rapid regression and a lack of sedimentation during the 21–17 Ma period.
- The *Carmen Silva and Castillo Formations* (Middle Miocene, 17–14 Ma), are characterized by micropaleontological assemblages typical of shallow, coastal and deltaic environments (Malumian and Olivero, 2005; Malumian and Olivero, 2006).

3.3. Geological records from the Patagonian Cordillera and the Austral basin

In the following section we compare the records of Tierra del Fuego with those from other part of the Austral basin (Fig. 1) including the foothill regions of the current Patagonian Cordillera, the Cordillera itself, and the east-coast of Argentina (Santa Cruz and Chubut provinces) (Figs. 4 and 5). The Cordillera experienced maximum deformation and uplift during the 30–14 Ma period, while the east-coast of Argentina represents the undeformed foreland basin of the South Andes and North Scotia orogenic wedges. The stratigraphic data are synthetized in the chronological table of Fig. 5 along with major events characteristic of the entire region.

3.3.1. Foothills region of Southern Patagonia

Along the Rio Turbio, in the Sierra Dorotea region (southwestern corner of the Santa Cruz Province) (Fig. 4), a continuous sedimentary sequence including Campanian to Miocene rocks gives the opportunity for a paleo-environmental study of Southern Patagonia. The Cretaceous–Paleocene beds are indicative of shallow marine waters (Dorotea, Man Aike Formations). The overlying Rio Turbio Formation (Fig. 5) of Middle Eocene age, includes marine and terrestrial sandstones and conglomerates with coal beds, indicating shallow environments unsuitable for planktonic elements (Griffin, 1991; Hill et al., 1997). It is followed by the Rio Guillermo and Rio Leona fluvial deposits (Upper Eocene–Lower Oligocene). These continental deposits are unconformably overlain by the marine, richly fossiliferous, Rio Centinela Formation (or Centinela Formation) of Uppermost Oligocene–Lower Miocene age. The Centinela Formation includes clastic beds, generally sandstones to conglomerates, deposited under marine, near-shore conditions (0–50 m depth) and is the record of a major Cenozoic transgression affecting Patagonia, known under the informal name of « *Patagoniano* ». Isotopic dating of oyster shells and an additional Ar/Ar study from the Centinela Formation gives ages between 20.48 Ma and 26.38 Ma (Parras et al., 2004), as confirmed by Guerstein et al. (2004).

A comparable depositional pattern is found north of the Rio Turbio area, in the lago Viedma region (Fig. 5). Here, conglomerates, sandstones and mudstones of the fluvial Rio Leona Formation (Upper Eocene–Lower Oligocene), rest with an erosional contact over the sandstones of the Man Aike formation (coastal environment, Lower Eocene age) (Marenssi et al., 2003). The Rio Leona beds grade into the marine sandstones of the Centinela Formation (Upper Oligocene–Lower Miocene) (Fig. 5). Both formations form a depositional sequence initiated with an important flux of clastic sediments deposited in anastomosing fluvial channels replaced by coastal plain deposits followed by shallow marine sediments. This is the record of a rapid subsidence due the flexural response of the foreland lithosphere to tectonic stacking operating to the west. According to Marenssi et al. (2003), the first stages of the constriction of Patagonia started with the first deposits of the Rio Leona conglomerates, close to the Eocene–Oligocene boundary (32–34 Ma), probably few Myrs only before onset of oceanic spreading along the West Scotia Ridge in the proto-Scotia Sea.

3.3.2. The Central Patagonian belt

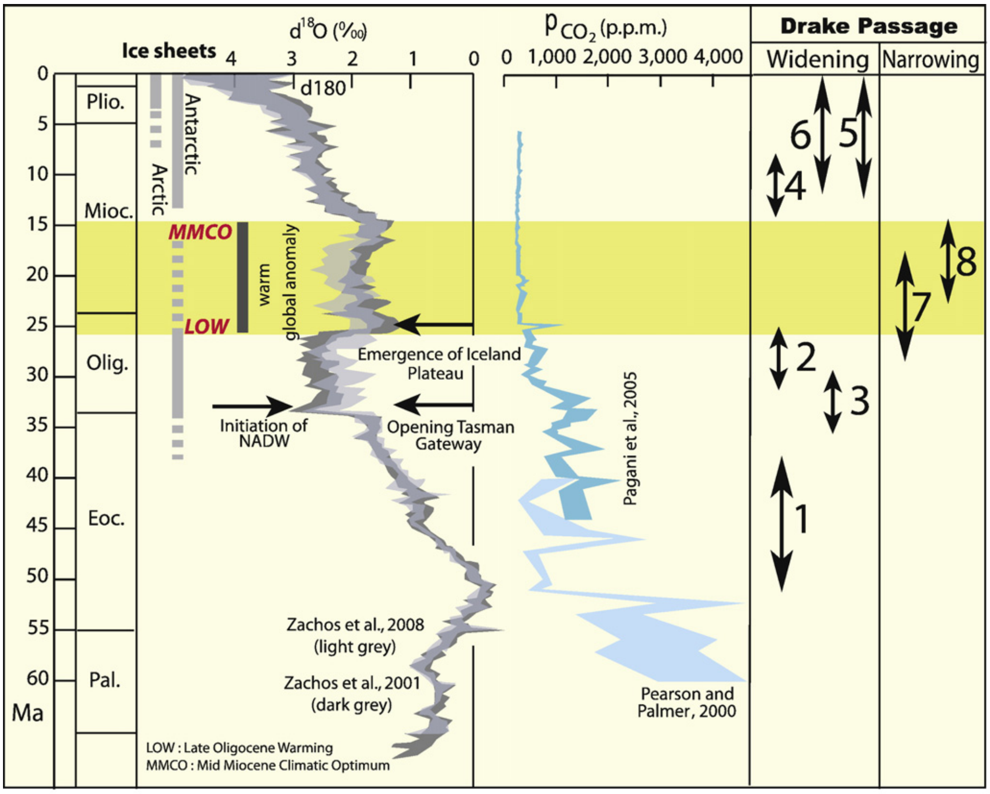
In all of Patagonia, the Santa Cruz Formation is a sequence of clastic fluvial deposits dominated by sand-, silt- and claystone beds locally with conglomerates which rests over the Centinela Formation recording both the end of marine conditions and the continuation of active tectonics and uplift of the Cordillera. The age of the Santa Cruz Formation near Lake Cochrane-Puyerredon (Fig. 4) was constrained by Blisniuk et al. (2005) between 22 and 14 Ma, with an important change in d^{13}C and d^{18}0 at 16.5 Ma, indicative of one km rapid uplift. At 14 Ma, the deposition ends due to absence of erosion in response to the rain shadow effect of the uplifted Cordillera and to the cessation of tectonics (Lagabrielle et al., 2004; Scalabrino et al., 2009) (Fig. 5).

The Santa Cruz and Centinela formations correlate with similar formations described in Central Patagonia, thus confirming their overall distribution. In the Lake General Carrera-Buenos Aires region (in the core of Central Patagonian belt, Fig. 4) the Pampa Castillo section of terrestrial sandstones, claystones and minor conglomerates contains a mammalian fauna of latest Early Miocene age. In the Cosmelli basin (Fig. 4), it overlies a 650 m thick section of marine strata, the Guadal Formation of Late Oligocene to Early Miocene age, a stratigraphic equivalent of the Centinela Formation. The transition between the Guadal and Pampa Castillo Formations marks the withdrawal of the middle Cenozoic Patagonia seaway after it reached its maximum northward and westward extent (Flynn et al., 2002). The Guadal beds overlie coarse conglomerates of the San Jose Formation (Flint et al., 1994), an equivalent of the Rio Leona Formation which is given an Upper Eocene–Lower Oligocene age by Suàrez et al. (2000). This clastic sequence shows that compressional deformation started before the deposition of the Guadal Formation, a scenario also deduced from records in the Lago Viedma and Rio Turbio regions. The lower part of the Cosmelli basin is folded and shows imbricate tectonic sheets revealing syn-depositional deformation during the Guadal times.

Along the Jeinimeni and Zeballos rivers (Fig. 4), at the morphological front of the Central Patagonian Cordillera, the Centinela formation grades without hiatus into the continental beds of the Grupo Rio Zeballos, a 1500 m thick sequence of fluvial sandstones, siltstones and conglomerates (Fig. 5). This sequence correlates with the Santa Cruz Formation and has recorded also active erosion of the uplifting reliefs (Escosteguy et al., 2002). At Cerro Zeballos, the sandstones are capped by lava flows dated at 16 Ma and 14 Ma (Espinoza et al., 2006). South of Lake General Carrera-Buenos Aires, sub-horizontal alkali basalts flows of Meseta Lago Buenos Aires dated at ca. 12.5 Ma extensively covered these deposits. This confirms that erosion and compressional tectonics ceased totally between 14 and 12 Ma in the front of the Cordillera (Lagabrielle et al., 2004).

3.3.3. The east-coast of Patagonia and the offshore domain

Synthesis of data from industrial wells in southern Patagonia is presented by Malumian (2002) (sites YPF-SC, RC, SEC: Figs. 5 and 6). Stratigraphic records display numerous similarities with that from the foothills region, but differ due to predominant marine conditions at eastern localities. Micropaleontological studies based on foraminiferas from drilled samples along the coast and in the Argentinian shelf, and studies of continental and marine palynomorphs (sites Da and Db, Fig. 4) are correlated with data from exposed section in the foothills (Barreda and Palamarczuk, 2000; Malumian, 2002; Malumian and Nanez, 2002). In the Late Eocene, the sedimentation is characterized by glauconitic rich beds, lateral marine equivalents of the Man Aike and Rio Turbio Formations. Thickness of these deposits increases southward and reaches up to 3.600 m, recording relatively deep



1. Crustal extension, subsidence, block rotation, opening of small basins in Drake Passage and formation of shallow gateways.
2. Subsidence of marine basins in present-day Tierra del Fuego and North Scotia Ridge (NSR) .
3. Spreading on West Scotia Ridge (WSR, fig. 1) commences.
4. Spreading on Antarctic-Phoenix Ridge (PAR, fig. 1) commences.
5. Normal faulting and collapse in Southern Patagonia due to slab window.
6. Spreading along the East Scotia Ridge (ESR, fig. 1) and rapid eastward migration of the Scotia arc.
7. Closure of proto-Drake seaways : inversion of marine basins in Tierra del Fuego and along the North Scotia Ridge (NSR) (e.g. Burdwood Bank).
8. Uplift of the Patagonian Cordillera, change from marine to continental environments in Patagonia.

Fig. 6. Table of the main events that affected the Drake Passage region plotted against the d^{18}O curves of benthic foraminiferas by Zachos et al. (2001, 2008) and the pCO$_2$ curve from Pagani et al. (2005) and Pearson and Palmer (2000). Events that favour a widening of the DP are separated from events that tend to narrow it.

marine conditions over the foothills region and offshore. In the offshore domain, the Monte Leon formation is characterized by deep, cold and aggressive waters that bear Antarctic characters with important biogenic silica input (Malumian and Nanez, 2002; Malumian, 2002). This indicates that Antarctic seas invaded the Austral basin region during the Late Oligocene (around 28 Ma, Fig. 5), thus confirming the development of deep seaways at that time in the proto-Drake passage. (Barreda and Palamarczuk, 2000; Parras et al., 2004).

In the foothills region and along the coast, the Rio Turbio Formation is followed by the continental Rio Leona Formation and by the San Julian Formation of Lower Oligocene age, indicative of shallow marine and coastal environments (Malumian and Nanez, 2002). Additional correlations from exposures in the foothills region confirm the Upper Oligocene to Lower Miocene age for the Centinela Formation (Parras et al., 2004) (29–22 Ma) (Fig. 5).

4. Discussion: tectonic evolution of Drake Passage, changes in oceanic circulation and possible climatic impact during the Cenozoic

In this section, we explore the possible implications of the tectonic evolution of the Drake Passage region as depicted in the sections above. We first propose a link between the geological and the plate tectonic records that allows us to recognize a period of constriction of the Drake Passage. Then we examine how such constriction may have had an impact on the global circulation trough influences on the ACC efficiency. Possible effect on global climate is discussed and tested using a coupled numerical model.

4.1. A synthesis of the kinematic and geological records: opening, narrowing and rewidening of Drake Passage

4.1.1. Early opening of Drake Passage and temporary closure of Eocene–Oligocene seaways in Tierra del Fuego starting at ca. 29 Ma

The development of deep marine connection in the proto-Drake Passage region is proposed by Eagles et al. (2006) who suggest the onset of seafloor spreading in the Dove Basin during the period 41–34.7 Ma, moving to Protector Basin between 34 Ma and 30 Ma. The above review of the geology of Tierra del Fuego emphasizing marine sedimentation during the late Eocene strengthens this hypothesis (Fig. 4). We report a phase of rapid deepening of seaways in that region allowing flows of cold, proto-ACC waters, between 37 and 34 Ma. Similar conclusions have been reached recently from stratigraphic data (Ghiglione et al., 2008). These authors report evidences for the presence of a latest Paleocene–early Eocene extensional basin (i.e., lateral rift) in Tierra del Fuego with an accurately dated postrift unconformity ca. 49 Ma.

The progressive northward migration of depocenters in relation with the propagation of a tectonic front occurred between 29 Ma to 22 Ma. During the Upper Eocene–Early Oligocene, deep basins are progressively closed and the sea is wiped out of these basins toward the NE, accompanied by deepening of the foreland region. The 21 Ma to 17–14 Ma period is characterized by the lack of marine sedimentation reflecting the formation of a very shallow or emerged, E–W trending Cordillera at the location of present-day Tierra del Fuego, closing the previous seaways. The scenario of a progressive migration of the depocenters is also well documented by seismic studies along the North Scotia Ridge showing northward propagation of thrust faults (Platt and Philip, 1995; Bry et al., 2004). This timing of progressive closure of Tierra del Fuego seaways from 29 Ma to 22 Ma deduced from the stratigraphic records is confirmed by the onset of the Punta Gruesa faulting event, estimated at 26 Ma (Ghiglione and Ramos, 2005) and coincides with the age of the first magnetic anomalies at the West Scotia Ridge around 26 Ma (and possibly at 28.7 Ma: Chron C10) indicating initiation of spreading and subsequent transpression along the North Scotia Ridge boundary (Eagles et al., 2005). We infer that as soon as new oceanic crust is created at the West Scotia Ridge, the North Scotia Ridge will act as a transpressive boundary that accommodates expansion in the proto-Scotia Sea (Fig. 6). Continuous spreading from 28–26 Ma to 20 Ma is transformed into transpression in Tierra del Fuego (Fig. 3), closing the deep basins. Transpression lasts until spreading rate along the West Scotia Ridge drops, which occurs from 16 to 11 Ma, a period during which the Punta Gruesa strike slip faulting terminates (Ghiglione and Ramos, 2005). Finally from 28–26 Ma to 20 Ma, there might be a competition between opening at the West Scotia Ridge and compression along the North Scotia Ridge, and the Drake Passage region cannot enlarge any more for some Myrs. Estimates for the amount of convergence and uplift during this period, compared to the width of new oceanic domain created at the West Scotia Ridge axis are difficult to perform because the detailed timing of the deformation along the North Scotia Ridge is not known for the Neogene. However, estimates of shortening along the North Scotia Ridge boundary are 200–150 km from kinematic models (Eagles et al., 2005) and 80 km from geological studies in Tierra del Fuego (Kraemer, 2003), while 100 km of new oceanic crust might have been emplaced along the West Scotia Ridge between 26 Ma and 22 Ma at a rate of 25 mm/yr. In addition, calculations by Brown et al. (2006) suggest that incipient oceanic spreading along the nascient West Scotia Ridge leads to uplift of the seafloor, reducing for a period the volume of the remaining seaway. As a result, despite oceanic spreading at the West Scotia Ridge, the Drake Passage likely experienced significant narrowing in the 29–22 Ma period (Fig. 7).

In Patagonia, the sedimentation is characterized by a generalized regression phase during the late Eocene–early Oligocene, in relation with the onset of uplift due to first compressional events in the Cordillera around 32 Ma. The maximum of this continental phase, characterized by the deposition of clastic continental sequences in the proto-Cordillera (Rio Leona, San Jose Formations) occurred around 30 Ma (e.g. Nullo and Combina, 2002). Thus, compression along the southern Andes has been active during the progressive closure of the Tierra del Fuego seaways from 29 to 22 Ma. This coincides also with a period of rapid relative motion between the Nazca and South America plates (Pardo-Casas and Molnar, 1987) (Fig. 5). Transgression of shallow marine waters occurred in Patagonia during the late Oligocene and the early Miocene (29–20 Ma). During this period, regions of southern Patagonia located north of Tierra del Fuego were invaded by the *Patagoniano Sea* which deposited the Centinela and Guadal Formations in the foothills domains as well as within the core of the present-day Cordillera, very close to the Pacific coast (Cosmelli basin, Fig. 5). These formations are typical of very near shore environments with temperate waters receiving fine-grained clastic debris by rivers flowing from a young Cordillera experiencing active uplift. This stage of relative high sea level occurred in a period of global cool climate with the development of the Antarctic Ice Sheet (Zachos et al., 2001). It is therefore better explained by foreland basin subsidence due to flexural response to crustal thickening of the western Cordillera rather than by a rapid rise in sea level. Around 28 Ma, Antarctic waters enter the Austral basin (Monte Leon Formation) which confirms deepening of the Patagonian platform and indicates that the Drake Passage has some connections to the north (Fig. 5).

Continuous shortening and uplift of the Patagonian Cordillera led to the shift from shallow marine to continental fluvial conditions in the foothills region. According the scarce available geochronological data, this major change in sedimentation conditions is thought to have occurred between 23 and 20 Ma (Fig. 5). The fluvial deposits forming the ubiquitous Santa Cruz sequences recorded continuous outflow of detrital products after 23–20 Ma. The main uplift crisis of the Cordillera are recorded around 18 Ma (Haschke et al., 2006) and 16 Ma (Blisniuk et al., 2005).

Finally, our compilation of geological data, show that emergence along the North Scotia Ridge which was achieved at 22 Ma, has been followed by elimination of the Patagoniano Sea in Patagonia, starting at 23 Ma and achieved at 20 Ma. This transition towards more continental sedimentation in southern South America is correlated with more shallow marine conditions in the Austral Basin. This succession of events had a strong influence on the general geometry of the Drake Passage, corresponding to a constriction of its northern limit, starting in the window 29–22 Ma and achieved at 21 Ma. This in turn may impact the general ocean circulation through changes in proto-ACC flows as explored further in Section 4.2.

4.1.2. *Re-widening of the Drake Passage, the post-15 Ma evolution*

Several important events occurred in southern South America after 15 Ma, that account for changes in the Drake Passage physiography, triggering its re-widening.

(1) In the Tierra del Fuego region, after an almost 10 Myr long hiatus, the deposition of upper Miocene–Pliocene marine sediments exposed in the Irigoyen region reflects renewed subsidence following the closure of the seaways (Malumian and Olivero, 2006). In addition, transtensional deformation along the Magallanes–Fagnano fault during the Pliocene led to opening of pull apart basins allowing new Pacific–Atlantic connections (Ghiglione and Ramos, 2005; Malumian and Olivero, 2006).

(2) The end of the compressional tectonics in the Patagonian Cordillera coincides with marine transgressions recorded along the Atlantic coast in the Santa Cruz and Chubut provinces after 15 Ma (Barreda and Palamarczuk, 2000). This transgressive phase is well explained by a generalized subsidence of Southern South America recorded in the Atlantic shelf due to continuous flexure under the load of the Scotia plate edge (Bry et al., 2004) and by extensional tectonics recognized in Southern Patagonia (Diraison et al., 1997) or in the Central Cordillera (Lagabrielle et al., 2007). Extension can be related to the development of an asthenospheric window opened at depth as a consequence of the subduction of the South Chile Ridge (Lagabrielle et al., 2004). This collectively contributed to increase oceanic areas between South America and Antarctica.

(3) Despite lowering of spreading rate at the West Scotia Ridge, the Drake Passage experienced further widening because of active oceanic spreading along the Phoenix–Antarctic Ridge between 15 and 8–3 Ma (Livermore et al., 2000; Eagles, 2003) and along the East Scotia Ridge since 20 Ma (Eagles et al., 2005). During the 15–0 Ma period, the Scotia arc migrated rapidly eastward allowing larger oceanic fluxes (Barker, 2001) (Fig. 7).

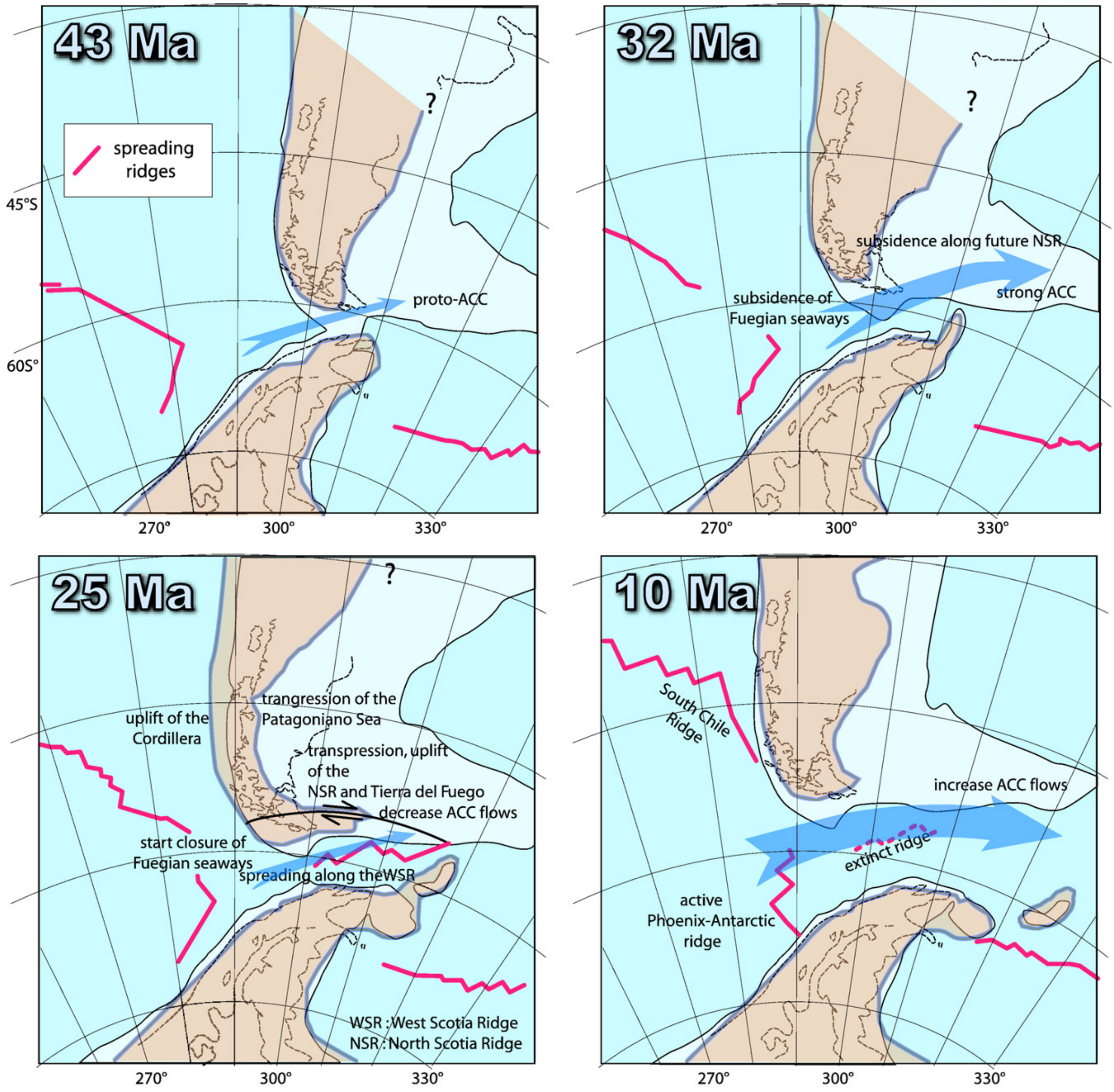


Fig. 7. Four step cartoon depicting the evolution of the Drake Passage region based on plate reconstruction from Brown et al. (2006). We emphasize subsidence south of South America in the Tierra del Fuego region followed by narrowing in response to closure of former seaways due to tectonic uplift of the North Scotia Ridge and of the Fuegian and Patagonian Cordillera. Transpression along the North Scotia Ridge (NSR) is due to spreading along the West Scotia Ridge (WSR). Inferred route of ancient ocean currents is shown (grey arrows). ACC: Antarctic circumpolar current.

4.2. Progressive constriction of the Drake Passage achieved at 21 Ma and re-opening after 15 Ma: possible effects on global climate

In this section, we first recall the climatic role of the ACC and Drake Passage, then we point at the synchronicity between an aberration in the Cenozoic global climate evolution and closure of seaways in Tierra del Fuego and along the North Scotia Ridge. Finally, we speculate about the possible impact of a temporary constriction of Drake Passage on global climate.

4.2.1. Drake Passage, onset of ACC and Cenozoic climate: a summary

The ACC circulates through the Tasmania–Antarctic Gateway and the Drake Passage and is the only current to flow around the globe without encountering any continental barrier. It connects the Atlantic, Pacific and Indian Ocean basins and is the principal pathway of exchange between these basins. It is a wind-driven current, 24.000 km long, composed of a number of fronts and is strongly constrained by landform and bathymetric features (Orsi et al., 1995). The current is very deep, extending to the sea-floor at about 4000 m depth, and its volume transport is therefore enormous (Open University, 1989). Any modification in seafloor bathymetry such as uplift of gateways due to tectonic causes will have important consequences on the global amount of water (and heat) transported by the ACC. The current continuously activates the Antarctic Divergence, where North Atlantic Deep Waters (NADW) rise up to the surface in the Antarctic region. Therefore, the ACC is a key-actor of the thermohaline circulation and has an impact on water fluxes originating from the Northern Hemisphere.

As revealed by the global deep-sea oxygen isotope records (Fig. 6) (Zachos et al., 2001), the Earth climatic Cenozoic cooling started during the early–middle Eocene, and was marked by the transition from a 'greenhouse-' to an 'icehouse-world' at the Eocene/Oligocene boundary, about 33.5 Myrs ago. The role of oceanic gateways in this global climatic evolution is still intensively debated, but there is a striking synchronicity between this climatic event and the opening of the southern gateways (Eagles et al., 2005; Livermore et al., 2007) as well as initiation of NADW in the Northern hemisphere (Via and Thomas, 2006; Abelson et al., 2008). Although the exact link between the onset of the ACC and the global climate is still to be fully determined and quantified, its impact on the global ocean circulation, carbon cycling and hence on global climate is strongly suspected (Shevenell et al., 2004) and confirmed by numerical modelling (Sijp and England, 2005). Onset of the ACC around 34 Ma is thought to have led to the definite thermal isolation of the Antarctic continent. This allowed the production of cool waters sinking around Antarctica to form the Antarctic Bottom Water (AABW) connected to the thermohaline circulation. However, the actual climatic impact of changes in the geometry of the southern hemisphere seaways during the entire Cenozoic remains a matter of debate. For instance, the onset of the ACC does not seem to explain by itself the rapid rise of the Antarctic icecap at the Eocene–Oligocene boundary, because it may have predated the event by at least more than 5 Myrs (Barker and Thomas, 2004; Eagles et al., 2006). Furthermore, recent studies (DeConto and Pollard, 2003; Tripati et al., 2005; Huber and Nof, 2006) have shown that the rise of the Antarctic ice sheet at the end of the Oligocene is mainly the result of declining atmospheric CO_2 levels confirmed by recent data (Pagani et al., 2005). Things appear different during the Miocene. First, atmospheric CO_2 is low enough to allow a stronger response of the Antarctic cryosphere to climatic forcing other than CO_2 (DeConto and Pollard, 2003). Second, the end of the warm Miocene interval at 14 Ma is well documented through Mg/Ca ratio of planktonic foraminifers from high southern latitudes (Shevenell et al., 2004). These data show a strong cooling of surface waters inside the ACC area by about 6 °C, suggesting intensification of this current.

4.2.2. The Late Oligocene warm episode and a temporary constriction of the Drake Passage: a possible link?

If oceanic gateways drive the global climate, apparent continuous widening of both Tasman Gateway and Drake Passage after 30 Ma would have led to a long-term regular global cooling without significant aberration. However, despite an overall evolution towards the Quaternary glaciations, the long term global cooling has not been monotonic since early Eocene time. Indeed, a warming period, starting with the Late Oligocene Warming around 26 Ma (Zachos et al., 2001, 2008), lasted almost 12 Ma long, and ended progressively after a peak warming between 15 and 14 Ma (Fig. 6). Until now, no large-scale geodynamic event has been proposed to explain such a long-term aberration in the global climatic trend, and we point for the first time to a synchronicity with the tectonic events that affected the Drake Passage region. Such synchronicity has to be investigated even if we are well aware that several causes with various origins have to be suspected, including major tectonic changes from remote regions.

Our compilation of geophysical data shows that seafloor spreading along the West Scotia Ridge is accommodated by transpressional motion along the North Scotia Ridge. This causes the progressive uplift at this boundary starting at 29 Ma and completed at 22 Ma and the definitive closure of the Fuegian seaways around 22 Ma along with probable emergence of the Burdwood Bank barrier and other banks farther east. In addition, the above compilation of geological records (Fig. 5), demonstrate that deep marine clastic sediments with Antarctic affinities accumulated in subsiding basins at the place of the present-day Tierra del Fuego and North Scotia Ridge during the 37–26 Ma interval (Late Eocene–Early Oligocene), thus confirming early opening of Drake Passage deduced from geophysical data (Livermore et al., 2007) (Fig. 6). Therefore, we assume that a proto-ACC started flowing through these regions, since the Tasman Gateway has been opening synchronously. This accounts for the pronounced peak in the ^{18}O curve at the Eocene/Oligocene boundary (Zachos et al., 2001). After 22 Ma, continuous uplift of the Cordillera leads to the retreat of the Patagoniano Sea and establishment of shallower water conditions offshore Patagonia. We assume that this uplift contributed also to reduce transfer of waters through the ACC system. The combination of these processes contributed to the temporary constriction of the Drake Passage, and we suggest a partial collapse of the Antarctic Circumpolar Current starting by 29 Ma and achieved at 22 Ma, as illustrated in a series of cartoons in Fig. 7.

The climatic impact of a postulated partial shut down and restart of the ACC is certainly complex. Activation of the ACC results in a cooling around Antarctica, and a warming of the Northern hemisphere by up to 3 °C, because of the transequatorial overturning circulation set up by the opening of the Drake Passage (Toggweiler and Bjornsson, 2000; Sijp and England, 2004; Huber and Nof, 2006). Indeed, North Atlantic deep water (NADW) formation increases as the Drake Passage opens, while proto-Antarctic Bottom Water formation decreases. This results in a warming of the Northern hemisphere, while Antarctica endures severe glaciation. Toggweiler and Bjornsson (2000) argue that this effect might be effective even if the Drake Passage is not very wide or very deep, a result confirmed by the simulations performed by Sijp and England (2004). Such climatic trend will have an impact on the global carbon cycle balance, and hence a feedback response might be expected on the CO_2 partial pressure and global climatic system. Indeed, most of the continental surfaces are located in the Northern hemisphere around Miocene times (68% of the continental surface are located between the Equator and 90°N). A global cooling of the Northern hemisphere accompanying a postulated shut down of the ACC in the 29–22 Ma time window, will trigger a decrease in global weathering of silicate rocks (Walker et al., 1981; Zachos and Kump, 2005). As a result, atmospheric CO_2 will start to rise, until silicate weathering, enhanced by a warmer climate, will match again the CO_2 production by solid Earth degassing. This may contribute to the initiation and persistence of a global warming partially triggered by the partial closing of the Drake Passage somewhere inside the 29–22 Ma window, although the amplitude of this climatic shift still remains to be quantified.

The late Miocene cooling event is well documented from various oceanographic and terrestrial records and coincides also with the second Antarctic ice-sheet expansion (Fig. 6). Our compilation allows to propose that increase in ACC flows due to re-widening of the Drake Passage occurred around 14–15 Ma, coevally with the inception of this cooling event and the possible return of the Northern Component Waters (NCW) at Agulhas ridge after 17 Ma (Scher and Martin, 2008). The corresponding 14–15 Ma stage is well documented by the geological records all around Patagonia and corresponds to the cessation of contractional tectonics and incipient extension in the region, together with active spreading in the Scotia Sea region.

Several remote causes have been proposed to account for the end of the warm period leading to the late Miocene cooling event. The closure of the eastern portal of the Tethyan seaways enhanced the poleward heat transport and strengthened the Southern ocean circumpolar circulation (Kennet et al., 1985). Apart from the oceanic regime, other global phenomena such as the declining atmospheric carbon dioxide concentration and the orbital configuration, contributed to the onset of a persistent Antarctic ice-sheet during the late Miocene (Shevenell et al., 2004; Holbourn et al., 2005). More specifically, the intensification of the Asian monsoon after 15 Ma (Ramstein et al., 1997) and the increase in weathering and burial of sediments produced by the erosion of the Himalayan belt consumed atmospheric CO_2 (Goddéris and François, 1996; France-Lanord and Derry, 1997). The uplift of the Andean Cordillera may have also contributed to this active CO_2 pumping.

4.2.3. Interpreting the ^{143}Nd/^{144}Nd record at Agulhas ridge and Walvis Ridge

Scher and Martin (2006) proposed that early opening of the Drake Passage is also recorded in ε_{Nd} data at ODP site 1090 (Agulhas Ridge, Southern Atlantic ocean). This site shows a prominent transition occurring between 43 and 39 Ma from less radiogenic Nd values (typical of Atlantic waters: $\varepsilon_{Nd}=-9$) to more radiogenic values typical of Early Cenozoic waters from the Pacific ocean ($\varepsilon_{Nd}=-3, -5$) (Fig. 8). This transition is interpreted as the record of a brutal input of Pacific waters into the ocean circulation indicating establishment of a proto-ACC. This fits remarkably with the proposition that Dove and Protector basins opened on the site of proto-Drake passage between 40 and 30 Ma (Fig. 5). Between 39 Ma and 35 Ma, the Nd curve at site 1090 shows a plateau suggesting continuous influence of Pacific waters flowing through the opening proto Drake Passage. This is confirmed by our compilation of geological data indicating deep waters over Tierra del Fuego during the same time interval. From 35 to 17 Ma, Nd isotope data at Site 1090 show a general decrease towards less radiogenic waters. This long-term decreasing is interpreted as the influence of a nonradiogenic Nd source invading the region, rather than as the effect of glacial weathering of the Antarctic basement (Scher and Martin, 2008). Increasing contribution of Northern Component Water (NCW) to the Southern Ocean is thus viewed as a mechanism responsible for the long-term Nd trend.

Between 35 and 29 Ma, this interpretation is in perfect agreement with our conclusion that Tierra del Fuego has been the locus of the circulation of a proto-ACC, activating in turn the southward export of NCW to the Southern Atlantic Ocean. However the overall trend towards less radiogenic values at Site 1090 is interrupted by at least two shifts towards more radiogenic values (Scher and Martin, 2008) (Fig. 8). The most prominent shift occurred in the early Miocene between 24 and 21 Ma, and is followed by a rapid decrease between 21 and 17 Ma. According to Scher and Martin (2008) three hypothesis can be proposed to explain such fact: (1) a source effect increasing the ^{143}Nd/^{144}Nd of the water masses, (2) a decrease of the proportion of nonradiogenic water mass, and (3) an increase in the proportion of Pacific waters. Hypothesis 1 is rejected by Scher and Martin (2008) because none of the Nd records worldwide show corresponding modification of Nd signatures sources in the given time interval, and authors tend to favour hypothesis 3. Our compilation showing that constriction of the proto-Drake Passage was achieved at 21 Ma cannot confirm the hypothesis of an increasing effect of Pacific waters. Therefore, we tend to favour an indirect effect of a partial closure of the Drake Passage on the export of NCW rather than a direct record of changes in the Pacific input, as explained in the following.

Several lines of evidence confirm that key-factors regulating Nd isotopic signal are located in the Atlantic: (1) Following Via and Thomas (2006), Nd data at Walvis Ridge (South Atlantic, ODP Sites 1262–1264) (Fig. 8) indicate that significant deep-water production started at 33 Ma in the northern Atlantic due to rapid deepening of the sill separating the North Atlantic from the Greenland Norvegian Sea (the Greenland–Scotland Ridge) in response to abrupt collapse of the Iceland mantle plume, which occurred around 34 Ma. This is in accordance with initiation of deep-water circulation from the Norwegian Sea into the North Atlantic Ocean which took place in the Early Oligocene as shown by drilling records (Davies et al., 2001). This tectonic event is correlated with the onset of the thermohaline circulation (Abelson et al., 2008). This is a fully independent tectonic cause from the opening of Drake Passage which occurred in the same time window but in the opposite hemisphere. Therefore, establishment of the proto-ACC had a superimposed effect on the activation of the NADW export but was not the only cause. Similar temporal coincidence can be invoked regarding the following 25–15 Ma period. Indeed, Abelson et al. (2008) point to the vigorous renewal of the Iceland plume some 25 Ma ago, leading to the emergence of the Iceland Plateau and to considerable retardation in NADW fluxes. This

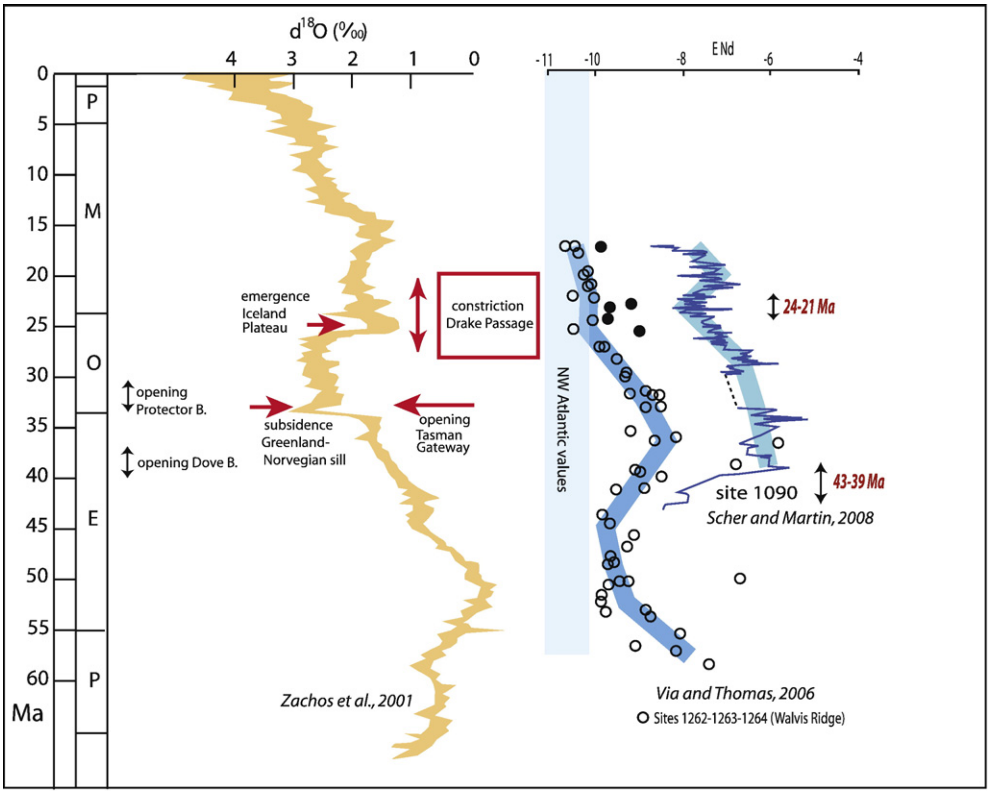


Fig. 8. A compilation of Nd isotopic data from southern Atlantic sites (Via and Thomas, 2006; Scher and Martin, 2008) plotted against the Oxygen isotope curve of Zachos et al. (2001) with indication of the major tectonic events discussed in this paper. Black dots represent Nd values that tend to escape from the NW Atlantic isotopic signature between 30 and 10 Ma at OPD Walvis Sites.

conclusion is important because it points to features that concern directly the production of NCW but which were not taken into consideration by Scher and Martin (2008) in their explanation of the Nd isotope shift observed at 24–21 Ma. In a possible scenario, the partial collapse of the ACC at the end of the 29–22 time window partially inhibited the transequatorial overturning circulation previously set up by the opening of the Drake Passage. This drove decreasing NCW export and triggered a shift towards less radiogenic waters at Atlantic sites. Reduction of NCW export was further enhanced by the uplift of the Iceland Plateau at 25 Ma limiting the southern limit reached by the NCW, as recorded by the change in 143Nd/144Nd at Agulhas ridge. It is even possible that this reduction in the input of NCW into the Southern ocean has been recorded at Walvis Ridge with a slight increase in the recorded ^{143}Nd/^{144}Nd between 26 and 23 Ma as shown in Fig. 8 (Via and Thomas, 2006). Finally, this suggests that the late Oligocene warming event is not related to a unique cause. It occurred as a response to a striking coincidence between 2 important geodynamic events which independently affected the Northern and Southern Hemispheres.

5. Conclusions

Our compilation of stratigraphic records from the active boundary between the South America and Scotia plates confirms that deep sea environments were present in the Tierra del Fuego and the North Scotia Ridge regions during the Eocene–Oligocene, thus confirming the early opening of the northern Drake Passage region to proto-ACC circulations. We also show that thermal anomalies which occurred during the 26–14 Ma period of the global climatic record are coeval with major tectonic events that affected the southernmost Andes including: (1) changes from deep marine to very shallow conditions along the newly formed North Scotia Ridge, (2) closure of deep marine connections that existed in Tierra del Fuego due to the emergence of the southern tip of the Fuegian Cordillera and (3) uplift of the Patagonian Cordillera. Based on our compilation of plate kinematic and geological records, we also infer that uplift of the North Scotia Ridge and closure of the Fuegian seaways are a direct consequence of oceanic spreading at the West Scotia Ridge during the 26–14 Ma period. We propose that these tectonic events drastically affected the physiography of the northern region of the Drake Passage. Our exploration of possible consequences of the narrowing of this key-gateway suggests a significant impact on the ACC by restricting water flows contributing to global climate warming. This period was followed by further widening in response to landmasses re-organization at the Antarctica–Patagonia connection around 14 Ma, likely triggering progressive cooling during the Miocene due to increased ACC water flows. This could represent a new case illustrating possible effect of large-scale tectonic causes on global climate. In addition, the 29–15 Ma event which affected the shape of the Drake gateway also coincides with the vigorous renewal of the Iceland plume some 25 Ma ago, leading to the emergence of the Iceland Plateau and to considerable retardation in NADW fluxes (Abelson et al., 2008). Therefore, it cannot be ruled out that the Late Oligocene Warming event occurred as a response to a coincidence between 2 important geodynamic events having strong impact on global ocean circulation, and which independently affected the Northern and Southern Hemispheres.

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