

Continental stretching preceding the opening of the Drake Passage: Evidence from Tierra del Fuego

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ABSTRACT

Age estimates for the onset of a seaway through the Drake Passage range from middle Eocene to early Miocene, complicating interpretations of the relation between ocean circulation and Cenozoic global cooling. Here we present evidence for the presence of a latest Paleocene–early Eocene extensional basin (i.e., lateral rift) in Tierra del Fuego. An accurately dated postrift unconformity indicates that extensional faulting ended in the studied area ca. 49 Ma, in concurrence with a previously reported eightfold increase in South America–Antarctica separation rate, and the proposed onset of oceanic basins in the incipient Drake Passage. The coincidence of these facts indicates progressive strain concentration on the zone of future crustal separation (i.e., Drake Passage) after abandonment of lateral rifts ca. 49 Ma. Although the described extensional depocenters did not allow the exchange of water between the Pacific and Atlantic Oceans, they represent a direct indication of continental lithospheric stretching preceding the recently proposed Eocene opening of embryonic basins in the West Scotia Sea.

Keywords: Tierra del Fuego, continental stretching, Scotia Sea, airborne magnetic data.

INTRODUCTION

The separation of South America from Antarctica and the subsequent formation of the Drake Passage (Fig. 1) are widely believed to have influenced Cenozoic global cooling because these events enabled the development of the Antarctic Circumpolar Current (Barker, 2001; Lawver and Gahagan, 2003). This cold water current is speculated to have reduced heat transport to Antarctica, triggering the Oligocene global cooling (Kennett, 1977). It also has been proposed that the opening of the Drake Passage influenced circulation-induced productivity increase that may have sequestered atmospheric CO₂, contributing to global cooling and Antarctic glaciation (Scher and Martin, 2006; Eagles et al., 2006).

Unfortunately, age estimates for the onset of a seaway through the Drake Passage range from middle Eocene (Livermore et al., 2005; Scher and Martin, 2006) to Oligocene (Lawver and Gahagan, 2003) or early Miocene (Barker, 2001), complicating interpretations of the relation between ocean circulation and global cooling. The youngest estimates for deep-water circulation via the Drake Passage are based on the ca. 28 Ma onset of seafloor spreading in the West Scotia Sea region (Barker, 2001; Eagles et al., 2005; Lodolo et al., 2006; Figs. 1 and 2). Others have recently argued that the marine connection may have started during the opening of small basins in the embryonic West Scotia Sea, during a period of extension preceding seafloor spreading (Eagles, 2000; Lawver and Gahagan, 2003; Eagles et al., 2006). Evidence for the middle Eocene(?) opening of two of these small depocenters, the Protector and Dove basins (Fig. 1), indicates the possible creation of a seaway in the southern part of the Drake Passage starting after a major increase in the separation rate between South America and Antarctica ca. 50 Ma (Livermore et al., 2005; Eagles et al., 2006; Fig. 2). Other evidence comes from secular variations of neodymium

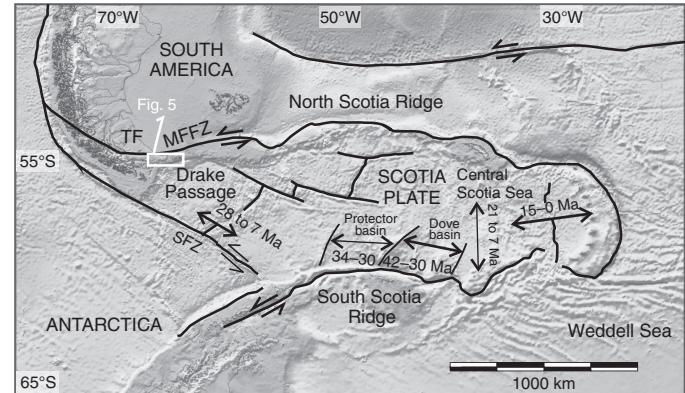


Figure 1. Location map of southernmost Andes showing tectonic plates, basins, and summary of ocean floor ages and directions of opening in Scotia Sea region from Barker (2001), Livermore et al. (2005), Eagles et al. (2006), and Lodolo et al. (2006). MFFZ—Magallanes-Fagnano fault zone; SFZ—Shackleton fracture zone; TF—Tierra del Fuego.

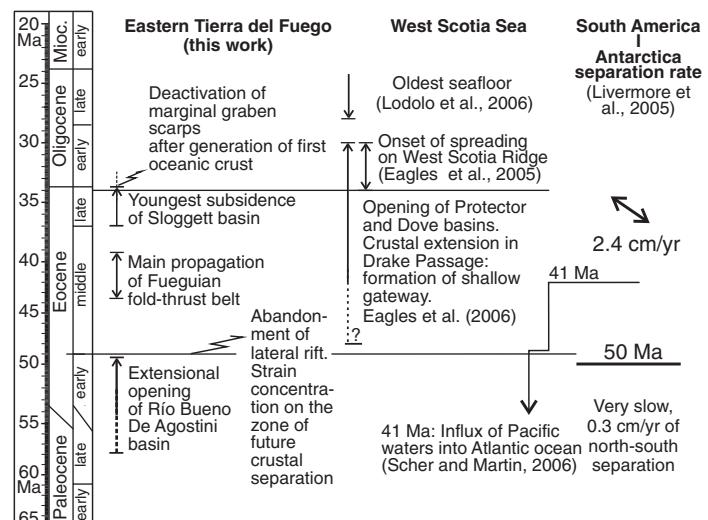


Figure 2. Correlation between events described here for eastern Tierra del Fuego with main tectonic events from West Scotia Sea.

isotope ratios from Agulhas ridge, suggesting an influx of Pacific seawater into the Atlantic Ocean ca. 41 Ma (Scher and Martin, 2006; Fig. 2).

Studying the southeast tip of Tierra del Fuego at the northern edge of the Drake Passage (Fig. 1), we discovered evidence for the opening of Eocene extensional depocenters that predates the onset of seafloor spreading in the West Scotia Sea (Fig. 2). Here we present direct evidence for late Paleocene–early Eocene extension and synextensional deposition in one of these depocenters. This extensional regime ended ca. 49 Ma, as

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evidenced by a postrift (i.e., breakup) unconformity (Fig. 3), while stretching migrated toward the zone of oceanic spreading. Although these depocenters did not allow Pacific-Atlantic water exchange, our data bolster interpretations of an early (Eocene) marine gateway (e.g., Scher and Martin, 2006) by confirming the prediction of a continental extensional regime in the region during the period prior to the opening of small basins ca. 42 Ma (Eagles et al., 2006).

PALEOGENE EXTENSIONAL BASINS

Río Bueno–De Agostini basin

The Río Bueno depocenter crops out along the Atlantic coast of Tierra del Fuego (Figs. 4B and 4C, and Fig. 5), and the De Agostini extensional depocenter is recognized in offshore multichannel seismic reflection profiles (Geletti, 2001; Yagupsky, 2003; Tassone et al., 2008; see data source in GSA Data Repository¹) 50 km to the east-northeast (Figs. 4A and 5). We correlated these two depocenters for the first time by integrating geological data, satellite gravity data (Sandwell and Smith, 1997), and airborne magnetic data showing a continuity of their major elements (Fig. 5). Total magnetic intensity/reduced to pole data (TMI/RTP; SEGEMAR [Servicio Geológico Minero Argentino], 1998) (for methods, see the Data Repository), shown in the lower half of Figure 5, show a strong correlation between the outcrop geology and the magnetic intensity. The available regional magnetic database for the northern part of the studied zone is of very low resolution, and therefore satellite gravity is shown instead (Fig. 5). However, this regional magnetic database was used during processing of the magnetic data to minimize edge effects.

Throughout the Río Bueno depocenter, an angular unconformity separates the basal middle Eocene (AP7–AP9 from Berggren et al. [1995], similar to ca. 49.5–43 Ma) carbonatic Río Bueno Formation from three older marine units (Malumíán and Jannou, 2000; Olivero et al., 2002; Figs. 4B, 4C): (1) a pelitic unit dated as Maastrichtian–Danian, on the basis of ammonites and foraminifera content, (2) massive sandstones with dynocist and foraminifera indicating an age around the Paleocene–Eocene boundary, and (3) fine sandstone and siltstone dated as early Eocene, on the basis of foraminifera content. This angular unconformity has previously been interpreted as a compression-related syntectonic unconformity because of its position inside a fold-thrust belt (Olivero et al., 2002; Ghiglione and Ramos, 2005).

The carbonatic Río Bueno Formation is tightly folded, blanketing the late Paleocene–earliest Eocene units tilted ~40–30°S, and the early Eocene siltstones dipping ~20–10°NW; to the south and east the carbonates overlie Maastrichtian mudstones (Figs. 4B, 4C). In Punta Noguera, the late Paleocene–earliest Eocene units present a SSE-thickening wedge shape and are multiply offset by small-scale extensional faults (Ghiglione and Ramos, 2005). The Paleocene–early Eocene sequences constitute a tilted monocline that shows a decreasing dip upsection from ~40°S to ~15°NW (Figs. 4B, 4C). At the Leticia River outlet, these sequences show a classical synrift arrangement, with internal onlaps and thickness variations forming extensional growth strata, that are unconformably overlain by the Río Bueno carbonates (Fig. 3). Farther south and east, the Paleocene–early Eocene sequences are absent, and a paraconformity representing at least 15 m.y. separates the carbonates from the Maastrichtian units (i.e., Policarpo paraconformity in Fig. 5; Ghiglione and Ramos, 2005).

The magnetic low associated with the Río Bueno depocenter implies an elongated trough, more than 60 km in length with an approximately WSW-ENE orientation (Fig. 5). Its southern boundary is taken as the sharp magnetic contrast, coinciding in part with the Policarpo paraconformity. It is clearly aligned with the extensional fault f5, which limits

¹GSA Data Repository item 2008154, methods and data sources, Figure DR1 (geological and aeromagnetic maps) and Figures DR2–DR4 (main features of syntectonic strata), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

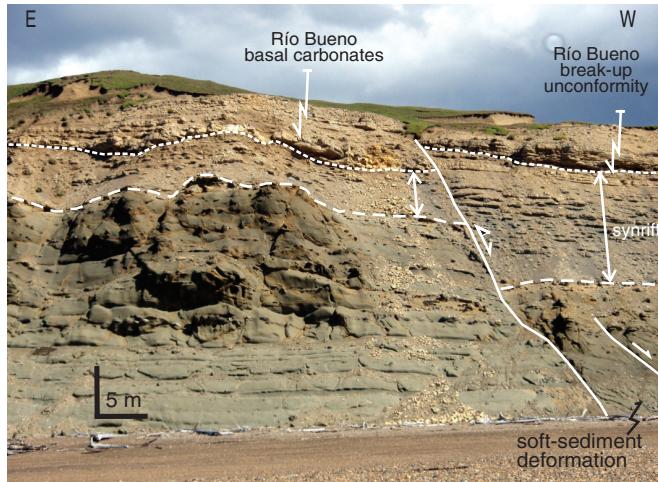


Figure 3. Carbonatic Río Bueno Formation unconformably overlying late Paleocene–early Eocene synrift sequences at Leticia River outlet (located at northwest corner of Fig. 4B).

the De Agostini depocenter to the south (Figs. 4A and 5). Two elongated and narrow east-west positive anomalies coinciding with two anticlines located around Noguera Point (Figs. 4B and 5) are interpreted as the result of a pop-up structure, similar to pop-up structures from the De Agostini depocenter (i.e., f8 in Fig. 4A; Fig. 4C). Outcrops of the Jurassic Lemaire (Tobiffera) Formation show this kind of positive magnetic response along the southern coast of Tierra del Fuego and in Isla de los Estados (Fig. 5).

The De Agostini extensional depocenter, depicted in the seismic line drawing shown in Figure 4A (Geletti, 2001; Tassone et al., 2008), is bounded by two high-angle normal faults, f5 and f8 in Figures 4A and 5. In concordance, the satellite gravity shows higher values south of f5, where the Mesozoic basement high is located, whereas values decrease in response to Tertiary infill thickening to the north (Fig. 5). A lower sedimentary sequence exhibits fan-shaped geometries, internal onlaps, and thickness variations, indicating continuous deposition during extensional faulting and subsidence (Fig. 4A). The dotted line in Figure 4A shows moderate truncation of the underlying reflectors with the development of an angular unconformity. A seismic unit covers this surface, amalgamating the previous constrained depocenters (Fig. 4A). The described sedimentary architecture is interpreted as a rift sequence with a basal synrift unit under a broad sag unit, separated by a postrift unconformity.

The Piedra Buena extensional depocenter is located offshore northwest of Isla de los Estados (Fig. 5), and has a similar tectono-stratigraphic architecture to that of De Agostini depocenter (Fig. 4A); however, no direct inference of its stratigraphic age can be made.

Our new field data showing synextensional deposition (Fig. 3) allow us to reinterpret the late Paleocene–early Eocene sequences from Río Bueno depocenter as synrift sequences, and the angular unconformity as a postrift unconformity (Fig. 4C). This idea is also supported by the existence of very different geometries and degree of folding on both sides of the unconformity (Fig. 4B), the presence of ubiquitous normal faulting affecting Paleocene rocks, and the S-SE-thickening wedge shape of the late Paleocene–early Eocene sequences (Fig. 4C). The presence of the Policarpo paraconformity and its 15 m.y. hiatus near the southern edge of the Río Bueno–De Agostini basin (Fig. 5) is also in concordance with a constrained extensional depocenter located to the north of the paraconformity (Fig. 4C). Continuity with the De Agostini depocenter, where the extensional geometry is evident (Fig. 4A), gives further support to our interpretation.

The extensional phase is bracketed by the late Paleocene–early Eocene age of synrift sediments located below the unconformity (Figs. 4B, 4C). The basal age of the postrift carbonates is well constrained by the planktic

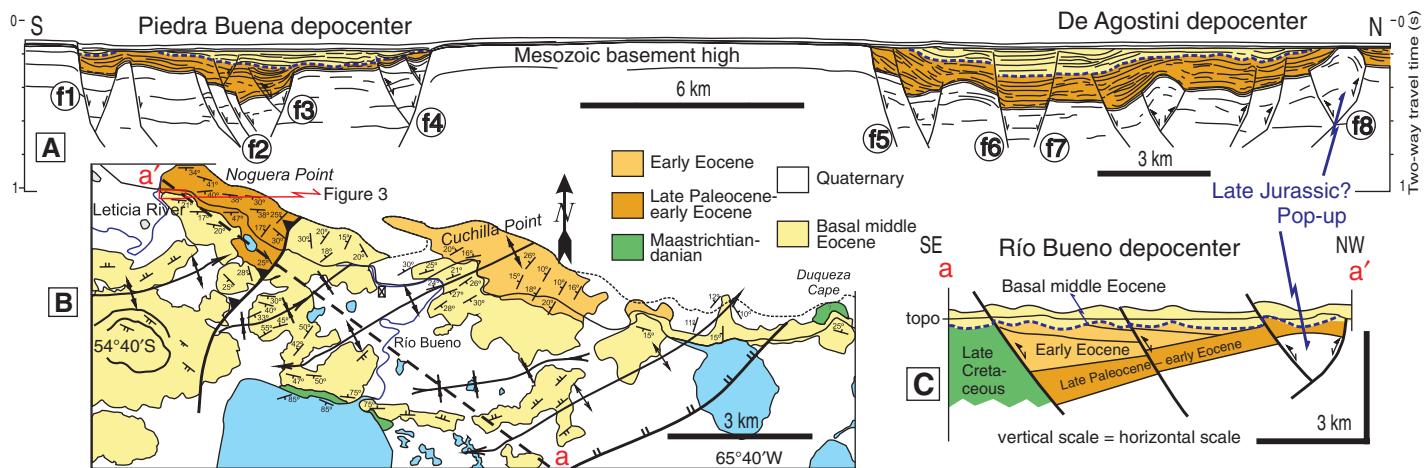


Figure 4. A: Line drawings of multichannel seismic reflection profile TM-08 (Geletti, 2001; Tassone et al., 2008); structural interpretation is after Yagupsky (2003). B: Structural map of Río Bueno depocenter. Dashed line indicates location of cross section from Figure 4C. For map location, see Figure 3. Stratigraphy and age are from Malumíán and Jannou (2000), Olivero and Martinioni (2001), Olivero et al. (2002), and Ghiglione and Ramos (2005). C: Río Bueno cross section. TWT—two-way traveltimetime. Note that horizontal scale is the same for A and C, whereas vertical scales are similar.

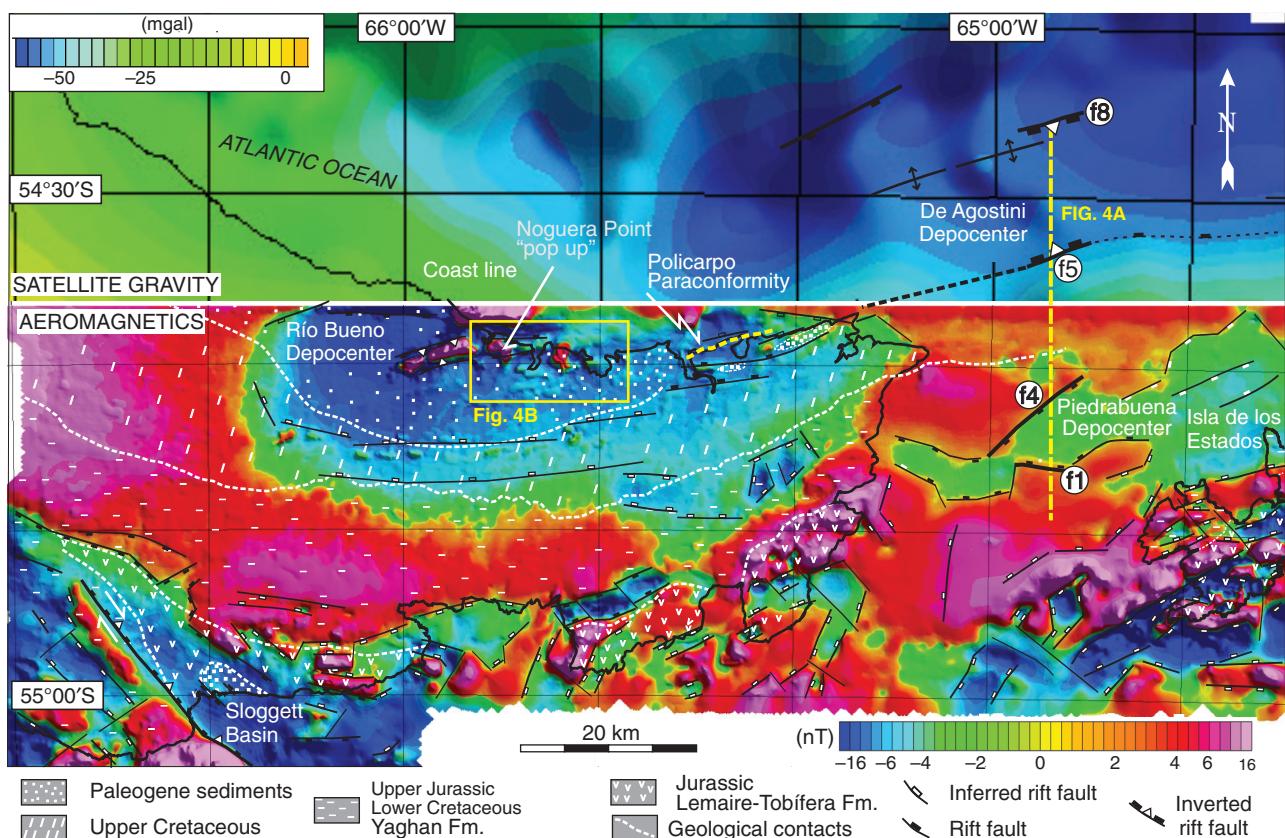


Figure 5. Geological and structural data superimposed on aeromagnetic image of study area. Satellite gravity (Version 7.2 after Sandwell and Smith, 1997) is shown in northern sector, where detailed aeromagnetic data are not available. Dotted lines show location of seismic line drawing of Figure 4A.

foraminifera *Planorotalites australiformis* and *Subbotina linaperta* to the basal middle Eocene (AP7, ca. 49 Ma; Berggren et al., 1995; Malumíán and Jannou, 2000; Olivero and Martinioni, 2001; Olivero et al., 2002).

Afterward, the region was affected by middle Eocene–Oligocene coeval strike-slip and compressional deformation due, respectively, to the fast (2.4 cm/yr) left-lateral motion between South America and Ant-

arctica (Livermore et al., 2005; Fig. 2), and the synergetic combination of fast spreading rates in the Drake Passage with rapid convergence and northward-directed subduction of the Farallon plate against South America (Ghilione and Cristallini, 2007). This tectonic scenario produced the observed positive inversion of previous normal faults (Figs. 3 and 4A–4C; Ghiglione and Ramos, 2005).

Sloggett Basin

The Sloggett basin is recognized in small outcrops in the northern coast of Beagle Channel (Fig. 5), and is composed of conglomerates, siltstones, and shales that bear palynofloras of late Eocene age that possibly but unlikely extend to an early Oligocene age (Fig. 2; Olivero et al., 1998; Olivero and Martinioni, 2001). The fining-upward succession shows abrupt changes from the margin to the central part of the basin, which reflects a taphrogenic control of the sedimentation. From the aeromagnetic map it is possible to distinguish that the depocenter has a strong NW-SE orientation, and its major sedimentary thickness is concentrated along a right-lateral strike-slip fault, as envisaged by Caminos et al. (1981). However, the southern part of the depocenter has a west-east orientation, controlled by a series of normal faults parallel to the oceanic-continental crust boundary (Fig. 5).

DISCUSSION AND CONCLUSIONS

In this work we present field and geophysical data supporting the existence of a series of widespread extensional depocenters in southeast Tierra del Fuego. We suggest that the existence of two extensional phases that can be connected with the early stretching between South America and Antarctica: (1) latest Paleocene–early Eocene and (2) late Eocene–early Oligocene(?)

The latest Paleocene–early Eocene extensional phase coincided with a slow north-south separation of South America and Antarctica (phase I of Livermore et al., 2005; Fig. 2). In the Río Bueno depocenter, stratigraphic and tectonic relations show that the rifting was aborted a short time before the ca. 49 Ma initial deposition of the basal middle Eocene carbonates. This is in coincidence with a threefold increase in the separation rate between South America and Antarctica ca. 50 Ma, which was followed by the opening of a gap between South America and Antarctica from 50 to 34 Ma (Livermore et al., 2005; Fig. 2). In major rift systems, the time at which crustal separation is achieved is largely a function of plate interaction and is usually preceded by a gradual reduction of tectonic activity in lateral graben systems, while tensional strain concentrates on the zone of future crustal separation (Ziegler and Cloetingh, 2004). In terms of rifting dynamics, the deactivation of Río Bueno–De Agostini basin can thus be explained as the abandonment of the lateral rift after strain concentration on the zone of future crustal separation due to a drastic acceleration in tectonic separation.

The Río Bueno–De Agostini extensional basin constitutes strong evidence for a period of continental lithospheric stretching, thinning, and subsidence that preceded the opening of embryonic basins (Livermore et al., 2005; Eagles et al., 2006). As suggested in previous works, after 50 Ma crustal extension concentrated in the Drake Passage (Fig. 2) could have allowed the formation of a shallow seaway across Protector and Dove basins (Livermore et al., 2005; Eagles et al., 2006) that ultimately led to a 41 Ma blend of Pacific waters into the South Atlantic (Scher and Martin, 2006).

The age of latest sedimentation from Sloggett basin can be constrained as late Eocene (ca. 33–37 Ma; Olivero et al., 1998; Olivero and Martinioni, 2001), coinciding with the suggested ca. 34–30 Ma onset of spreading in the West Scotia Sea (Livermore et al., 2005). Thus, abortion of Sloggett basin could be reflecting the final abandonment of marginal graben scarps before generation of first oceanic crust just 25–50 km to the southeast (Figs. 1 and 2; Lodolo et al., 2006).

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REFERENCES CITED

- Barker, P.F., 2001, Scotia Sea regional tectonic evolution: Implications for mantle flow and palaeocirculation: *Earth-Science Reviews*, v. 55, p. 1–39, doi: 10.1016/S0012-8252(01)00055-1.
- Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.P., 1995, A revised Cenozoic geochronology and chronostratigraphy, in Berggren, W.A., et al., eds., *Geochronology, time scales, and global stratigraphic correlations: SEPM (Society for Sedimentary Geology) Special Publication 54*, p. 129–212.
- Caminos, R., Haller, M., Lapido, J., Lizuain, O., Page, A., and Ramos, V.A., 1981, Reconocimiento geológico de los Andes Fueguinos. Territorio Nacional de Tierra del Fuego: San Luis, Argentina, VIII Congreso Geológico Argentino, Actas, v. 3, p. 759–786.
- Eagles, G., 2000, Modelling plate kinematics in the Scotia Sea [Ph.D. thesis]: Leeds, University of Leeds, 304 p.
- Eagles, G., Livermore, R.A., Fairhead, J.D., and Morris, P., 2005, Tectonic evolution of the west Scotia Sea: *Journal of Geophysical Research*, v. 110, B02401, doi: 10.1029/2004JB003154.
- Eagles, G., Livermore, R., and Morris, P., 2006, Small basins in the Scotia Sea: The Eocene Drake Passage gateway: *Earth and Planetary Science Letters*, v. 242, p. 343–353, doi: 10.1016/j.epsl.2005.11.060.
- Geletti, R., 2001, Elaborazione delle linee sismiche multicanale acquisite nella campagna TESAC 1999: Istituto Nazionale di Oceanografia e di Geofisica Sperimentale Open-File Report 90GS/11GDL, 43 p.
- Ghiglione, M.C., and Cristallini, E.O., 2007, Have the southernmost Andes been curved since Late Cretaceous time? An analog test for the Patagonian orocline: *Geology*, v. 35, p. 13–16.
- Ghiglione, M.C., and Ramos, V.A., 2005, Progression of deformation in the southernmost Andes: *Tectonophysics*, v. 405, p. 25–46, doi: 10.1016/j.tecto.2005.05.004.
- Kennett, J.P., 1977, Cenozoic evolution of Antarctic glaciation, the Circum-Antarctic ocean, and their impact on global paleoceanography: *Journal of Geophysical Research*, v. 82, p. 3843–3860, doi: 10.1029/JC082i027p03843.
- Lawver, L.A., and Gahagan, L.M., 2003, Evolution of Cenozoic seaways in the circum-Antarctic region: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 198, p. 11–37, doi: 10.1016/S0031-0182(03)00392-4.
- Livermore, R.A., Nankivell, A.P., Eagles, G., and Morris, P., 2005, Paleogene opening of Drake Passage: *Earth and Planetary Science Letters*, v. 236, p. 459–470, doi: 10.1016/j.epsl.2005.03.027.
- Lodolo, E., Donda, F., and Tassone, A., 2006, Western Scotia Sea margins: Improved constraints on the opening of the Drake Passage: *Journal of Geophysical Research*, v. 111, no. 6, B06101, doi: 10.1029/2006JB004361.
- Malumíán, N., and Jannou, G., 2000, Lower Eocene unilocular foraminifers from Tierra del Fuego Island and adjacent continental platform, Argentina: *Ameghiniana*, v. 37, p. 91–102.
- Olivero, E.B., and Martinioni, D.R., 2001, A review of the geology of the Argentinian Fuegian Andes: *Journal of South American Earth Sciences*, v. 14, p. 175–188, doi: 10.1016/S0895-9811(01)00016-5.
- Olivero, E.B., Marenssi, S., Santillana, S., and Martinioni, D.R., 1998, Estratigrafía y sedimentología de la Formación Sloggett (Terciario), Tierra del Fuego, Argentina: *Revista de la Asociación Geológica Argentina*, v. 53, p. 505–516.
- Olivero, E.B., Malumíán, N., Palamarcuk, S., and Scasso, R.A., 2002, El Cretácico superior-Paleogeno del área del Río Bueno, costa atlántica de la Isla Grande de Tierra del Fuego: *Revista de la Asociación Geológica Argentina*, v. 57, p. 199–218.
- Sandwell, D.T., and Smith, W.H.F., 1997, Marine gravity anomaly from Geosat and ERS-1 satellite altimetry: *Journal of Geophysical Research*, v. 102, no. B5, p. 10,039–10,054, doi: 10.1029/96JB03223.
- Scher, H., and Martin, E., 2006, Timing and climatic consequences of the opening of Drake Passage: *Science*, v. 312, p. 428–430, doi: 10.1126/science.1120044.
- SEGEMAR (Servicio Geológico Minero Argentino), 1998, Levantamiento geofísico aéreo: Magnetometría aérea de Tierra del Fuego: Buenos Aires, Argentina, Proyecto Pasma.
- Tassone, A., Lodolo, E., Menichetti, M., Yagupsky, D., Caffau, M., and Vilas, J.F., 2008, Seismostratigraphic and structural setting of the Malvinas Basin and its southern margin (Tierra del Fuego Atlantic offshore): *Geologica Acta*, v. 6, p. 55–67.
- Yagupsky, D.L., 2003, Estudio sismoestratigráfico y estructural del sector meridional de las cuencas de Magallanes y Malvinas [thesis]: Buenos Aires, Universidad de Buenos Aires, 111 p.
- Ziegler, P.A., and Cloetingh, S., 2004, Dynamic processes controlling evolution of rifted basins: *Earth-Science Reviews*, v. 64, p. 1–50, doi: 10.1016/S0012-8252(03)00041-2.

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