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The opening of the Magellan Strait and its geodynamic implications

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ABSTRACT

The existence of a Neogene-Quaternary rift system responsible for the opening of the eastern Magellan strait has been one of the more peculiar tectonic features of the southernmost Andes since its discovery more than a decade ago. However, until now there has been no explanation pinpointing the specific tectonic factors that led to the development of the rift. This work focuses on the interaction between the fault systems and the tectonic regimes that have affected Tierra del Fuego north of the South America–Scotia left lateral strike-slip plate boundary. Due to a good match between a Jurassic extensional fault array orientation and the principal stress directions related to the strike-slip plate boundary, we conclude that Jurassic transfer faults reactivated extensionally generating the Magellan rift system. This process was enhanced by northward continental drift, and has implications for the geodynamic behind the separation of South America from Antarctica.

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Introduction

Several intriguing questions remain regarding the geodynamic evolution of the southernmost Andes of Tierra del Fuego. This Andean segment has been affected by processes leading to the opening of the Scotia Sea (Ghiglione *et al*., 2008; Barbeau *et al*., 2009; Gombosi *et al*., 2009) and is currently offset by the Magallanes-Fagnano strike-slip fault zone bounding the South America and Scotia plates (Pelayo and Wiens, 1989; Lodolo *et al*., 2003; Fig. 1). The Magellan strait that connects the Atlantic and Pacific oceans (Fig. 1) consists of a NW–SE western section controlled by the transtensional Magallanes-Fagnano fault zone within the Cordillera (Lodolo *et al*., 2003) and an eastern section oriented E to NE along the Magellan rift (Diraison *et al*., 1997a).

This work focuses on the interaction between fault systems and tectonic regimes acting in the thin-skinned Fuegian fold–thrust belt and the adjacent depocenter of the Austral basin (Figs 1 and 2). We attempt to connect the following features with the aim of enhancing our understanding of tectonic deformation in the Scotia Sea region (Figs 1 and 2): (1) A widespread Jurassic extensional fault array consisting of N to NW oriented grabens and half-grabens and E to NE oriented transfer faults (Figs 2 and 3); (2) an external fold-thrust belt composed of Palaeogene to Neogene folds trending W to NW (Fig. 4); (3) the development of a Neogene-Quaternary rift system along the eastern Magellan Strait (Diraison *et al*., 1997a); and (4) strike-slip shear faults and lineaments related to the Magallanes-Fagnano fault zone (Lodolo *et al*., 2003).

Our main conclusion is that, due to the good match between the Jurassic extensional fault array orientation and the principal stress directions related to the left lateral plate boundary, Jurassic transfer faults reactivated extensionally generating the Magellan rift system. We argue that a similar combination of strike-slip and extensional faulting could have also played an important role in the middle Eocene rifting of the land bridge that existed between South America and Antarctica, leading to the initial opening of a waterway in the Scotia Sea connecting the Pacific and Atlantic oceans (Livermore *et al*., 2005; Eagles *et al*., 2005, 2006).

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Tectonic framework and studied features

Patagonia was affected by widespread Jurassic extension and related silicic volcanic activity during Gondwana break-up (Dalziel, 1981; Uliana *et al*., 1989; Pankhurst *et al*., 2000). The first extension-related silicic volcanic episode (early Jurassic; 188–178 Ma) crops out in northern Patagonia and can be followed along the Antarctic Peninsula (Storey *et al*., 1996; Pankhurst *et al*., 2000). This extensional process produced the opening of the late Jurassic to early Cretaceous Rocas Verdes basin floored by basaltic crust with mid-ocean ridge affinities along the Pacific rim of the Southernmost Andes (Dalziel *et al*., 1974; Stern, 1980; Dalziel, 1981). Uplift of the Patagonian-Fuegian Andes started during the late Cretaceous with the compressional inversion of the rift basin (Dalziel, 1981; Kraemer, 2003), and continued during the Palaeogene, producing a foreland stage in the Austral (Magallanes) basin.

The resultant Cordillera can be divided (after Klepeis and Austin, 1997; Diraison *et al*., 2000; Kraemer, 2003; Fig. 1) into (i) an Internal or Basement thick-skinned Domain composed of Palaeozoic Metamorphic rocks, sedimentary and magmatic remnants of the Rocas Verdes basin and intrusive rocks of the Patagonian Batolith; and (ii) a fold-thrust belt subdivided into an Internal zone exposing Jurassic to Cretaceous sequences and a thin-skinned External zone affecting the Tertiary foreland sequence (Fig. 4).

The subjects of this study are the thin-skinned Fuegian fold–thrust belt and the adjacent depocenter of the

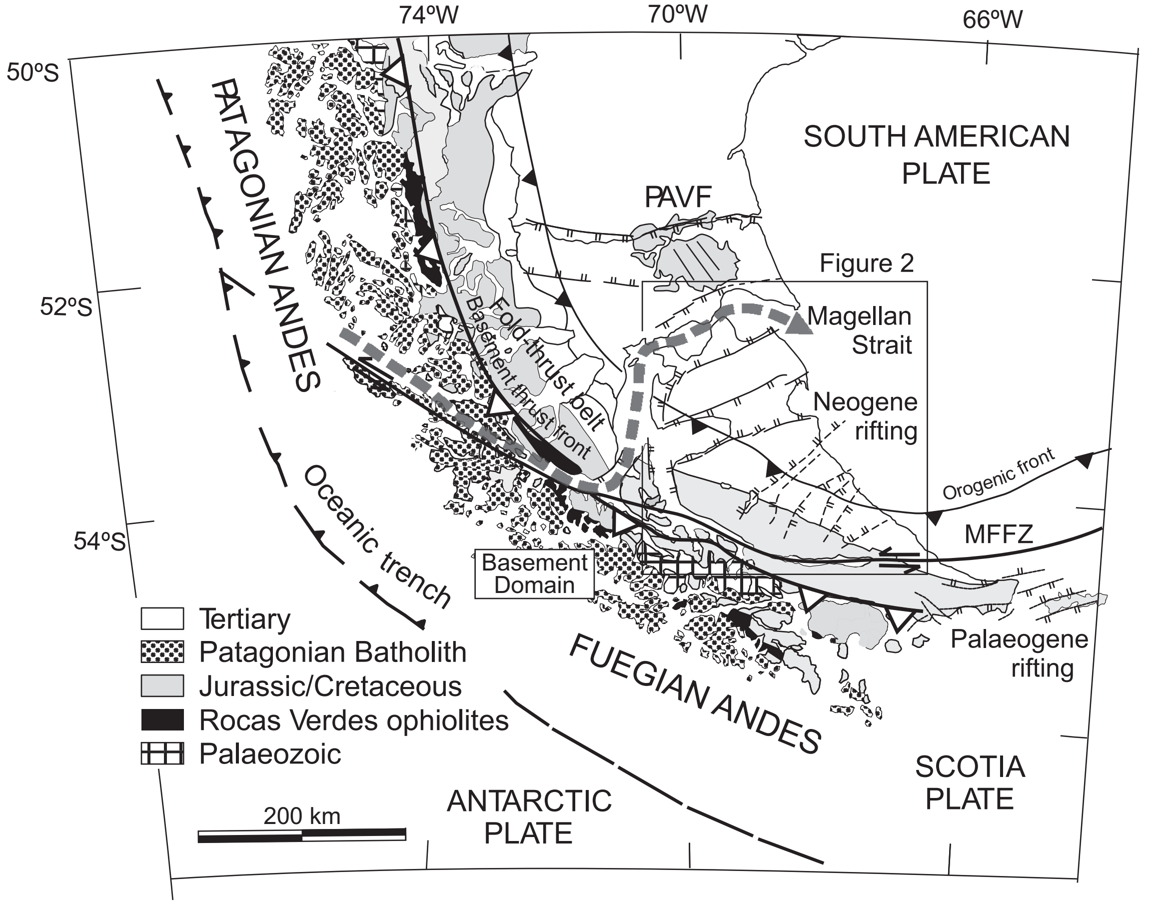

Fig. 1 Location map of the southernmost Andes showing tectonic plates and main structural domains. Neogene rifting as defined by Diraison *et al.* (1997a,b) is shown in thick solid lines, new interpreted grabens and half-grabens from our work are in dashed lines. Palaeogene rifting from Ghiglione *et al.* (2008) is also outlined. PAVF, Pali Aike volcanic field from Mazzarini and D'Orazio (2003); MFFZ, Magallanes-Fagnano fault zone.

Austral basin. Widespread Mesozoic extensional grabens and synrift deposits are preserved below the lowest Tertiary detachment surface of the fold-thrust belt as shown by seismic data (Uliana *et al*., 1989; Diraison *et al*., 1997b; Corbella, 2002; Menichetti *et al*., 2008; Figs 5 and 6). A latest Palaeocene to early Eocene rift developed on the southeastern tip of the fold-thrust belt (Ghiglione *et al*., 2008; Fig. 1) preceding the opening of small basins of the embryonic Drake Passage (Barker, 2001; Eagles *et al*., 2006). Shortening across the external thin-skinned fold-thrust belt was at a maximum from middle Eocene to early Oligocene (Ghiglione and Ramos, 2005; Navarrete-Rodríguez, 2006; Barbeau *et al*., 2009; Gombosi *et al*., 2009), with shortening directions trending towards the NE in the Fuegian Andes (Diraison *et al*., 2000; Ghiglione and Cristallini, 2007; Fig. 4). Beginning in the late Oligocene to early Neogene, a left-lateral strike-slip regime started as a consequence of the creation of the Scotia plate, and its plate boundary with South America, represented in the southernmost Andes by the Magallanes-Fagnano fault system (Klepeis and Austin, 1997; Diraison *et al*., 2000; Lodolo *et al*., 2003; Ghiglione and Ramos, 2005; Figs 1 and 2). A Neogene rifting system perpendicular to the orogen developed during the strike-slip phase (Diraison *et al*., 1997a; Fig. 1).

Jurassic extensional fault array

We used seismic information (i.e. Figs 3 and 5) to construct a comprehensive structural map of the Jurassic fault array (Fig. 2). From our data, it is possible to recognize a widespread extensional fault array consisting of grabens and half-grabens (Fig. 2). Also, some Cretaceous and Neogene extensional activity is recorded in the off-set of dated seismic reflectors, especially in grabens located away from the Cordillera (Figs 3, 5 and 6). Extensional faults change orientation from a N–S trend in the northwest towards a NW–SE trend in the southeast (Fig. 2). There are also extensional transfer faults at high angle with the rift (Figs 2 and 5) that accommodated displacement between zones of differential extension (Gibbs, 1984), and which change orientation accordingly from an E towards a NE trend (Fig. 2). We defined several broad Jurassic transfer zones by correlating mapped transfer faults, with abrupt lateral ending of extensional faults and grabens (Figs 2 and 4).

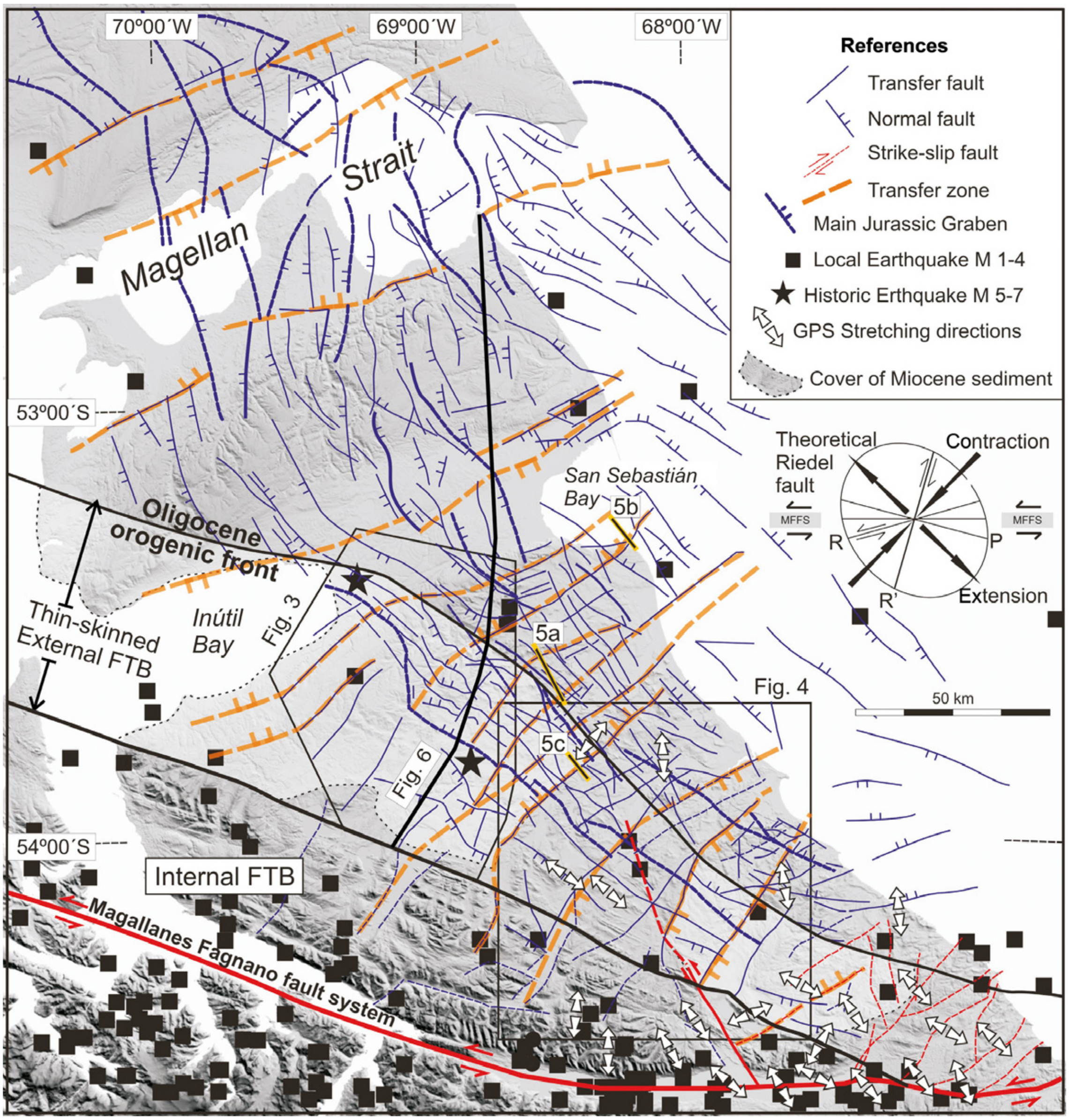

Fig. 2 High-resolution digital elevation model (Mercator projection) from processed National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission data (SRTM; Farr *et al*., 2007) with superimposed faults array. Main extensional grabens from the Chilean side are from Moraga *et al*. (2004) and Navarrete-Rodríguez (2006). FTB, fold-thrust belt; Seismicity of Tierra del Fuego from: Pelayo and Wiens (1989); Sabbione *et al*. (2007); Buffoni *et al*. (2009). GPS Stretching directions are from Mendoza *et al*. (2011). See Fig. 1 for location.

Some main Jurassic asymmetric grabens are bounded by two main antithetic extensional faults (Fig. 6). Detailed mapping of these extensional depocenters, such as the Fuegian Central Graben, shows a deepening to the southwest and concentration of smaller extensional faults distributing stretching within the grabens (Figs 5 and 6).

Palaeogene–Neogene external fold-thrust belt

The external fold thrust belt involves Cretaceous to Oligocene sediments forming W–NW oriented doubly plunging anticlines and thrusts (Fig. 4) rooted in a detachment surface at the base of the Tertiary (Fig. 6). The analysis of growth strata shows a two-step folding formation involving thin-skinned folding during the Palaeogene, followed by Neogene anticlinal culmination through thick-skinned inversion of Jurassic extensional faults (Ghiglione *et al*., 2002; Ghiglione and Ramos, 2005; Navarrete-Rodríguez, 2006). Some discrete segments of the external fold-thrust belt had a sedimentary cover of horizontal Miocene to Pleistocene sediments (Figs 2 and 4). From our

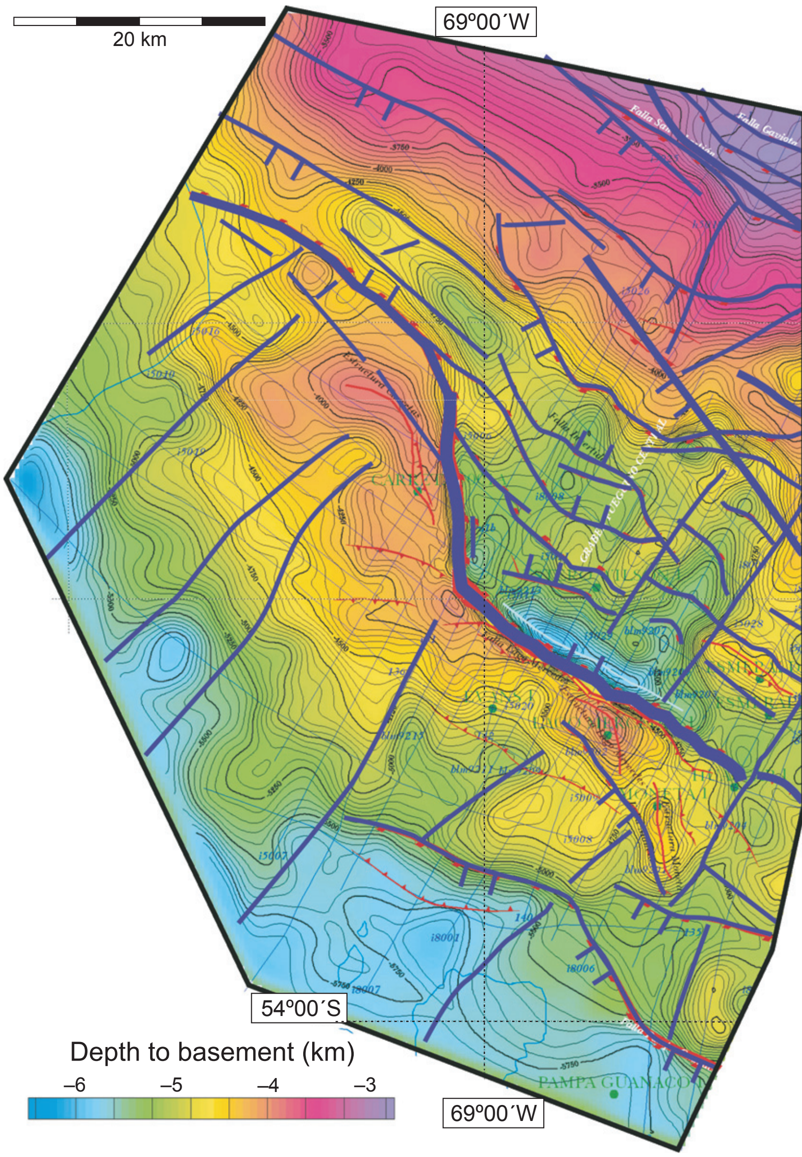

Fig. 3 Example from Lago Mercedes area of depth to basement map and interpretation. Modified after Navarrete-Rodríguez (2006). See Fig. 2 for location.

structural mapping, it came to light that there is a striking coincidence between transfer faults and the boundaries of this Miocene sedimentation, showing that the Neogene rift system produced a transverse segmentation of the fold-thrust belt (Figs 2 and 4). The central sector where the fold thrust belt crops-out (Fig. 4) seems to be a horst, bounded by Neogene grabens (Fig. 2). Because the Cenozoic anticlines are double plunging and terminate laterally towards our mapped Jurassic transfer faults (Fig. 4), it appears that the transfer zones worked as mechanical boundaries during the folding process between fault bounded blocks.

Neogene rift system

On the basis of satellite imagery and field data, Diraison *et al.* (1997a) interpreted the Magellan strait and the depressions of glacial valleys as grabens (Figs 1 and 2), for example, the Inútil and San Sebastián bays (see also Lodolo *et al.*, 2003; Menichetti *et al.*, 2008). The onset of the rift may be associated with the tectonic complexity that characterized the Neogene, and is still active as shown by the presence of neotectonic scarps (Diraison *et al.*, 1997a). Diraison *et al.* (1997a) proposed two main general possible explanations for the development of the rift: (1) Since South America has moved westward, relative to Antarctica and Scotia, left-lateral drag against Scotia is responsible for the rifting off Tierra del Fuego or (2) Extension parallel to the orogen may also be due to subduction of the Chile Ridge, which collided with Tierra del Fuego at *c.* 14 Ma (Cande and Leslie, 1986).

However, there is still no explanation that pinpoints the specific tectonic features and factors that lead to the development of the Magellan rift. The intense volcano-tectonic activity in the Pali Aike area (Corbella, 2002) marks a major Pliocene-Quaternary phase in the development of the Magellan rift system (Mazzarini and D'Orazio, 2003; Fig. 1). This volcanic field shows alignment of volcanoes indicating ascent of magma throughout reactivated NW trending Jurassic extensional faults (Corbella *et al.*, 1996; Corbella, 2002). The widespread spatial distribution of mainly shallow (depth < 10 km) low-magnitude (Ms < 4) earthquakes recorded on the recently installed local seismic network also seems to be associated with modern tectonic activity in the Magellan rift (Sabbione *et al.*, 2007; Buffoni *et al.*, 2009; Fig. 2).

Strike-slip shear faults and stress directions

Active strike-slip faulting in Tierra del Fuego has been previously interpreted through the analysis of lineaments visible on optical satellite images and digital elevation models (i.e. Lodolo *et al.*, 2003). Comparison of satellite image lineaments orientation with a theoretical Riedel shear system (Lodolo *et al.*, 2003) and recent GPS studies demonstrate that modern principal strain components show mainly a stretching of the crust oriented in a NW–SE direction, and subordinate contraction with a SW–NE trend (Mendoza *et al.*, 2011; Figs 2 and 4).

Discussion and conclusions

Opening of the Magellan rift

Our structural mapping shows a good match between the orientation of the

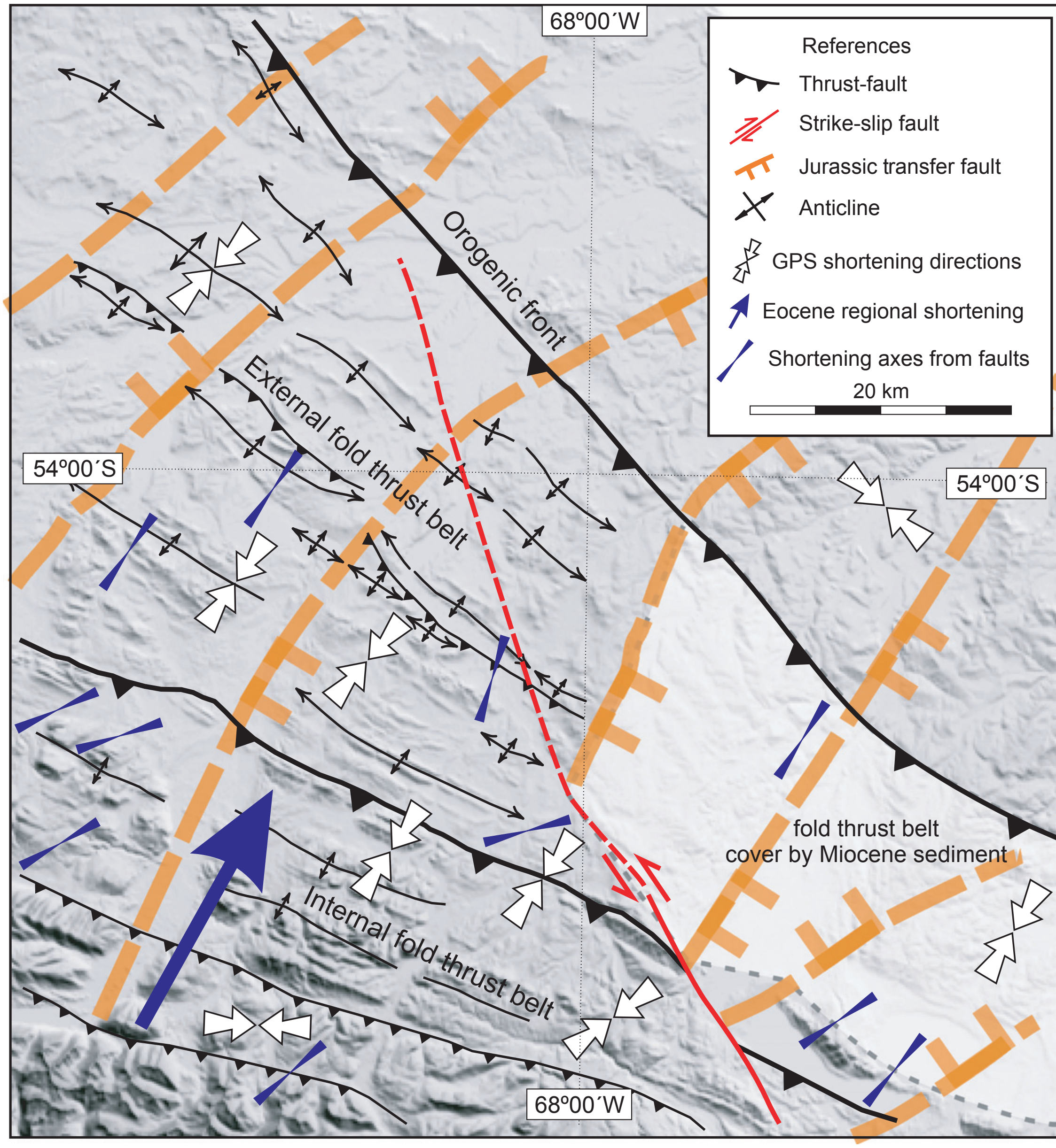

Fig. 4 Structural map of the fold-thrust belt constructed from field-based data. Jurassic transfer zones are superposed. GPS shortening vectors are from Mendoza *et al.* (2011); Eocene regional shortening vector is from Ghiglione and Cristallini (2007). Blue bars show strikes of shortening axes obtained by fault analysis from Diraison *et al.* (2000). See Fig. 2 for location.

Jurassic fault array and the theoretical and GPS strain directions from the Magallanes-Fagnano fault zone (Figs 2–4). W to NW trending Jurassic transfer zones coincide with graben boundaries proposed by Diraison *et al.* (1997a), and they are at right angles to strike-slip stretching directions (Fig. 2). We conclude that transfer zones were extensionally reactivated during Neogene strike-slip deformation generating the Magellan rift system (Fig. 5). This reactivation must have been enhanced by a late accommodation of the Cenozoic northward continental drift (Somoza, 2007) in the trailing edge of South America. We also conclude that ascent of magma in the Pali Aike volcanic field occurred throughout both sets of Jurassic faults, completing the ideas of Corbella *et al.* (1996) and Mazzarini and D'Orazio (2003). In this regard, geodetic determinations show that GPS points located in the northern rim of the Neogene rift, in San Sebastian Bay (Fig. 2) and in the Pali-Aike volcanic field (Fig. 1) are moving northward $\sim$1 mm a^{-1} with respect to stable South America (Smalley *et al.*, 2003). This shows that the influence of the Magallanes-Fagnano fault zone may extend up to 52° SL.

The Neogene rift system produced a transverse segmentation of the external fold-thrust belt, where some seg-

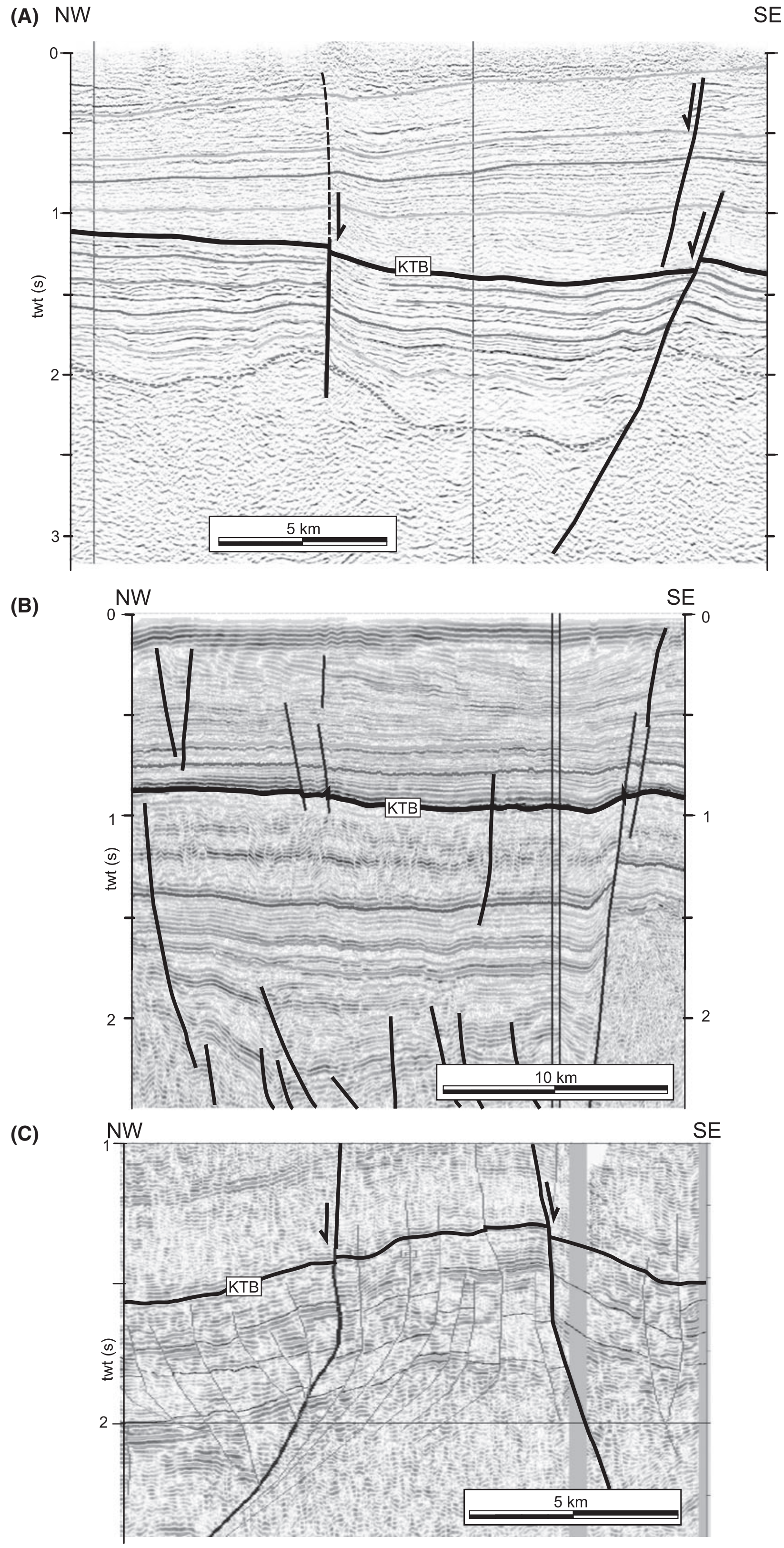

Fig. 5 Seismic data from inland Tierra del Fuego showing Jurassic transfer zones affecting Neogene strata. KTB, Cretaceous-Tertiary boundary. For locations, see Fig. 2.

ments are outcropping, while other are cover in angular unconformity by Miocene horizontal sediments (Figs 2 and 4). The transition from compression to strike-slip deformation occurred without a significant change in shortening direction (Fig. 4), thus a synergetic transition took place from Eocene–Oligocene compression to Neogene transpression. Transpression and inversion was also facilitated by the orientation of the strike-slip compressional vector orthogonal to both previous compressional structures and to Jurassic extensional faults, facilitating reactivation by inversion (Fig. 4).

We suggest that the presence of a network of relatively shallow (i.e. ~5–10 km deep) structures in an arrangement perpendicular to current regional stress field (Fig. 2) allowed the dispersion of energy in an array of low magnitude seismic events.

Geodynamic in the Scotia Sea

The opening of Drake Passage allowed the full development of the Antarctic Circumpolar Current (Lawver and Gahagan, 2003; Barker *et al.*, 2007), which could have contributed to Oligocene global cooling and Antarctic glaciation by changes in ocean circulation that reduced heat transport to low latitudes (Kennett, 1977). Others argue that a shallow early opening of the Drake Passage during the middle Eocene influenced a circulation-induced biogenic productivity increase that may have sequestered CO_2 (Eagles *et al.*, 2006; Scher and Martin, 2006) producing a fall in atmospheric pCO_2 that caused Oligocene cooling without a global change in ocean circulation (De Conto and Pollard, 2003). However, the possibility of an early seaway is still under debate (Barker *et al.*, 2007), and various continental fragments may have formed an effective barrier to substantial deepwater circulation until at least 28 Ma (Lawver *et al.*, 2011).

Whereas the western section of the Magellan strait is controlled by the transtensional Magallanes-Fagnano fault zone (Lodolo *et al.*, 2003), our data and discussion argued that the Patagonian Jurassic transfer faults were prone to reactivation under small amounts of stretching orthogonal to their orientation, developing the east-

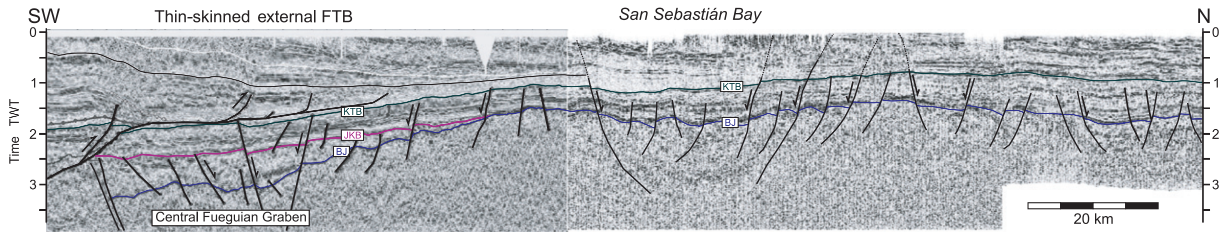

Fig. 6 Regional interpreted seismic section from inland Tierra del Fuego. BJ, Base of Jurassic; JKB, Jurassic-Cretaceous boundary; KTB, Cretaceous-Tertiary boundary. Modified after Navarrete-Rodríguez (2006). See Fig. 2 for location.

ern Magellan strait. As a result of this combination of strike-slip and extensional faulting, a water connection 550 km long and 4–30 km wide (Fig. 1) between the Atlantic and Pacific Oceans was formed, with maximum depth of over 500 m.

We propose that a similar combination of strike-slip and extension by fault reactivation could have also controlled Cenozoic rifting around the Scotia Sea. Relative left-lateral plate motion along the Magallanes-Fagnano fault system, for instance, is $\sim$6 mm a^{-1} and Pali Aike is moving northward $\sim$1 mm a^{-1} (Smalley *et al.*, 2003, 2007), while the final separation of South America and Antarctica started at 50 Ma at a rate of 24 mm a^{-1} NW–SE (Livermore *et al.*, 2005, 2007; Eagles *et al.*, 2006). Other sections of the proto Drake Passage could have been controlled by strike-slip fault zones, in a similar manner to the western Magellan Strait. In this context, the tectonic development of the Magellan strait could be considered like the early Drake Passage, and its broad parameters could be used to model the tectonic opening of an early Pacific–Atlantic waterway.

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