Kinematic Evolution of the Southern Andean Orogenic Arc

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Abstract In the classic book 'Origin of Continents and Oceans' written 40 years before the plate tectonics theory was postulated, Alfred Wegener suggested that map-view curvatures in orogenic belts were the result of the motion of continents. In the mid-1950s, Carey coined the term 'orocline' to indicate a curved mountain belt formed by secondary bending of an originally straight orogen. Oroclines are genetically different from primary arcs, which are curved mountain belts whose curvature is primary and not due to secondary tectonic processes. A typical example of curved mountain belt is the southernmost segment of the Andean Cordillera, where the regional N–S trend of the Patagonian Andes sharply changes to ESE–WNW in the Fuegian Andes south of 53°S. Given the complex tectonic history of this region and the paucity of geological constraints, the nature, timing of deformation, and kinematics of formation of this orogenic bend have long been debated since its first definition by Carey as 'Patagonian orocline.' The dispute revolves around the question whether the southernmost Andes is an orocline or a primary arc. Implications for both options are significant and directly related to the understanding of fundamental tectonic processes operating at plate boundaries. More specifically, unraveling the tectonic evolution of the curved segment of the southernmost Andes is key to understand the geodynamic evolution of this region and the complex interaction between South America, Scotia, and Antarctica plates. Based on paleomagnetic, structural, and magnetic fabric data gathered in the last four decades, the orogenic curvature of the southernmost Andes does not specifically fit in any of the classic definitions of curved mountain belts, as it rather represents a 'hybrid' curved belt. While the outer side of the curvature (inner structural domains) seems to represent an orocline (or a progressive arc), the inner part of the curvature (external structural domains) developed as a primary arc throughout the Cenozoic. For this reason, the more generic term of 'Patagonian Arc' has recently been proposed as a more suitable name to describe the curved segment of the southernmost Andes. While oroclinal bending of the external part of the arc is generally associated with the closure of the Rocas Verdes marginal basin

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in Late Cretaceous–Early Paleocene times, the mechanisms of formation of the primary arc represented by the Magallanes fold and thrust belt are unclear. A recent model proposed that slip-partitioning mechanisms along preexisting fault controlled the formation of the Magallanes fold and thrust belt by enabling propagation of ~N-ward and ~ENE-ward contraction in the Fuegian and Southern Patagonian Andes, respectively. Future studies are, however, still needed to better constrain the timing and kinematics of formation of the Patagonian Arc.

Keywords Southernmost Andes · Magallanes fold and thrust belt · Orocline · Primary arc · Tectonics · Deformation · Paleomagnetism

1 Introduction

The area encompassing the South America, Scotia, and Antarctica plates underwent a complex tectonic history, characterized by alternation of extensional, compressive, and strike-slip tectonics over time and space (Klepeis and Austin 1997). Within this extremely variable tectonic regime, a regional-scale curvature developed in the southernmost segment of the Andean Cordillera at the tip of the South American plate, namely Patagonian orocline (Carey 1958). Ambiguities, however, reside on the use of the term ‘orocline’ for such curvature. While the term orocline (*sensu stricto*) denotes an orogenic curvatures developed after the bending of an originally straight mountain belt, the nature, style, and timing of the tectonic processes leading to the formation of the Patagonian orogenic curvature, as well as their timing and kinematics, have remained elusive for a long time and are still not entirely understood.

Curved mountain belts may be primary arcs, progressive arcs, or oroclines, depending on whether or not the curvature is acquired during secondary tectonic processes involving vertical-axis rotations of different portions of the arc. So far, all the three hypotheses have been considered to explain the present-day curvature of the southernmost Andes. Defining the true nature of this orogenic arc is key to constrain the fundamental tectonic processes operating at plate boundaries and, more in particular, the tectonic evolution of the region at the intersection between the South American, Scotia, and Antarctica plates.

For a long time, it has been thought that the specular curvature of the South American and Antarctic continents could be genetically connected with the formation of the Scotia plate and the opening of the Drake Passage between them. In the last four decades, structural geological, paleomagnetic, and magnetic fabric constraints have been instrumental to characterize the kinematics and timing of deformation at the southernmost Andes and frame these results into a broader regional context. Here, a comprehensive review of the up-to-date paleomagnetic, structural, and magnetic fabric data is presented, together with a discussion on current models and future challenges.

2 Geological and Tectonic Setting of the Southernmost Andes

The southernmost Andes is composed of five adjacent tectonic domains; from the hinterland toward the foreland, they are as follows: (1) a Late Jurassic–Neogene magmatic arc (Patagonian batholith, see Guillot 2016) formed during initial subduction below South America (Hervé et al. 1984, 2007; Pankhurst et al. 2000; González Guillot et al. 2011); (2) a marginal basin assemblage (Rocas Verdes basin) composed of oceanic floor relics (Stern and De Witt 2003; Cunningham 1994) and overlying sediments (Calderón et al. 2007; Olivero and Malumián 2008); (3) a metamorphic core zone (Cordillera Darwin) exposing uplifted blocks of the metamorphosed Paleozoic basement (Kohn et al. 1995; Klepeis 1994; Hervé et al. 2008; Klepeis et al. 2010; Maloney et al. 2011, 2013); (4) a fold and thrust belt (Magallanes fold and thrust belt) formed by deformation of a ~7-km-thick Upper Cretaceous–Miocene foreland marine sedimentary sequence (Biddle et al. 1986; Alvarez-Marrón et al. 1993; Klepeis 1994; Olivero and Malumián 1999; Olivero et al. 2003; Ghiglione et al. 2002; Ghiglione and Ramos 2005; Malumián and Olivero 2006; Olivero and Malumián 2008; Torres Carbonell et al. 2008); (5) an undeformed foreland basin (Magallanes-Austral basin). The E–W-trending Magallanes-Fagnano left-lateral strike-slip fault system cut preexisting structures of the Fuegian Andes from the Atlantic to the Pacific coast of South America and is considered the present-day South America–Scotia transform plate boundary (Cunningham 1993, 1995; Barker 2001; Lodolo et al. 2002, 2003; Eagles et al. 2005; Rossello 2005).

To the south, the deep-sea Drake Passage separates South America from Antarctica (Barker 2001; Eagles et al. 2005; Livermore et al. 2005; Lodolo et al. 1997, 2006; Eagles 2016). The opening of the Drake Passage is believed to have played an important role in global climate changes. The formation of this marine 'gateway' may have triggered the onset of the Antarctic Circumpolar Current (Lawver and Gahagan 2003; Barker et al. 2007a), which thermally isolated the Antarctic continent resulting in local development of permanent ice sheets (Barker et al. 2007b). Such event seems to have had global repercussion as suggested by its synchronicity with the onset of a global cooling event at the Eocene/Oligocene boundary (Zachos et al. 2001). The opening of the Drake Passage is commonly related to the spreading of the Scotia Sea, where oldest marine magnetic anomalies have been dated back to 34–28 Ma (Lawver and Gahagan 2003; Livermore et al. 2005; Lodolo et al. 2006).

Tectonic style changes considerably across the southernmost Andes. The internal structural domains exposing magmatic and metamorphic units are characterized by thick-skinned tectonics involving basement rocks; in the external domains, mainly non-metamorphic sedimentary rocks are involved in a thin-skinned deformation, which led to the formation of a fold and thrust belt (Ghiglione and Ramos 2005; Torres Carbonell et al. 2008, 2013). Overall, fold axes and thrust faults strike sub-parallel to the regional trend of the orogenic curvature. Both domains are folded into a curved orogen showing an interlimb angle of $\sim 110°$. In the northern segment of the curvature (Southern Patagonian Andes) the main structural directions (fold axes and faults) are NNW–SSE, while in the southern branch (Fuegian Andes), they progressively change from NW–SE in the bend hinge to E–W and ENE–WSW to the east along the Atlantic Coast.

3 Tectonic Evolution of the Southernmost Andes

To understand how a large-scale orogenic curvature developed at the southernmost Andes, it is essential to analyze the sequence of tectonic events that characterized the formation of the Andean Cordillera in this sector. During the first stages of emplacement of the magmatic arc, an extensional tectonic phase affected the western margin of the South American plate, resulting in lithospheric attenuation. The extensional faults cutting the continental margin of South America played a key role in controlling the subsequent sedimentation and deformation in the Magallanes-Austral foreland basin during the early orogenic phases (Winslow 1982; Fosdick et al. 2011, 2015; Likerman et al. 2013; Ghiglione et al. 2013). This extensional tectonic event culminated in the opening of the Rocas Verdes backarc marginal basin in the Late Jurassic (Kyrtz 1973; Dalziel et al. 1974; Bruhn and Dalziel 1977; Bruhn et al. 1978; Dalziel 1981; Calderón et al. 2007). Sedimentation in the marginal basin continued during the Early Cretaceous (Wilson 1991; Fildani and Hessler 2005; Olivero and Malumián 2008; Klepeis et al. 2010). Opening of the South Atlantic Ocean at ~ 100 Ma transmitted compression into the Rocas Verdes marginal basin, leading to widespread thrusting episodes (Hervé et al. 1981; Biddle et al. 1986). This regional tectonic event marked the onset of the main tectonic phase in the southernmost Andes during basin closure. Contraction propagating into the basin led to regional ductile deformation, isoclinal folding, and low-grade metamorphism of its sedimentary infill (Bruhn 1979). Deep burial of underthrust basement continental rocks of the South American plate currently exposed in Cordillera Darwin led to peak metamorphism at upper amphibolite facies conditions (7–11 kbar and 580–600 °C; Kohn et al. 1993) (Klepeis et al. 2010; Maloney et al. 2011).

In the Late Cretaceous between ~ 100 and 86 Ma, complete closure of the Rocas Verdes basin determined the collision of the Patagonian batholith against the South American continental margin (Halpern and Rex 1972; Bruhn and Dalziel 1977; Cunningham 1994, 1995; Klepeis et al. 2010; Calderón et al. 2012). This major event caused thick-skinned deformation in the South American continental margin and possibly initial continental basement blocks uplift. This early contractional episode has been constrained in time by $^{40}Ar/^{39}Ar$ and fission track thermochronology from Cordillera Darwin, which has shown cooling ages as old as

90–70 Ma (Nelson 1982; Kohn et al. 1995). Furthermore, growing of the orogenic wedge produced the first foreland deposits whose basal depositional age has been constrained at 101–88 Ma using U/Pb in tuffs and detrital zircons (Fildani et al. 2003; Fosdick et al. 2011; McAtamney et al. 2011).

Crustal thickening in the hinterland characterized by out-of-sequence thrusting, continued throughout the Late Cretaceous and Paleogene, yielding uplifting of the most internal structural domains, and continuous lithospheric loading, flexural subsidence, and sedimentation in the foreland basin (Winslow 1981; Biddle et al. 1986; Ramos 1989; Wilson 1991; Alvarez-Marrón et al. 1993; Klepeis 1994; Coutand et al. 1999; Fildani et al. 2003; Olivero et al. 2003; Ghiglione et al. 2010, 2016a, b). Since then, propagation of deformation in the foreland basin produced the Magallanes fold and thrust belt. In the Fuegian Andes, also thanks to the presence of well-developed syntectonic unconformities in the sedimentary record, most of the main compressive events have been identified and constrained in time. The first compressive event in the fold and thrust belt, marked by the San Vicente thrust, occurred at 61–55 Ma (Ghiglione and Ramos 2005) or slightly before (Torres Carbonell et al. 2013). Compression in the foreland basin continued through the Eocene with the Rio Bueno thrusting event (49–34 Ma; Ghiglione and Ramos 2005) and other minor events in the Early Eocene and Late Oligocene (Alvarez-Marrón et al. 1993; Olivero et al. 2003; Olivero and Malumián 2008; Torres Carbonell et al. 2008, 2013). The Punta Gruesa strike-slip event (∼24–16 Ma) marked the beginning of the strike-slip tectonics associated with the development of the Magallanes-Fagnano fault system (Cunningham 1993, 1995; Ghiglione 2002; Lodolo et al. 2003; Eagles et al. 2005; Rossello 2005). Finally, sub-horizontal units above Lower Miocene beds marked the end of compressional tectonics in the southern Magallanes-Austral basin (Ghiglione et al. 2010).

Along-strike age constraints from the Southern Patagonian Andes are not sufficient to test whether the tectonic phases occurred synchronously throughout the southernmost Andes. Few events have been defined in the Patagonian Andes, suggesting that deformation may have been, at least occasionally, synchronous. Paleocene deformation in the Patagonian Andes was mainly localized in the Basement domain (Kraemer 1998). Collision of the Farallon–Phoenix ridge in the Middle Eocene (Cande and Leslie 1986; Somoza and Ghidella 2005, 2012) determined an eastward shifting of the orogenic front into the foreland. Angular unconformities and growth strata at Río Turbio (Malumián et al. 2000), and emplacement of an Eocene basaltic plateau (Mesetas) (Ramos 1989, 2005) were the direct evidence of this tectonic event. A major compressive phase and uplift in the Paleogene has also been identified in the eastern sectors of the Southern Patagonian Andes using zircon (U–Th)/He dating (Fosdick et al. 2013). To the south, fast ∼NE-directed subduction of the Phoenix plate between 47 and 28 Ma resulted in more substantial tectonic deformations (Ramos and Aleman 2000; Kraemer 2003; Ghiglione and Ramos 2005; Somoza and Ghidella 2005, 2012; Ghiglione and Cristallini 2007). Compressive events in the western domains of the Patagonian

Andes during the Late Oligocene (30–23 Ma; Thomson et al. 2001) propagating to the east in the Early Miocene (22–18 Ma; Fosdick et al. 2013) and Middle to Late Miocene (12–8 Ma; Thomson et al. 2001) have also been identified using apatite fission track and apatite and zircon (U–Th)/He age constraints.

4 The Contribution of Paleomagnetism to the Study of Curved Mountain Belts

Carey (1955) first introduced the concept of 'orocline' to describe an originally straight mountain belt whose map-view curvature has been acquired during younger tectonic phases. Formation of oroclines, therefore, necessarily requires vertical-axis block rotation of different parts of the curvature. Oroclines are genetically distinguished from primary arcs where curvature is not acquired upon block rotation but represents a primary feature.

More recently, Weil and Sussman (2004) and Marshak (2004) proposed new classifications and terminology, respectively, for map-view curved orogens. Weil and Sussman (2004) distinguished three different types of orogenic arcs based on the time relationship between thrusting and vertical-axis rotations: non-rotational arcs, progressive arcs, and oroclines. Non-rotational (or primary) arcs are orogenic curves that formed originally curved, with no tectonic rotations occurring during their formation. Progressive arcs and oroclines are both secondary arcs, meaning that they acquired their curvature after secondary processes. Progressive arcs gradually increase their curvature during deformation, and tectonic rotations are synchronous to the main thrusting phase. In oroclines, the curvature develops after bending of an originally straight belt. Tectonic rotations in oroclines are therefore subsequent to the main tectonic phase, i.e., the one that produced the originally straight orogenic belt.

Being able to detect the amount and timing of tectonic rotations in curved mountain belts is therefore essential to constrain their nature and untangle the tectonic processes responsible for their formation. Since the 1980s, paleomagnetism has been widely used in the study of orogenic arcs (Van der Voo and Channell 1980; Eldredge et al. 1985; Lowrie and Hirt 1986; Van der Voo 1993, 2004; Van der Voo et al. 1997; Speranza et al. 1997; Muttoni et al. 1998; Marshak 2004; Cifelli et al. 2007; Maffione et al. 2008, 2009, 2010, 2013; Yonkee and Weil 2010; Weil et al. 2010; Weil and Sussman 2004). Paleomagnetism can in fact quantify absolute and relative magnitudes of block rotations by determining changes in paleomagnetic remanence vectors between individual localities (Fig. 1). Paleomagnetic data are key constraints to define horizontal- and vertical-axis rotation patterns in curved orogenic systems; yet, structural and strain data should also be considered and integrated to define the bulk translation (slip on major faults) and internal strain (accommodated by cleavage and minor folds and faults).

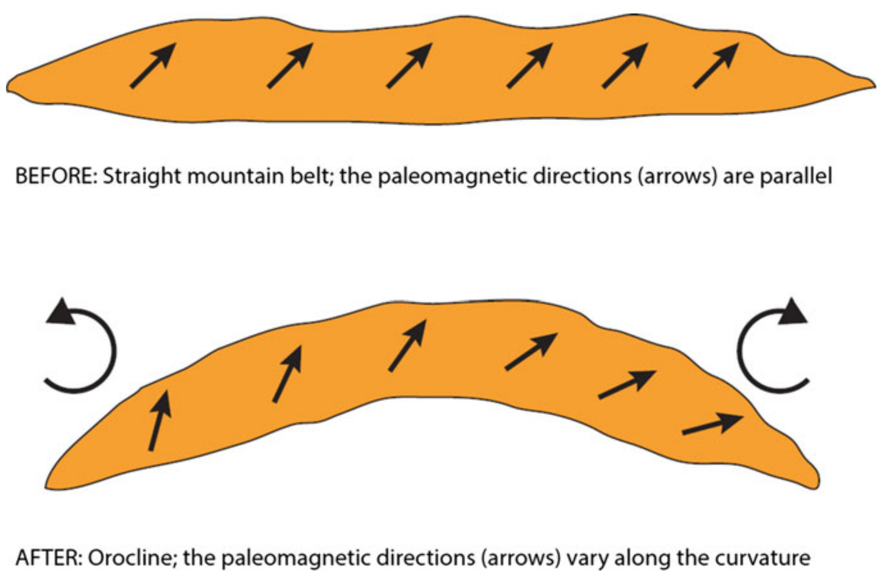

Fig. 1 Illustration of the consequences of oroclinal bending on the pattern of magnetic declination in a thrust belt. The *orange-shaded area* represents the mountain belt in map view, and the *arrows* represent paleomagnetic directions. (*Above*) Before bending, all *arrows* point in the same direction. (*Below*) Bending deflects the paleomagnetic directions along the strike of the bend

Reliable tectonic models should therefore be reconstructed using a combined approach where paleomagnetism and strain analysis represent the main tools.

5 Paleomagnetic Constraints from the Southernmost Andes

The observed geometrical relationships in the southernmost Andes initially induced Carey (1958) and then Dalziel and Elliot (1973) to propose a similar amount of bending that occurred to produce the present-day geometry, starting from a relatively straight orogen. In particular, Dalziel and Elliot (1973) put forward that a symmetrical bending of the southernmost Andes and northern tip of the Antarctic Peninsula occurred as a consequence of the opening of the Drake Passage. Since then, also because of the name (Patagonian orocline) given by Carey, this regional-scale curvature of the southernmost Andes has been considered an orocline until first controversial paleomagnetic data became available, questioning the real tectonic origin (rotational versus non-rotational arc, sensu Marshak 1988) of the curvature.

In this section, a comprehensive review of the available paleomagnetic data in the southernmost Andes is presented and discussed. The quality of these

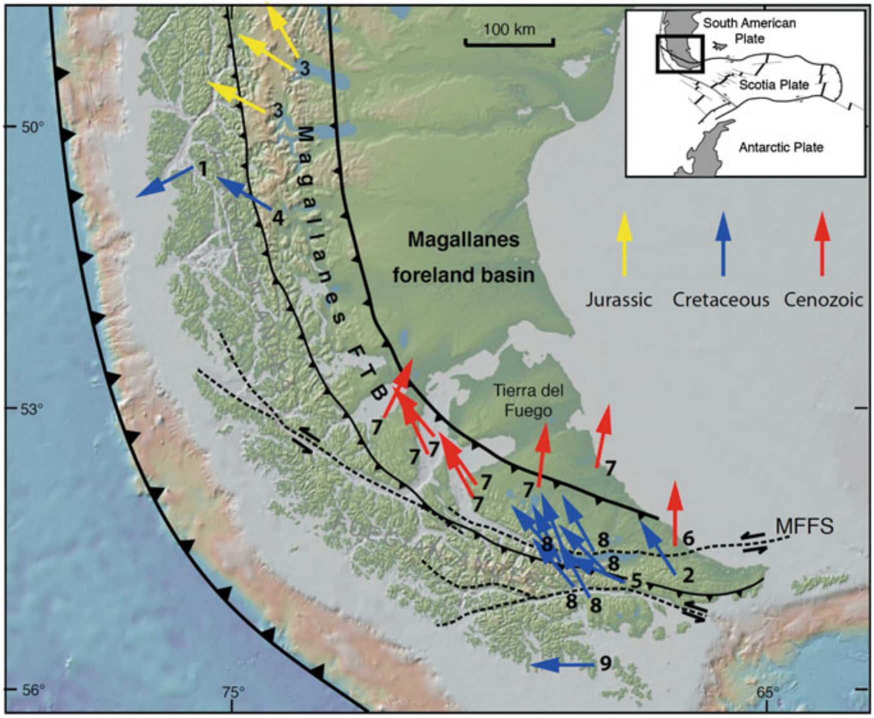

Fig. 2 Available paleomagnetic directions from the southernmost Andes (*arrows*). Numbers refer to the relative work: *1* Rapalini et al. (2001); *2* Baraldo et al. (2002); *3* Iglesia Llanos et al. (2003); *4* Rapalini et al. (2004); *5* Rapalini et al. (2005); *6* Maffione et al. (2010); *7* Poblete et al. (2014); *8* Rapalini et al. (2015); *9* Cunningham et al. (1991). *MFFS* Magallanes-Fagnano fault system. *FTB* fold and thrust belt

paleomagnetic data is critically evaluated, and the dataset filtered to consider only the most reliable data that are relevant for tectonic interpretations (Fig. 2 and Table 1). The adopted filtering criteria are as follows: (1) Paleomagnetic analyses followed modern standard techniques (e.g., stepwise demagnetization); (2) paleo-horizontal controls are available, or in their absence, a large dataset is considered; and (3) the age of magnetization can be identified.

5.1 *Southern Patagonian Andes*

A northern boundary located at ~48°S can be identified in the southernmost Andes for the area subjected to tectonic vertical-axis rotations. North of this boundary, the absence of tectonic rotations in Jurassic to Cretaceous rocks has been documented by several authors (Roperch et al. 1997; Beck et al. 2000; Iglesia Llanos et al. 2003).

Table 1 Available paleomagnetic results from the Southern Andes

Lithology	Age	Magnetization age (Ma)	*N*	Rotation	Flattening	Paleohorizontal control	Author
Sediments/volcanics	U. Jurassic–L. Cretaceous	Mid-Late Cretaceous?	7	−90.0 ± 12	−0.2	No	Cunningham et al. (1991)
Ignimbrite/tuff/lava	Upper Jurassic	Late Jurassic	5	−30 ± 14	–	Yes	Iglesia Llanos et al. (2003)
Ignimbrite/tuff/lava	Upper Jurassic	Late Jurassic	4	−57 ± 9	–	Yes	Iglesia Llanos et al. (2003)
Ignimbrite/tuff/lava	Upper Jurassic	Late Jurassic	4	−62 ± 15	–	Yes	Iglesia Llanos et al. (2003)
Basalts and limestones	U. Carboniferous–L. Permian	Post-Early Cretaceous	9	−117.7 ± 29.9	5.4 ± 9.7	No	Rapalini et al. (2001)
Lava/dykes/sills	Upper Jurassic	Late Cretaceous?	1	−59 ± 17	–	No	Rapalini et al. (2004)
Sills/volcanics	Upper Jurassic	Late Cretaceous?	3	−66 ± 10	–	No	Rapalini et al. (2005)
Monzodiorite	Upper Cretaceous (93 ± 4 Ma)	Late Cretaceous	1	−33 ± 7	–	No	Baraldo et al. (2002)
Sediments	lower Eocene	Lower Eocene	1	−5.6 ± 12.5	−33.8 ± 8.3	Yes	Maffione et al. (2010)
Sediments	lower Eocene	Lower Eocene	1	−3.7 ± 12.3	−50.4 ± 9.7	Yes	Maffione et al. (2010)
Sediments	middle-upper Eocene	middle-late Eocene	1	−16.7 ± 19.2	−36.0 ± 11.4	Yes	Maffione et al. (2010)
Sediments	middle-upper Eocene	middle-late Eocene	1	6.3 ± 15.9	−54.2 ± 9.9	Yes	Maffione et al. (2010)
Sediments	U. Eocene–L. Oligocene	L. Eocene–E. Oligocene	1	−19.2 ± 20.7	−37.9 ± 15.7	Yes	Maffione et al. (2010)
Sediments	Paleocene	Paleocene	1	−15.4 ± 8.5	−5.3 ± 3.5	Yes	Poblete et al. (2014)
Sediments	Paleocene	Paleocene	1	−26.3 ± 15.1	0.1 ± 5.3	Yes	Poblete et al. (2014)
Sediments	Paleocene	Paleocene	1	−1.6 ± 8.6	−6.9 ± 3.7	Yes	Poblete et al. (2014)
Sediments	Paleocene	Paleocene	1	−22.9 ± 11.6	6.5 ± 3.2	Yes	Poblete et al. (2014)
Sediments	Paleocene	Paleocene	1	−21.8 ± 8.9	0.3 ± 3.1	Yes	Poblete et al. (2014)
Sediments	Paleocene	Paleocene	1	26.1 ± 15.2	−0.5 ± 5.5	Yes	Poblete et al. (2014)
Sediments	Paleocene	Paleocene	1	16.7 ± I1.3	−9.1 ± 4.1	Yes	Poblete et al. (2014)
Pluton	Upper Cretaceous	Late Cretaceous	5	−29.2 ± 6.1	35.9 ± 3.9	No	Rapalini et al. (2015)
Pluton	Upper Cretaceous	Late Cretaceous	7	−20.8 ± 16.5	17.7 ± 13.3	No	Rapalini et al. (2015)
Dacite	Upper Cretaceous	Late Cretaceous	3	−40.2 ± 7.9	2.6 ± 5.7	No	Rapalini et al. (2015)
Pluton	Upper Cretaceous	Late Cretaceous	3	−28.5 ± 9.7	−3.3 ± 6.3	No	Rapalini et al. (2015)
Sills	Upper Jurassic	Late Cretaceous	1	−44.6 ± 12.0	9.7 ± 8.0	No	Rapalini et al. (2015)
Sills	Upper Jurassic	Late Cretaceous	1	−41.7 ± 17.7	−0.3 ± 13.4	No	Rapalini et al. (2015)
Sills	Upper Jurassic	Late Cretaceous	1	−25.4 ± 9.5	11.1 ± 5.1	No	Rapalini et al. (2015)

To the south, between 48°S and 50°S post-Late Jurassic counterclockwise (CCW) rotation of 30° ± 14°, 57° ± 9°, and 62° ± 15° has been documented from the Upper Jurassic El Quemado Complex, a suite of sedimentary and volcanic rocks (Iglesia Llanos et al. 2003). The authors interpreted these rotations as the effect of local tectonics unrelated to the formation of the regional curvature of the orogen. Further south, remagnetized samples from upper Carboniferous to lower Permian basalts and lavas from the Madre de Dios Archipelago on the Pacific coast have shown 118° ± 30° of CCW rotation of possible post-Early Cretaceous age (Rapalini et al. 2001), interpreted as the result of strike-slip tectonics characterizing the frontal part of the orogen, adjacent to the Pacific trench. At ~52°S, within more external domains of the belt, data from Upper Jurassic–Lower Cretaceous lava, dykes, and sills from the Sarmiento ophiolite have shown a 59° ± 17° post-Late Cretaceous CCW rotation of possible local tectonics origin (Rapalini et al. 2004).

Excluding rotations associated with the local tectonics, it can be concluded that this sector of the southernmost Andes did not undergo significant rotation relative to stable South America.

5.2 *Fuegian Andes*

The first paleomagnetic data from the Fuegian Andes were obtained by Dalziel et al. (1973) from Mesozoic granodiorite plutons and Cenozoic dykes from 27 sites distributed across three main areas within the most internal structural domains of the belt: Navarino Island, the western Canal Beagle, and the southern Chile fiords region north of 52°S. These authors documented progressive variation of the paleomagnetic directions along the orogenic curvature, with CCW rotations increasing southward up to 150°. Conversely, paleomagnetic directions from the Cenozoic samples did not show significant geographical variation. The authors interpreted these results as clear evidence of a secondary origin of the curvature of the southernmost Andes, as previously speculated by Carey (1958). Shortly after, Burns et al. (1980) carried out a more extensive paleomagnetic sampling from Jurassic volcanics (Tobifera Formation) and Cretaceous to Cenozoic dykes and sills from more external structural domains of the belt. Maximum rotations up to 48° CCW, much lower than the whole curvature of the orogen (~90°) led these authors to propose that the paleomagnetic data recorded only part of the oroclinal bending. Burns et al. (1980) suggested that rotations started in the Late Jurassic and continued until Miocene times.

Although the early works of Dalziel et al. (1973) and Burns et al. (1980) have for long been the most significant to be consider for the oroclinal bending hypothesis, data processing and interpretation do not satisfy modern standard reliability criteria (Van der Voo 1990). The low reliability of these data is due to the fact that paleomagnetic directions were not obtained using (now broadly used) stepwise demagnetization technique and principal component analysis (Kirschvink 1980) to discriminate between different components of the magnetic remanence. These studies, in contrast, adopted old-fashioned blanket demagnetization techniques with no application of vectorial analysis. For this reason, the paleomagnetic directions from these studies are not reliable and should not be used to test the orocline hypothesis in the southernmost Andes.

Paleomagnetic data satisfying standard reliability criteria were then gathered almost one decade later by Cunningham et al. (1991). These authors sampled seven sites within sedimentary rocks, mafic sills, volcaniclastic breccias, debris flow deposits, and a pyroclastic unit from the Lower Cretaceous Andean magmatic arc on Peninsula Hardy in the most internal structural domains of the orogen. Consistent normal polarity directions and a negative fold test indicated remagnetization of these rocks during the Cretaceous normal polarity super-chrone (102–83.3 Ma). Based on the isolated paleomagnetic directions, a consistent 90° ± 12° CCW rotation was calculated for the studied area. Cunningham et al. (1991) proposed that this rotation reflected a uniform ~90° rotation of the entire Fuegian Andes occurred between ~100 and 35 Ma, prior to the opening of the Drake Passage. A combined effect of the closure of the Rocas Verdes marginal basin and the regional transpressional regime was invoked as the main driving mechanisms for the oroclinal bending.

To the north, toward more external structural domains, Rapalini et al. (2005) reported 66° ± 10° of CCW rotation from a Upper Jurassic basaltic sill of the Lemaire Formation, likely remagnetized during the Late Cretaceous and a Upper Cretaceous dacite near Ushuaia. CCW rotations of 33° ± 7° were also documented from Upper Cretaceous (93 ± 4 Ma) monzodiorites from the hinterland in Tierra del Fuego (Baraldo et al. 2002). Within the same structural domain, Rapalini et al. (2015) sampled Upper Jurassic–Lower Cretaceous metabasalts and metagabbros. Reliable paleomagnetic directions were obtained from six different geological bodies at 26 sites. Ages of the plutons, previously established with different geochronological methods, range between 72 and 85 Ma. Since these intrusive bodies were emplaced after the main Andean tectonic phase in the hinterland of the Fuegian Andes, their remanences were interpreted to be primary (hence acquired during the cooling of the magmatic bodies). Less clear is the age of magnetization for the Upper Jurassic sills of the Lemaire Formation, which has been tentatively attributed by these authors to ~80 Ma. None of the units sampled by Rapalini et al. (2015) provided paleohorizontal controls, implying that in situ paleomagnetic direction was used for tectonic interpretations. Three out of ten mean directions showed unusual low inclinations, likely due to the effect of local tilt. The remaining seven reliable mean directions showed consistent CCW rotations varying between 21° ± 16° and 45° ± 12°. Based on these data, Rapalini et al. (2015) proposed a uniform 30° of CCW rotation of the central structural domains of the Fuegian Andes occurred after Late Cretaceous times (72 Ma) following to (partial) oroclinal bending of the Fuegian Andes. However, these authors did not exclude the possibility for these rotations to be caused by local deformation.

Surprisingly, the Magallanes fold and thrust belt has only recently received the attention of paleomagnetists despite its high potential to preserve primary magnetizations, due to the absence of metamorphism, and provides paleohorizontal-controlled paleomagnetic directions. The most comprehensive paleomagnetic study

(85 sites), encompassing large part of the northern and southern branches of the Magallanes fold and thrust belt, is that of Poblete et al. (2014). Unfortunately, due to the low intensity and stability of magnetization, and the absence of paleohorizontal control for several sites, reliable paleomagnetic directions could be obtained from only seven sites from the Paleocene ($\sim$65 Ma) sedimentary units of the Magallanes fold and thrust belt in the Magallanes and Tierra del Fuego provinces. Excluding two sites that provided anomalous moderate clockwise (CW) rotations, and one site at the northern edge of the fold and thrust belt in Tierra del Fuego showing no significant rotation, the remaining four sites located in the Magallanes province and western Tierra del Fuego showed consistent CCW rotations ranging between $15° \pm 9°$ and $26° \pm 15°$. The authors interpreted these rotations as resulted from the accommodation of differential shortening, increasing eastward, rather than oroclinal bending of the Fuegian Andes.

The most external domains of the Magallanes fold and thrust belt were sampled by Maffione et al. (2010). Due to the low intensity and stability of the remanence, only five sites out of 22 provided reliable paleomagnetic directions. Although somewhat noisy, the remanence isolated at these five sites was interpreted to be prefolding and likely primary, with opposite polarity directions that passed the fold test. The mean paleomagnetic directions at these five sites have an inclination that is substantially lower than expected, likely because of compaction of the clay-rich sediments during diagenesis. Despite the limitation due to the low number of sites and the not ideal quality of data, this study provided the first paleomagnetic constraints from the Cenozoic sedimentary sequences of the Magallanes-Austral basin. The results of this study have three major implications. First, the absence of rotations in the Fuegian Andes during the last $\sim$50 Ma excluded that oroclinal bending occurred during the formation of the fold and thrust belt. Second, the curved Magallanes fold and thrust belt mainly developed during the Cenozoic; hence, the absence of tectonic rotations since 50 Ma classifies it as a non-rotational (primary) arc. Third, the present-day curvature of the southernmost Andes was already acquired prior to the opening of the Drake Passage in the Early Oligocene. This implies that the opening of the Drake Passage and growth of the Scotia plate did not play any role in the evolution of the curvature at the southernmost Andes.

5.3 Antarctic Peninsula

Data from the curved segment of the Antarctic Peninsula, mirroring the shape of the southernmost Andes, are scarce but sufficient to exclude any connection between the tectonic evolutions of the two continental margins. Early paleomagnetic data from the Antarctic Peninsula (Grunow 1993) documented in fact two distinct phases of earlier rotation: CW with respect to East Antarctica between 175 and 155 Ma due to the early opening in the Weddell Sea basin, and CCW with respect to West Antarctica in the 155–130 Ma time interval. Poblete et al. (2011) reported paleomagnetic results from Permo-Triassic and Jurassic rocks remagnetized during the Middle Cretaceous and primarily magnetized Cretaceous and Cenozoic rocks. These data indicated no relative rotations between the different sectors of the Antarctic Peninsula since the Cretaceous. Therefore, well before the beginning of the Andean orogeny in the Late Cretaceous, the curved shape of the Antarctic Peninsula was already developed.

6 Structural and Strain Data from the Southernmost Andes

The most prominent structural feature of the southernmost Andes is the change in direction of its structural lineaments. The main strike of faults and fold axes varies from 345° in the Southern Patagonian Andes to 320°–295° at the hinge of the bend and to 285°–260° in the Fuegian Andes. This geometry is reflected in a similar variation of the shortening directions along the curvature. Diraison et al. (2000) carried out an extensive structural geological study measuring 1600 fault planes in Mesozoic–Cenozoic sedimentary units of the Magallanes fold and thrust belt. Shortening directions in the southernmost Andes are sub-perpendicular to major folds and thrusts and progressively rotate from 075° in the Southern Patagonian Andes to 052° in the western part of the Fuegian Andes and to 043° in the eastern Fuegian Andes (Fig. 3) (see Sue and Ghiglione 2016 for a review). At the easternmost tip of the Fuegian Andes ~N–S, shortening directions have also been documented by Diraison et al. (2000) and Torres Carbonell et al. (2013).

These two studies also showed a progressive southeastward increase of the shortening in the Fuegian Andes from ~5 to ~22 %. Shortening estimates along the belt are quite variable. Regional balanced cross sections of the Fuegian Andes by Kraemer (2003) indicated a total shortening of 300–600 km. This author proposed that most of this shortening occurred in the Middle Cretaceous during the closure of the Rocas Verdes marginal basin, while minor shortening was accommodated during subsequent tectonic phases until the Neogene. Kraemer (2003) suggested that the amount of shortening in the southernmost Andes was consistent with a model of oroclinal bending.

Besides fault kinematic analyses, anisotropy of magnetic susceptibility (AMS) is a powerful tool to perform strain determination even when macroscopic kinematic constraints are either absent of difficult to identify (Tarling and Hrouda, 1993; Sagnotti et al. 1994; Parés et al. 1999). Clustering of the longest axis of the AMS ellipsoid defines a magnetic lineation, which tends to orient sub-parallel to the maximum axis of the strain ellipsoid during deformation. As a first-order approximation, magnetic lineation is parallel to the shortening direction in compressive settings, or to the stretching direction in extensional regimes. With AMS analyses, it is therefore possible to calculate the style of tectonics (compressive versus extensional) and the shortening or stretching directions.

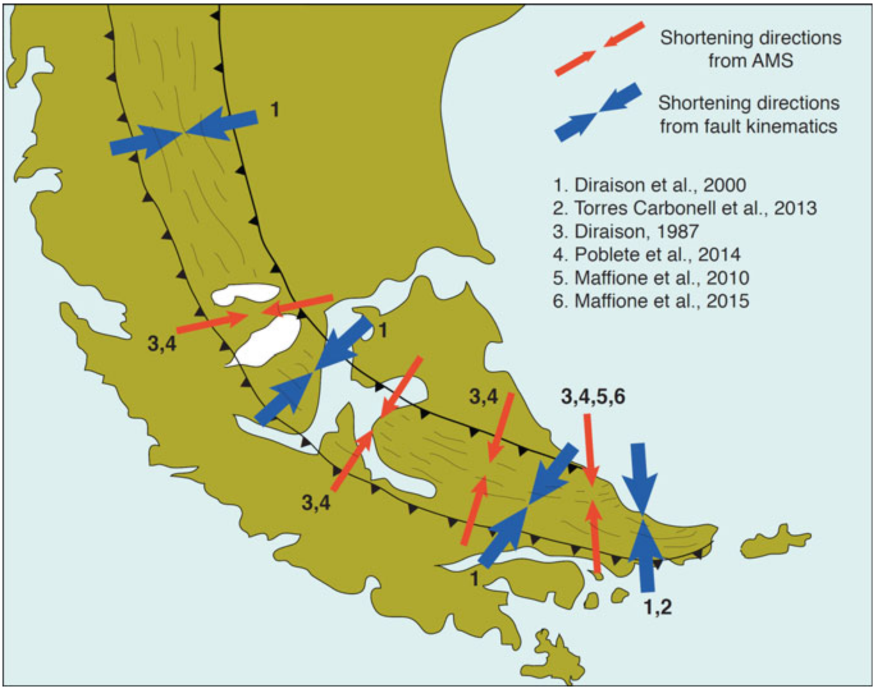

Fig. 3 Shortening directions in the southernmost Andes inferred from fault kinematics analyses (*blue arrows*) and anisotropy of magnetic susceptibility (AMS) analyses (*red arrows*)

Few AMS studies have been performed in the southernmost Andes (Diraison, 1998; Rapalini et al. 2005; Maffione et al. 2010, 2015; Esteban et al. 2011; Poblete et al. 2014). AMS analyses from the non-metamorphic sedimentary units of the Magallanes fold and thrust belt reveal the presence of well-developed magnetic lineations of clear compressive origin, which are sub-parallel to local faults and fold axes (see review by Maffione et al. 2015). These magnetic lineations change in direction following the curvature of the southernmost Andes and rotating from a ~N–S direction in the Southern Patagonian Andes to a ~NNE–SSW trend in the Fuegian Andes. Since the orientation of the AMS and strain ellipsoids are comparable, the lineations from the southernmost Andes identify a radial strain pattern where the shortening direction progressively rotate from ~ENE–WSW in the Southern Patagonian Andes to ~N–S in the eastern sectors of the Fuegian Andes (Fig. 3). Importantly, Maffione et al. (2015) show that this radial strain field was continuous in this region from the Early Cretaceous until at least the Oligocene (Fig. 4).

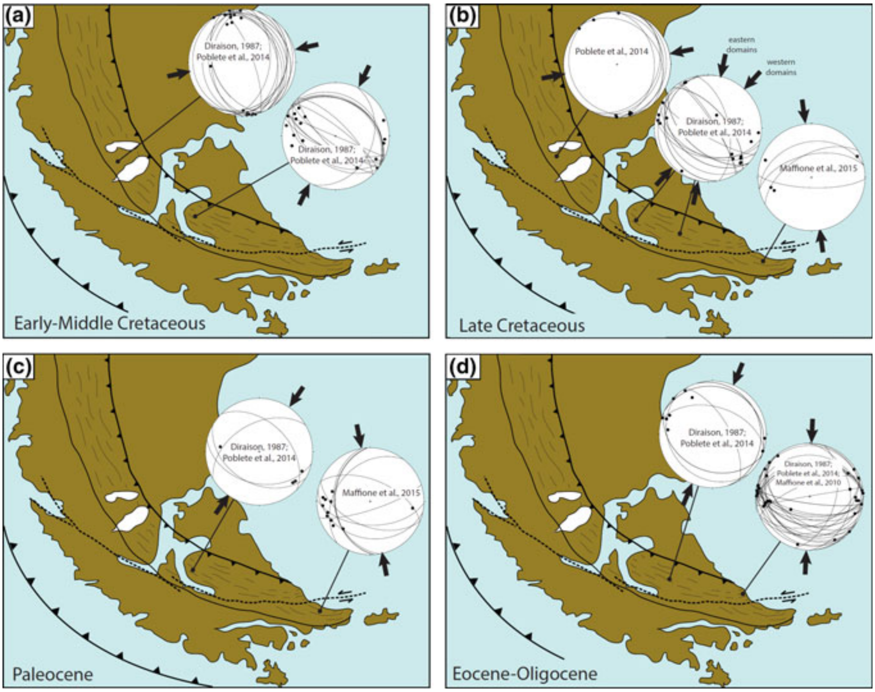

Fig. 4 Evolution of the paleostrain field (*black arrows* on the stereonets) within the Magallanes fold and thrust belt during four progressive time intervals, inferred from the published AMS data. Stereonets in each figure show the site mean lineations (*black dots*) and local bedding planes (*great circles*). Redrawn from Maffione et al. (2015)

7 Nature and Tectonic Evolution of the Curved Segment of the Southernmost Andes as Inferred from Available Paleomagnetic and Strain Constraints

Several hypotheses on the origin of the curvature of the southernmost Andes have been put forward since the 1950s in the absence of paleomagnetic and structural constraints. Early models considered the formation of the orogenic curvature as due to the drag associated with the left-lateral shearing between the South America and Scotia–Antarctic plates (Carey 1958; Winslow 1982). Paleomagnetic data obtained since the first study of Dalziel et al. (1973) have been crucial to provide a first-order reconstruction of the main tectonic events responsible for the present-day geometry of the southernmost Andes. However, although the amount and quality of data have recently increased, more than forty years of paleomagnetic investigations in the southernmost Andes have not yet been sufficient to provide a straightforward answer to the key question: Is the curved segment of the southernmost Andes (so far ambiguously called Patagonian orocline) a primary arc or an orocline? In other words, was the Fuegian Andes a southern extension of the ~N–S-oriented Patagonian Andes that acquired its present-day ESE–WNW trend after ~90° of CCW rigid block rotation?

The causes for such uncertainty are multiple. First and most important cause is the relatively poor quality of the paleomagnetic data. Early works (Dalziel et al. 1973; Burns et al. 1980), which more strongly supported an oroclinal model for the southernmost Andes, cannot be considered, as they do not satisfy modern reliability criteria. Also, rocks exposed in the most internal domains of the belt are either magmatic or metamorphic. Typical magmatic rocks sampled in the previous studies are plutons, dykes, and sills (Cunningham et al. 1991; Rapalini et al. 2001, 2004, 2005; Baraldo et al. 2002). None of these units provide paleohorizontal controls that are necessary to remove the effect of local tilt on the isolated paleomagnetic directions (Morris et al. 1998). Only tilt-corrected directions should be used to calculate the correct magnitude of vertical-axis rotation. Several more recent studies have however proposed that the inevitable scatter of paleomagnetic directions due to local tilt is minimized in large datasets (Poblete et al. 2014; Rapalini et al. 2015). On the other hand, where metamorphic rocks are sampled for paleomagnetic studies, the main issue is related to the definition of the age of magnetization (Cunningham et al. 1991; Rapalini et al. 2004, 2005). During high-temperature metamorphism (>500 °C), the original remanence is likely to be reset as soon as the Curie temperatures of the main magnetic carrier are exceeded, with acquisition of a new remanence at the end of the metamorphism event. Large age uncertainties on the remagnetization event can therefore bias the estimates on the timing of the tectonic rotations. Most of the remagnetized samples from the hinterland of the Fuegian Andes have probably been magnetically overprinted during the Late Cretaceous tectonic phase (Menichetti et al. 2008); still, a precise definition of the timing of the rotations cannot be achieved using metamorphic rocks.

A second issue even when high-quality paleomagnetic data are available is the distinction between regional and local tectonic rotations. The southernmost sector of the Fuegian Andes was affected by widespread left-lateral strike-slip tectonics (Cunningham 1993; Diraison et al. 2000; Menichetti et al. 2008). CCW vertical-axis rotations can be associated with sinistral strike-slip faults. The tectonic rotations documented in the southern Patagonian Andes by Iglesia-Llanos et al. (2003) and Rapalini et al. (2001) are a typical example of rotation associated with local faulting, and similar data should therefore not be used to test the orocline hypothesis (Rapalini 2007). Large strike-slip fault-related rotations have also been identified in the most internal domains of the belt along the southern shore of the Canal Beagle (Rapalini et al. 2015). Local deformation was also invoked as a possible cause of the ~20° CCW rotations in the southern sectors of the Magallanes fold and thrust belt (Poblete et al. 2014).

Finally, a third potential cause for the ongoing debate on the nature of the curvature of the southernmost Andes is the scarce and unevenly distributed paleomagnetic sampling coverage that still inhibits precise tectonic reconstructions by sheding uncertainties on the local versus regional character of the tectonic rotations.

So far, all three possible models have been proposed for the nature of the curvature of the southernmost Andes: primary or non-rotational arc (Diraison et al. 2000; Ramos and Aleman 2000; Ghiglione and Cristallini 2007), rotational arc or orocline sensu stricto (Dalziel and Elliot 1973; Burns et al. 1980; Cunningham et al. 1991; Kraemer 2003), and a 'hybrid' structure composed of a rotational and a non-rotational arc (Poblete et al. 2014; Maffione et al. 2015; Rapalini et al. 2015). What seems to emerge from the most recent paleomagnetic and structural geological data is that the hybrid model seems the most plausible possibility.

Although, as discussed, paleomagnetic data from Burns et al. (1980) cannot be used for tectonic interpretation, these authors were the first to put forward the hypothesis of a systematic pattern in the Fuegian Andes in which the magnitude of rotations decreased northward from a maximum value of ~90° comparable with the interlimb angle between the Patagonian and Fuegian Andes. The available paleomagnetic data seem to confirm this scenario with ~90° of CCW rotation of the southernmost (most internal) domains of the Fuegian Andes (Cunningham et al. 1991), ~30° of CCW rotations in the central belt where metamorphic sedimentary and magmatic rocks are exposed (Baraldo et al. 2002; Rapalini et al. 2015), and little (~20° CCW; Poblete et al. 2014) or no rotation (Maffione et al. 2010) affecting the non-metamorphic sedimentary sequences of the Magallanes fold and thrust belt in the most external domains of the belt. Furthermore, the timing of the rotations appears to decrease northward, from post-mid-Late Cretaceous (~90 Ma) in the south to post-Late Cretaceous (~72 Ma) in the central belt, and to post-Paleocene (~65 Ma) until ~50 Ma in the fold and thrust belt. Similar patterns of magnitude and timing of rotations are commonly found in fold and thrust belts like the Southern Apennines (Italy), where the magnitude of the rotations decrease from the firstly deformed nappes from the most internal paleogeographic domains to the youngest nappes from the frontal part of the belt (e.g., Maffione et al. 2013). This mechanism is typical of progressive arcs (sensu Weil and Sussman 2004) in which the tectonic rotations accompany the propagation of the orogenic front into the foreland. Based on the sparse data from the Fuegian Andes, it can only be speculated that a similar mechanism occurred here. According to this scenario, the largest rotations in Peninsula Hardy from the innermost domains of the belt (Cunningham et al. 1991) would be the effect of initial compressive deformation of the most internal paleogeographic domains.

Most of the tectonic models explaining the evolution of the curvature of the southernmost Andes invoked the closure of the Rocas Verdes marginal basin as a possible cause (Burns et al. 1980; Cunningham et al. 1991; Kraemer 2003; Maffione et al. 2010, 2015; Poblete et al. 2014; Rapalini et al. 2015). According to these reconstructions, at the beginning of the southern Andean orogeny (~100 Ma), the Jurassic magmatic arc (Patagonian Batholith) formed a relatively straight structure along the Pacific coast, bounding a triangle-shaped marginal basin to the west. Closure of the marginal basin occurred by continuous CCW rotation of the southern segment of the magmatic arc, leading to progressive nappe stacking in the basin's sedimentary cover until the magmatic arc collided with the South American continental margin in the Late Cretaceous. It is therefore plausible that during this event, tectonic slices originally rooted in different paleogeographic domains of the basin recorded different amounts of rotation. After continental collision, rigid rotation of what is today the Fuegian Andes might have continued for few million years progressively involving more external paleogeographic domains. Evidence against this reconstruction is the magnitude of shortening along the Fuegian Andes. Although shortening increases from west to east (Diraison et al. 2000), the magnitude of the gradient is not enough to explain a ~90° bending, as inferred from paleomagnetic data (Cunningham et al. 1991) and the overall geometry of the southernmost Andes. The total amount of oroclinal bending remains therefore unclear.

The beginning of a possible rigid block rotation of the Fuegian Andes is constrained to a general Late Cretaceous time due to remagnetization of the rocks exposed in this region (Cunningham et al. 1991). Conversely, the end of the rotations is more precisely constrained at ~50 Ma by paleomagnetic data from the Cenozoic Magallanes fold and thrust belt (Maffione et al. 2010). These data for the first time proved that no rotations were produced during the deformation of the Magallanes-Austral foreland basin since ~50 Ma. Minor (~20°) post-65 Ma CCW rotations documented by Poblete et al. (2014), of possible local origin, seem to confirm this trend. Assuming that the formation of the Magallanes fold and thrust belt started at ~61 Ma (Ghiglione and Ramos 2005) or slightly earlier (Torres Carbonell et al. 2013) and ended in the Early Miocene, the absence of tectonic rotations since 50 Ma (and possibly 65 Ma) classifies this curved belt as a primary (non-rotational) arc.

Combining all the available paleomagnetic data, a complex tectonic evolution of the curved segment of the southernmost Andes emerges. What has been so far implicitly defined as an orocline due to its more popular name of Patagonian orocline is more likely a hybrid orogenic arc composed of two parts: an older orocline or progressive arc in the outer side of the curvature, mainly formed in Cretaceous times upon closure of the Rocas Verdes marginal basin, and a younger primary arc in the inner side of the orogenic arc, developed in the Cenozoic (Poblete et al. 2014; Maffione et al. 2015). For this reason, Maffione et al. (2015) have recently proposed to use the more generic name of 'Patagonian Arc' to describe the curved segment of the southernmost Andes.

Precise discrimination between temporal and geographical patterns of oroclinal bending is still necessary to validate this model.

8 Mechanisms of Bending of the Southernmost Andes

Considering the hypothesis that the southernmost Andes form a hybrid orogenic arc, it is likely that different tectonic processes contributed to their formation. As previously mentioned, oroclinal bending of the outer part of the arc has been commonly associated with the closure of the Rocas Verdes marginal basin in the mid-Late Cretaceous. Reconstructing the evolution of the primary arc in the inner side of the orogenic curvature is much more complicated once strain data from fault kinematics, AMS, and analogue experiments are taken into account. The first high-resolution structural model for the Patagonian bending taking into account faults kinematics and Cenozoic brittle faulting was proposed by Cunningham (1993). This author proposed the Patagonian orocline to be the product of broad interplate shearing accommodated by strike-slip faulting, block rotation, and contraction, i.e., the strike-slip orocline model. However, this model implies a succession of E–W-oriented, left-lateral faults cutting the trend of folds and thrusts transversally to the orogen; the strike-slip faults recognized so far in the southernmost Andes are orogen-parallel; and faults and folds are continuous along strike (Figs. 2 and 3) (Ghiglione and Cristallini 2007).

Analogue sandbox experiments were performed by Ghiglione and Cristallini (2007) using both indentation of a curved rigid buttress and rotation of one arm of the indenter. Models using indentation of a rigid indenter provided the most consistent results with the geological evidence. In particular, these authors concluded that a two-phase indentation, NE-ward and then ESE-ward, was able to reproduce with a higher detail the deformation pattern observed in the fold and thrust belt. The deformation paths produced by this model are, however, not entirely consistent with the shortening directions from fault kinematic analysis reported by Diraison et al. (2000). While shortening directions show a progressive variation along the orogenic arc (Fig. 3), the models of Ghiglione and Cristallini (2007) indicate the formation of two distinct, overlapping families of shortening directions parallel to the motion of the indenter.

When shortening directions from both fault kinematic and AMS analysis are considered, a clear pattern emerges, defined by Maffione et al. (2015) as a radial strain field (Figs. 3 and 4). Different processes, other than oroclinal bending, need to be found to explain the presence of a radial strain field in a primary (non-rotational) arc such as the Magallanes fold and thrust belt. Although radial strain patterns have been documented in primary arcs, caused by, e.g., gravitational forces within the growing wedge (Ramsay 1981; Marshak 2004; Weil et al. 2010), extreme ~90° variation of the shortening directions as observed in the southernmost Andes is likely caused by more complex tectonic processes. Paleomagnetic data from Rapalini et al. (2015) indicate a post-72 Ma CCW rotation of ~30° in the central belt just south of the Magallanes fold and thrust belt. This result suggests that minor rotations could have occurred before the beginning of deformation in the foreland basin at ~60 Ma (Ghiglione and Ramos 2005). A rigid indenter model like that proposed by Ghiglione and Cristallini (2007), where an already curved proto-Andes converged during the Cenozoic into the Magallanes-Austral foreland basin to produce a thin-skinned fold and thrust belt, has been considered as a plausible scenario (Maffione et al. 2015).

Simple convergence of a rigid indenter cannot produce a radial strain field (Ghiglione and Cristallini 2007). A two-phase indentation mechanism, as already discussed, is inconsistent with both the pattern of shortening directions and the geological evidence that seems to indicate continuous deformation along both branches of the orogenic arc during the Cenozoic (Maffione et al. 2015).

Maffione et al. (2015) proposed that a radial strain field could be produced upon indentation of a curved rigid buttress if slip partitioning operated along preexisting faults oriented parallel to the margin of the indenter. Jurassic normal faults rooted in the basement of the South American continental margin played a key role in the evolution of the Magallanes-Austral foreland basin sedimentation and subsequent deformation (Menichetti et al. 2008; Likerman et al. 2013; Fosdick et al. 2011, 2014; Ghiglione et al. 2013). The occurrence of ∼N–S-oriented normal faults in the Southern Patagonian Andes and ∼E to NE oriented in the Fuegian Andes associated with the rifting of the Rocas Verdes basin has also been documented (Ghiglione et al. 2009, 2013; Fosdick et al. 2011; Likerman et al. 2013). Based on this evidence, Maffione et al. (2015) proposed that the preexisting Jurassic faults in the basement of the southernmost Andes controlled the Late Cretaceous to Cenozoic kinematic evolution and final geometry of the curved Magallanes fold and thrust belt (Fig. 5). Slip-partitioning mechanisms along these faulted blocks in the central belt allowed

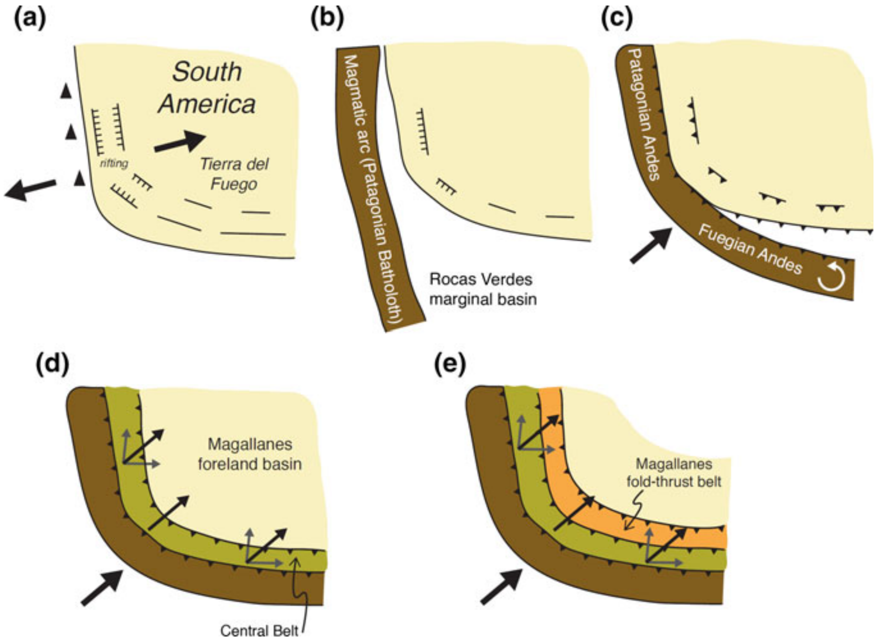

Fig. 5 Kinematic model for the evolution of the southernmost Andes from the Middle Jurassic to the Oligocene proposed by Maffione et al. (2015). *Thick black arrows* indicate the direction of the regional stress field. **a** *Black triangles* indicate active magmatism. **c** *Circular white arrow* indicates the regional vertical-axis rotation of the Fuegian Andes during the closure of the Rocas Verdes basin. **d**, **e** *Thin black arrows* indicate the displacement vectors of the basement-rooted faulted blocks within the central belt; *thin gray arrows* indicate the fault-parallel and fault-perpendicular components resulting from slip partitioning propagating into the Magallanes-Austral foreland basin and leading to the formation of the fold and thrust belt. Redrawn from Maffione et al. (2015). **a** Mid-Late Jurassic, **b** Late Jurassic, **c** Early Late Cretaceous, **d** Middle Late Cretaceous, **e** Paleocene–Oligocene

transference of fault-normal compression components into the Magallanes-Austral foreland (~N-ward and ~E-ward contraction in the Fuegian and Patagonian Andes, respectively) throughout the Cenozoic, resulting in a radial strain field.

9 Conclusive Remarks

Since its first definition as Patagonian orocline by Carey (1958), the real nature and evolution of the regional-scale curvature of the southernmost Andes have been controversial. The debate revolved around the two conflicting hypotheses considering the curvature of the southernmost Andes either as a non-rotational (primary) arc, or a rotational arc (i.e., orocline or progressive arc). The curved shape of the Antarctic Peninsula and the growth during the Cenozoic of a new oceanic plate (Scotia plate) intervening between the South American and Antarctic plate were used as evidence at the basis of early tectonic models. With time, most of the early models resulted to be imprecise. Only with the acquisition of the first paleomagnetic data from the southernmost Andes, the debate on the nature of its curvature was resumed, continuing until today.

The mechanism proposed by Maffione et al. (2015) requires widespread sinistral and dextral strike-slip displacements on main thrusts from the internal domains of the Fuegian and Patagonian Andes, respectively. Further data identifying and quantifying such strike-slip tectonics in the southernmost Andes are, however, needed to fully test the proposed model.

Although more than 40 years of paleomagnetic investigation in the southernmost Andes has provided key constraints to define the timing, style, and kinematics of deformation in this region, their number and quality are still too low to allow detailed reconstructions. The available paleomagnetic data indicate that ~90° of CCW vertical-axis rotation affected the most internal structural domain of the Fuegian Andes (i.e., the outer part of the curvature) since ~90 Ma, ~30° of which occurred after ~72 Ma, and that rotations in the Magallanes fold and thrust belt (i.e., the inner part of the curvature) ended at ~50 Ma. Although these data are affected by uncertainties related to the age of magnetization, the absence of paleohorizontal control, and a poor stability of the magnetic remanence, an overall pattern of CCW rotations in the internal sectors of the belt appear evident, while rotations did not affect the Magallanes fold and thrust belt at least since the Early Eocene. These data suggest that the outer part of the curvature represents an orocline or a progressive arc (sensu Weil and Sussman 2004). Definition of precise timing and total amount of the bending awaits further investigations. On the other side, the absence of tectonic rotations in the Magallanes fold and thrust belt indicates that it developed in the Cenozoic as a primary arc (sensu Weil and Sussman 2004).

Based on the available paleomagnetic constraints and the most recent tectonic models, the broadly used term of 'Patagonian orocline' appears to be outdated and inappropriate. According to formal definitions (e.g., Weil and Sussman 2004), an orocline is a large-scale curved mountain belt formed upon bending of a previously straight orogen. This definition, as demonstrated, may only apply to the outer side of the curvature of the southernmost Andes, being the inner side a primary arc. As recently proposed by several authors (Poblete et al. 2014; Maffione et al. 2015), the orogenic bend of the southernmost Andes is composed of two adjacent arcs: a rotational arc (orocline or progressive arc) and a non-rotational arc (primary arc) in the outer and inner part of the curvature, respectively. For this reason, Maffione et al. (2015) suggested that the old term 'Patagonian orocline' should be abandoned in favor of a more generic 'Patagonian Arc'.

A broad consensus exists that invokes the closure of the Rocas Verdes marginal basin in the Late Cretaceous as the main mechanism of oroclinal bending of the internal sectors of the southernmost Andes. More uncertain is the evolution of the primary arc of the Magallanes fold and thrust belt. Proposed scenarios to explain the formation of the curved fold and thrust belt, in the context of a primary arc model, considered indentation of a curved rigid buttress (represented by the previously bent internal domains of the southernmost Andes) into the foreland sediments of the Magallanes-Austral basin. The presence of highly variable (radial pattern) shortening directions along the Magallanes fold and thrust belt (Maffione et al. 2015), uncommon in primary arcs, has been explained by the possible effect of slip partitioning along preexisting Jurassic faults at the South American margin, which could have enabled ~N-ward contraction in the Fuegian Andes and ~E-ward contraction in the Patagonian Andes. A slip-partitioning model in the southernmost Andes requires widespread strike-slip tectonics with dextral and sinistral kinematics in the Patagonian and Fuegian Andes, respectively. Future investigations are needed to test the occurrence of such tectonics and validate this model.

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