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Patagonia: A paleozoic continent adrift?

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ABSTRACT

The evolution of Patagonia as an independent and exotic microcontinent from the rest of South America was a recurrent hypothesis since the XIX century, reaching notoriety during the discussion times of continental drift theory. The arrival of plate tectonics triggered different hypotheses, some of them with fixist interpretations that consider Patagonia as an autochthonous part of Gondwana, and others more mobilistic that postulate an allochthonous origin. After several decades, although some consensus exists among those hypotheses that postulate its allochthony, there is no agreement in its boundaries, subduction, accretion, and final amalgamation times to the Gondwana supercontinent. In this review the different magmatic belts are analyzed, their deformation and metamorphism, the associated sedimentary basins, as well as the existing geochronologic controls. Aware that important uncertainties still remain, a new model is proposed with two magmatic arcs: a western belt that was active from the Devonian to the mid Carboniferous, and a northern one partially coeval that led to the collision of Patagonia against the southwestern margin of Gondwana in the Lower Permian. It is hypothesized that the termination of the western magmatic arc activity was linked to the collision of the Antarctic Peninsula and associated terranes. The reconstruction of the plate tectonic history of Patagonia during the Paleozoic shows the existence of several episodes of fragmentation and rifting, convergence and accretion, renewed periods of rifting and reaccretion to the Gondwana margin. Those processes were intrinsic to the formation of Terra Australis orogen, controlled by the absolute motion of the Gondwana supercontinent and guided by successive global plate reorganizations.

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RESUMEN

La evolución de la Patagonia como un continente independiente y exótico al resto de América del Sur ha sido una hipótesis recurrente desde el Siglo XIX, alcanzando notoriedad durante los tiempos de la discusión de la teoría de la deriva continental. Con el advenimiento de la tectónica de placas cobró nuevo impulso, dividiéndose las interpretaciones en una serie de hipótesis fijistas que la consideraron como parte autóctona del Gondwana y en otras más movilistas que postularon un origen alóctono. Después de varias décadas, si bien ha ganado consenso las hipótesis que postulan su aloctonía, no hay acuerdo en sus límites, tiempos de subducción, acreción y amalgamiento final al supercontinente de Gondwana. En esta revisión se analizan las diferentes fajas magmáticas, su metamorfismo y deformación, las cuencas sedimentarias asociadas, así como los controles geocronológicos existentes. Consciente que aún quedan notables incertidumbres se propone un modelo con dos arcos magmáticos: uno occidental que fue activo desde el Devónico hasta el Carbonífero medio, y otro que se traslapó parcialmente en el tiempo y que lleva a la colisión de la Patagonia contra el margen sudoccidental del Gondwana en el Pérmico inferior. Se hipotetiza que el cese de la actividad del arco magmático occidental estuvo ligado a la colisión del basamento de la Península Antártica y terrenos asociados. La reconstrucción de la historia tectónica de placas durante el Paleozoico pone en evidencia la existencia de varios episodios de ruptura y rifting, convergencia y acreción, renovados períodos de rifting y reacreción al margen del Gondwana. Estos procesos son intrínsecos a la formación del orógeno de Terra Australis, controlados por el movimiento absoluto del supercontinente de Gondwana y guiados por sucesivas reorganizaciones globales de las placas.

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1. Introduction

Patagonia, one of the less populated areas of South America, and a vast semidesert land in a cold to temperate region, was the inspiration for many unusual hypotheses on its geologic origin. The region south of the Río Colorado (see Fig. 1), attracted the premature attention of eminent naturalists such as the Perito Francisco P. Moreno as early as in the XIX century, who wondered about the "exotic nature" of its landscape and flora. He emphasized its closest connections with the Antarctica Peninsula, Australia and New Zealand, and he wondered why some landscapes and rocks of Patagonia were so different from the rest of South America and strikingly similar, and with strong affinities, to the southern continents (Moreno, 1882). This hypothesis was reminded during the years of the continental drift discussion by Keidel (1925) and Windhausen (1931), who claimed with similar reasoning that Patagonia was an isolated continent during pre-Cretaceous times, and had been later welded to the rest of Gondwana. However, most of these speculations were based on a poor and incomplete knowledge of the processes related to continental drift, and do not resist a modern screening with the present knowledge of the region.

Paleocurrent studies in some Paleozoic basins along the coast in southern Peru were consistent with an apparent provenance of Devonian sediments from the Pacific side (Martínez, 1980). This last author to explain these observations resuscitated the old hypothesis of a Pacifica continent of Burckhardt (1902). Although the original proposal was based on the geosynclinal theory that required an inner supply of sediments in the orogenic stage, Martínez (1980) speculated that a displaced Patagonia could be the source of these sediments. This proposal produced a new wave of hypotheses that tried to evaluate via paleomagnetic studies the apparent post-Devonian displacements of Patagonia (Valencio and Vilas, 1985). However, the present knowledge of processes such as tectonic erosion by subduction, or vertical axis rotation of the studied blocks, could easily negate all these proposals.

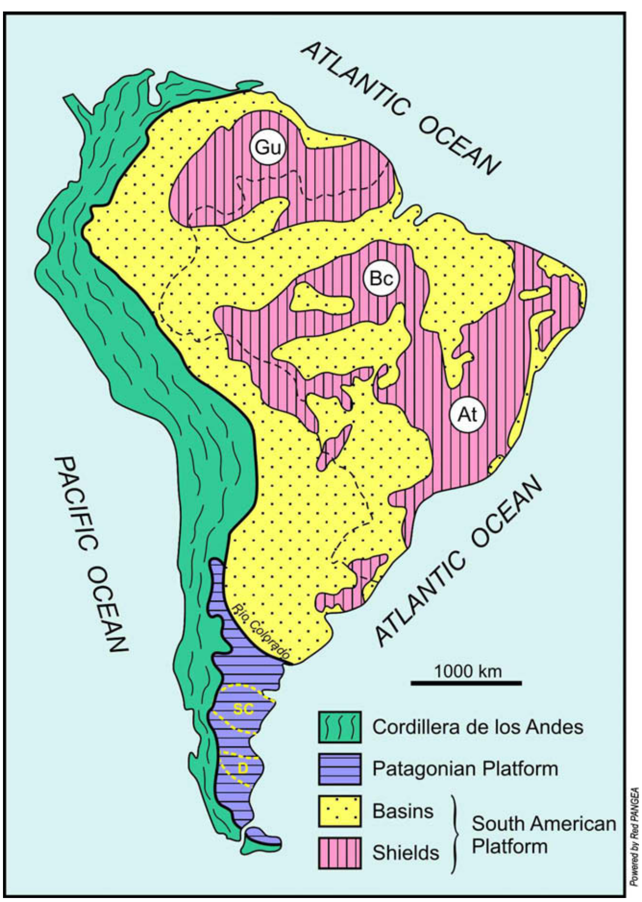

Fig. 1. Regional location of the Patagonia Platform with most important basement massifs: the Deseado (D) and Somún Cura (SC). Gu: Guyana, Bc: Brasil Central, At: Atlántico (based on Almeida et al., 1976).

The first modern ideas that tried to explain some peculiar geologic and tectonic features of Patagonia were proposed by Frutos and Tobar (1975). These authors were the first to envisage that the Deseado and Somún Cura massifs were separated by an early Paleozoic subduction zone (Fig. 2a). That inference was based on structural studies of the oblique NW-trending penetrative fabrics of some metamorphic rocks of the Deseado massif, in contrast with the dominant north-trending structures of the Andean basement. This hypothesis, but based on different criteria, has been revisited by Gallagher (1990) who proposed that the Deseado Massif was accreted to Gondwana during Carboniferous times, in a similar way to that proposed more recently by Pankhurst et al. (2006).

Most of the studies performed at continental scale on the origin of the South American basement noted the differences between the Brazilian (or South American) platform (Fig. 1), amalgamated and consolidated as a craton by the end of the Proterozoic and Patagonia consolidated during the Paleozoic (Almeida et al., 1976). Two basement massifs were differentiated in Patagonia by Harrington (1962) who described them as nesocratons, basement areas remobilized during the Paleozoic orogenies.

The development of the terrane concept by Monger et al. (1982) fostered some new ideas about the origin of Patagonia. Soon after that proposal, complemented by the suspect terrane notion proposed by Coney et al. (1980), two different points of view were continuously debated. Some authors favored the autochthony of the Patagonian block (eg. Forsythe, 1982) while others interpreted the Patagonia as an accreted terrane (Ramos, 1984, 1986). These conflicting hypotheses stimulated more than 20 years of active research, discussion and collection of new data on the Patagonian basement (see Fig. 2b and c).

2. General features of patagonia

There are several ways to define the extension and limits of Patagonia on geological, geophysical and geographic grounds. The continent–ocean transition along the Atlantic sea is the natural eastern border, while the southern Andes are the western limit, although the region west of the main cordillera is also sometimes included as part of Patagonia. A focused study by the Geological Survey of Argentina determined that the characteristics of the basement, changes in crustal thickness, important truncations by N70°W-trending lineaments of the north–south fabrics of the northern basement, and other geological and geophysical features, complemented by historical grounds, defined the northern limit of Patagonia as indicated in Fig. 3 (see discussion in Ramos et al., 2004).

Based on these criteria, the Patagonia geological province encompasses a series of basement outcrops, mainly exposed along the eastern side of the Andes, which can be grouped in two distinct massifs following Leanza (1958) and Harrington (1962): the Somún Cura and Deseado massifs.

The northern block known as the Somún Cura (or northern Patagonian) massif is bounded in the north by the Neuquén and Colorado basins (Fig. 3). However, the basement of the southern one third of the Neuquén Basin has WNW-trending fabrics, which control the orientation of the Huincul ridge, and has common basement fabrics with the Somún Cura Massif (Franzese and Spalletti, 2001; Mosquera and Ramos, 2006). The surface expression of this

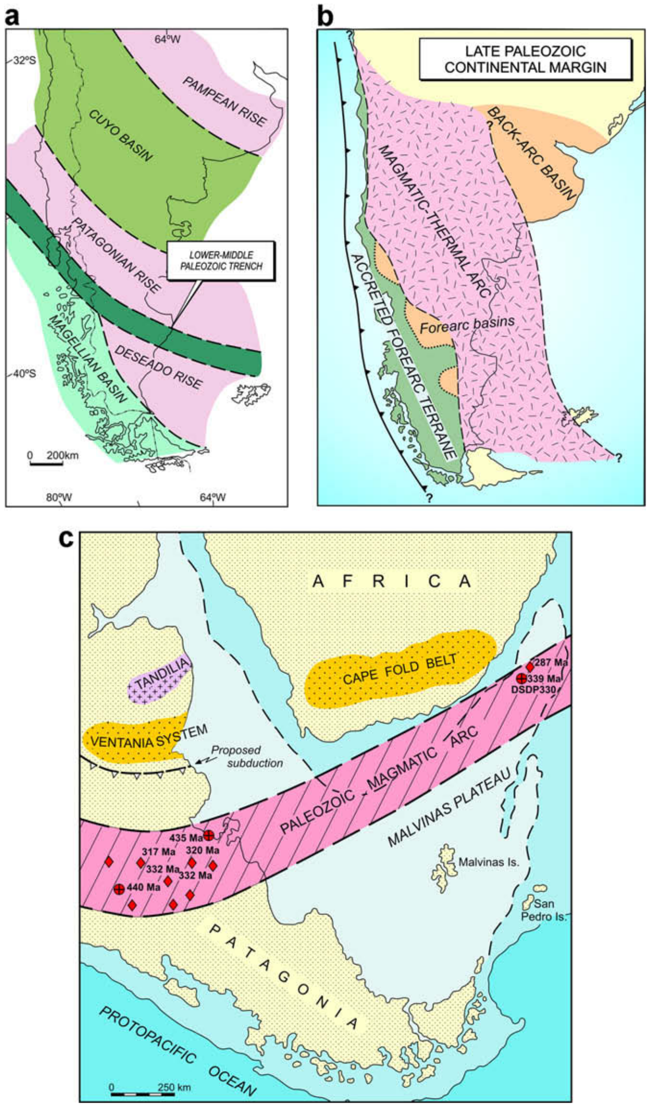

Fig. 2. (a) Early proposal where an early subduction zone split the Somún Cura and the Deseado Massifs, implying that the Deseado Massif was allochthonous (based on Frutos and Tobar (1975)); *pars* Pankhurst et al. (2006). (b) Autochthonous hypothesis where a wide magmatic arc crosses the entire Patagonia (Forsythe, 1982; Caminos and Llambías, 1984; Rapela et al., 1989; Dalla Salda et al., 1990, among others). (c) Allochthonous hypothesis proposed by Ramos (1984, 1986).

ridge and the subsurface evidence based on 3D seismic data, gravimetric and magnetometric surveys define the northernmost limits of Patagonia.

The Somún Cura Massif is bounded to the south by the Cañadón Asfalto Basin (Fígari, 2005). This basin was formed by NE–SW extension prior to 160 Ma during the opening of the Weddell Sea (Ghidella et al., 2002; Ramos, 2004a). The Cañadón Asfalto Basin extends to the north beneath the basalts of the central part of Somún Cura as noted by Cortiñas (1996). This author proposed that the Somún Cura is formed by two highs, one in the north with an east–west trend, and another with a N30°W trend, defined as the Chubut high, consistent with the two igneous–metamorphic belts identified in the present work (see Fig. 5). The present southern border is enhanced by the subsidence of the San Jorge Basin, which is interpreted as an aulacogen (De Wit, 1977; Fitzgerald et al., 1990; Ramos, 1996) formed as a consequence of the Weddell Sea opening, and reactivated during the opening of the South Atlantic.

The Deseado Massif is exposed south of the San Jorge Basin and is bounded by the Austral (or Magallanes) Basin to the south (Fig. 3). Consequently, the Patagonia is composed by two large basement massifs, bounded by Mesozoic basins, which were mildly deformed by the Andean orogeny (Ramos, 2004b).

3. The basement of Patagonia

The basement of northern Patagonia have been extensively studied by Caminos and Llambías (1984), Rapela and Llambías (1985), Rapela and Caminos (1987), Dalla Salda et al. (1992a,b, 1994), Von Gosen (2002, 2003), Varela et al. (2005, 2007), and Pankhurst et al. (2006), among others. These studies allow the definition of two different metamorphic and magmatic belts: the northern and the western belts. The northern metamorphic and magmatic belt is preserved parallel to the southern margin of the Neuquén and Colorado basins along the Río Limay valley from the city of Bariloche in the west up to the Sierra Grande region along the Atlantic coast (Varela et al., 1998a; Basei et al., 1999). The western metamorphic and magmatic belt crosses the central Patagonia with a north–northwestern trend and continues into the Deseado Massif and further south.

3.1. The northern magmatic and metamorphic belt

This belt of metamorphic and igneous rocks with a dominant NW to WNW trend, is well exposed along the Río Limay valley and in La Esperanza, Yaminué, Valcheta, Mina Gonzalito, and Sierra Grande regions. The main foliation of these rocks nearby Bariloche has a top-to-the-east and northeast vergence (Heredia et al., 2006).

The eastern sector of the belt has Ordovician granitoids, well known since the early work of Weber (1983) and Ramos (1984). Recent studies, with more precise U–Pb and SHRIMP data indicate crystallization ages of 475 ± 6 Ma and 476 ± 4 Ma for granitic rocks of Arroyo Salado and Sierra Grande (Varela et al., 1998a, 2005, 2007; Pankhurst et al., 2006).

The host rocks of these intrusives are metamorphic rocks in amphibolite facies, well represented by the Mina Gonzalito Gneiss (Ramos, 1975) (Fig. 4) which has metamorphic zircons dated by U–Pb. The metamorphic peak of these rocks has 468.7 ± 4.3 Ma (Pankhurst et al., 2001), age similar to some previous Rb–Sr ages obtained for these metamorphic rocks (Varela et al., 1997, 1998a, 2005). Some associated low grade schists as the El Jagüelito Ectinites have an ichnofauna that help to constrain the age of deposition between Cambrian and Early Ordovician (González et al., 2002). The geochemical study of these low grade metamorphic rocks of the eastern sector shows derivation from marine facies associated with a magmatic arc in an attenuated continental crust setting (Cagnoni et al., 1993). The inherited zircons of these rocks (Fig. 4) have an important Neoproterozoic contribution, indicating a Brasiliano–Panafrican source, which possibly implies a para-autochthonous origin within Gondwana for the Somún Cura Massif.

These metamorphic rocks have been recently studied at Yaminué (Fig. 5), where Llambías et al. (2002) described Late Carboniferous orthogneisses metamorphosed in amphibolite facies, emplaced by undeformed Late Permian granitoids. The host rock of the orthogneisses is amphibolite, marble and phyllite of possibly early Paleozoic age which are unconformably covered by the Sierra Grande Formation, a series of orthoquartzites deposited in a passive margin setting. This last unit of Silurian to Early Devonian age has a ductile deformation with thrusts with top-to-the-south vergence (Von Gosen, 2003). There are also several mylonitic belts with ductile deformation that affected the Carboniferous–Early Permian rocks. U–Pb dating in the Yaminué region indicates 295 ± 13 Ma

Fig. 3. Main topographic features of Patagonia and surrounding areas.

in Puesto Peynecura, 307 ± 23 Ma in Treneta, and 300 ± 6 Ma in Puesto Tardugno (Varela et al., 1998b). Most of these igneous rocks are preserved as orthogneisses and recent paleomagnetic studies have indicated, based on the magnetic fabric, an important ductile deformation consistent with a SW–NE compression (Rapalini et al., 2008). This magnetic fabric is absent in the Late Permian granites.

Similar mylonitic rocks are seen in Cerro Los Viejos, at the northern margin of the Colorado Basin (see Fig. 9 for location) which also record late Paleozoic ductile fabrics described by Tickyj et al. (1997), as part of the same late Paleozoic deformation. Metamorphic rocks, mainly granitoids and gneisses preserved in amphibolite facies in Cerro Los Viejos, have northwest-trending foliation with S–C structures that indicates a top-to-the-northeast vergence.

The age of the metamorphic rocks of the northern belt was traditionally assigned to the Precambrian along the Río Limay valley and in the Bariloche region, until the studies of Basei et al. (1999), who found a U–Pb age of 345 ± 4.3 Ma for an amphibolite south of Bariloche, and Varela et al. (1999), that reported an age of 292 ± 9 Ma for a tonalitic gneiss of Paso Flores both interpreted as ages of crystallization of the protolith (Fig. 5).

3.2. The western magmatic and metamorphic belt

A second and western belt of magmatic and metamorphic rocks is exposed from San Martín de Los Andes – Bariloche to Paso de Indios, along the Río Chico valley, with a NNW to NW trend identified as the Chubut basement ridge by Cortiñas (1996) depicted in Fig. 5. The presence of this magmatic arc along the eastern side of the Patagonian Cordillera was suggested by the K–Ar dating of 345 ± 10 Ma in Lago Lacar and 380 ± 15 Ma in Lago Puelo (Toubes and Spikermann, 1974; Lizuaín, 1981) and extended further south by Ramos (1983). These rocks were studied by Dalla Salda et al. (1992a) who obtained K–Ar ages of 354 ± 4 Ma and 324 ± 6 Ma for tonalitic gneisses, and 376 ± 9 Ma for a biotitic granodiorite in the Lago Lacar area, near San Martín de Los Andes. These Devonian to Carboniferous ages were interpreted as younger tectonothermal events affecting the early Paleozoic magmatic arc.

The age of the metamorphic rocks of this region was assumed to be either Precambrian or early Paleozoic until the geochronologic studies of Basei et al. (1999), that found 345 ± 4.3 Ma old zircons in an amphibolite in the Cañadón de la Mosca of the Bariloche region, which implies that these rocks have been metamorphosed in late Paleozoic times. Basei et al. (2005) based on conventional U–Pb zircon dating constrained the age of the plutonic rocks between 420 and 380 Ma. An age on U–Pb in titanite ca. 360 Ma together with K–Ar ages in the range of 375–310 Ma were interpreted as cooling ages of the metamorphic peak. Subsequent studies in the northern part of the western belt were able to recognize two distinct episodes and precisely date the igneous emplacement and the peak metamorphism of these rocks (Pankhurst et al., 2006).

Further south, these igneous–metamorphic complexes are exposed along the Río Chico valley, and were described by Dalla Salda et al. (1994). In this area, metamorphic rocks in greenschist to amphibolite facies are associated with foliated tonalites and granodiorites, mylonites and granitic cataclasites, formed in a collisional setting. The metamorphic grade increases to the east of the valley, and the protoliths of the metamorphic rocks are shales and graywackes. The main metamorphic episode is syntectonic with important anatexis, and has a N49–34°W-trending main foliation. Dalla Salda et al. (1994) supported a magmatic arc setting followed by a collisional episode based on geochemical and isoto-

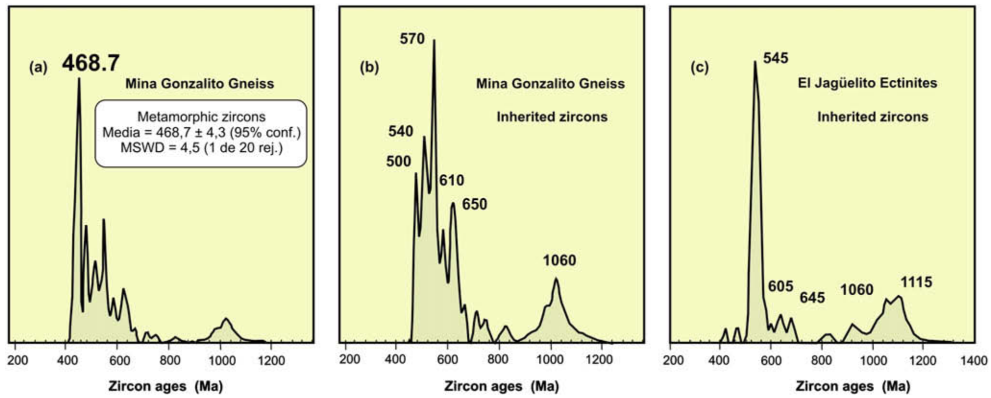

Fig. 4. Relative probability plot for the best-estimated ages derived from the Mina Gonzalito Gneiss and El Jaguelito Ectinites. (a) Age of metamorphism; (b) and (c) dominant inherited zircons of brasiliano events (based on Pankhurst et al., 2001).

pic grounds. Regional constraints indicate that coeval tonalites and granodiorites were emplaced along a decompressing path slightly postdating the climax of regional metamorphism in the basement, and that monzogranitic intrusion occurred at upper crustal levels (López de Lucchi et al., 1992; Dalla Salda et al., 1994; Cerredo and López de Luchi, 1998; López de Lucchi and Cerredo, 2008). The first reliable U–Pb ages were published by Varela et al. (2005). Recently a muscovite migmatite, west of Mamil Choique, has been dated by U–Pb in 281 ± 2 Ma (Pankhurst et al., 2006).

These igneous–metamorphic complexes permit identification of a belt of exposures of (Devonian) Carboniferous to Permian deformed rocks. In the north, the belt consists of two-mica granite of Piedra del Aguila with a U–Pb zircon age of 290 ± 3 Ma (Varela et al., 2005) and the La Potranca further south of the Río Chubut, with a deformed leucogranite associated with migmatite, dated by U–Pb in a 289 ± 2 Ma (Pankhurst et al., 2006).

The western igneous–metamorphic belt with its typical arc and collisional settings with a northwest-trending structure (see Fig. 5) has been precisely dated by Pankhurst et al. (2006). These authors indicate that the basement has experienced an important collision in the mid Carboniferous prior to the emplacement of peraluminous S-type garnet-bearing leucogranites of Paso del Sapo and Sierra de Pichiñanes which yielded 314 ± 2 Ma and 318 ± 2 Ma crystallization ages.

This belt of exposures is unconformably covered by the foreland continental Cretaceous deposits of the San Jorge Basin (Fig. 5). However, in the northern and southern flanks of this basin, several wells recovered cores of the late Paleozoic basement (Sylwan, 2001). Drilling cores of some of these wells have been dated by K–Ar yielding ages between Middle Carboniferous and Early Permian (Linares and González, 1990). The range of the drilling core ages is similar to the ages obtained in the exposures between Bariloche and Paso de Indios (see Fig. 5), and are along the same structural trend as the northern sector of this belt. Some wells north of Comodoro Rivadavia, to the east of this granitoid belt, reached the metamorphic basement composed of amphibolites of unknown age (Lesta et al., 1980).

Further south, the basement is again exposed in the Deseado Massif, where scattered exposures of granitoids and metamorphic rocks with the same NW trend occur (Giacosa and Márquez, 2002). Although available U–Pb zircon ages of the granitoids are mainly early Paleozoic, ranging in age between 472 and 454 Ma (Loske et al., 1999), some new SHRIMP data on these zircons yielded Devonian and Middle Carboniferous ages (Pankhurst et al., 2003). Based on the continuity of the magmatic belt with dominant northwest structures, and the range of U–Pb ages, it is assumed that the igneous and metamorphic western belt is connected through the San Jorge Basin with the Deseado Massif as depicted in Fig. 5. Most of these rocks are assumed to have been emplaced in a Precambrian basement. U–Pb SHRIMP data from zircons from the Dos Hermanos phyllites corroborate a typical Brasiliano age, with some strong inheritance of Grenville Middle Proterozoic zircons between 1000 and 1060 Ma (Fig. 6), similar to the age obtained in Cabo Belgrano (*Cape Meredith*) in the Malvinas (*Falkland*) Isles by Cingolani and Varela (1976).

It is interesting to mention that the western half of the La Modesta schists, also considered late Proterozoic based on some minimum K–Ar ages of 540 Ma (Pezzuchi, 1978), have been recently dated by U–Pb SHRIMP by Moreira et al. (2007). These authors found that the deposition of the muscovite–chlorite schists, metaquartzites, and tourmalinite strata-bound schists, was no older than ~473 Ma, and that the source of the zircons was probably the granitoids exposed to the east. They also found inherited zircons of Brasiliano and Grenville age similar to the Dos Hermanos phyllite, together with older zircons (Moreira et al., 2007). This clearly indicates that deposition and low grade metamorphism of La Modesta schists are younger than Middle Ordovician.

Thick sequences of Carboniferous to Early Permian graywackes, shales and diamictites of the Tepuel Basin are exposed west of the igneous–metamorphic belt between Esquel and José de San Martín (Page et al., 1984; Andreis et al., 1987). These foreland basin deposits reaching more than 5000 m (López Gamundi and Breitkreuz, 1997) continue in the subsurface of the San Jorge Basin, where they have been described in the Pastos Blancos well by Cortiñas and Arbe (1982). Sedimentological analyses indicate submarine fans prograding to deltaic systems that up-sequence culminate in fluvial continental deposits (López Gamundi and Limarino, 1985). The outcrops have dominant paleocurrents from northeast to southwest, which are also observed in the subsurface data (Cortiñas and Arbe, 1982). The Early-Middle Carboniferous to Early Permian deposition age is based on the brachiopod fauna (Andreis et al., 1987). The rocks are mildly deformed and in general postdate an early Paleozoic deformation. These deposits are intruded by tholeiitic gabbros with K–Ar ages of 211–243 Ma, which are interpreted as minimum ages due to the very low-K contents of the gabbros (Page, 1984; Poma, 1986). These authors interpreted the magmatic suites as to have been emplaced in an extensional setting. Dominant vergence is toward the southwest. The tectonic setting of these sequences was interpreted as forearc (Forsythe, 1982; Uliana and Biddle, 1987); marginal basin on attenuated crust (Ramos, 1983; Page, 1984); forearc to foreland (López Gamundi and Breitkreuz, 1997), and collisional foreland (Pankhurst et al., 2006).

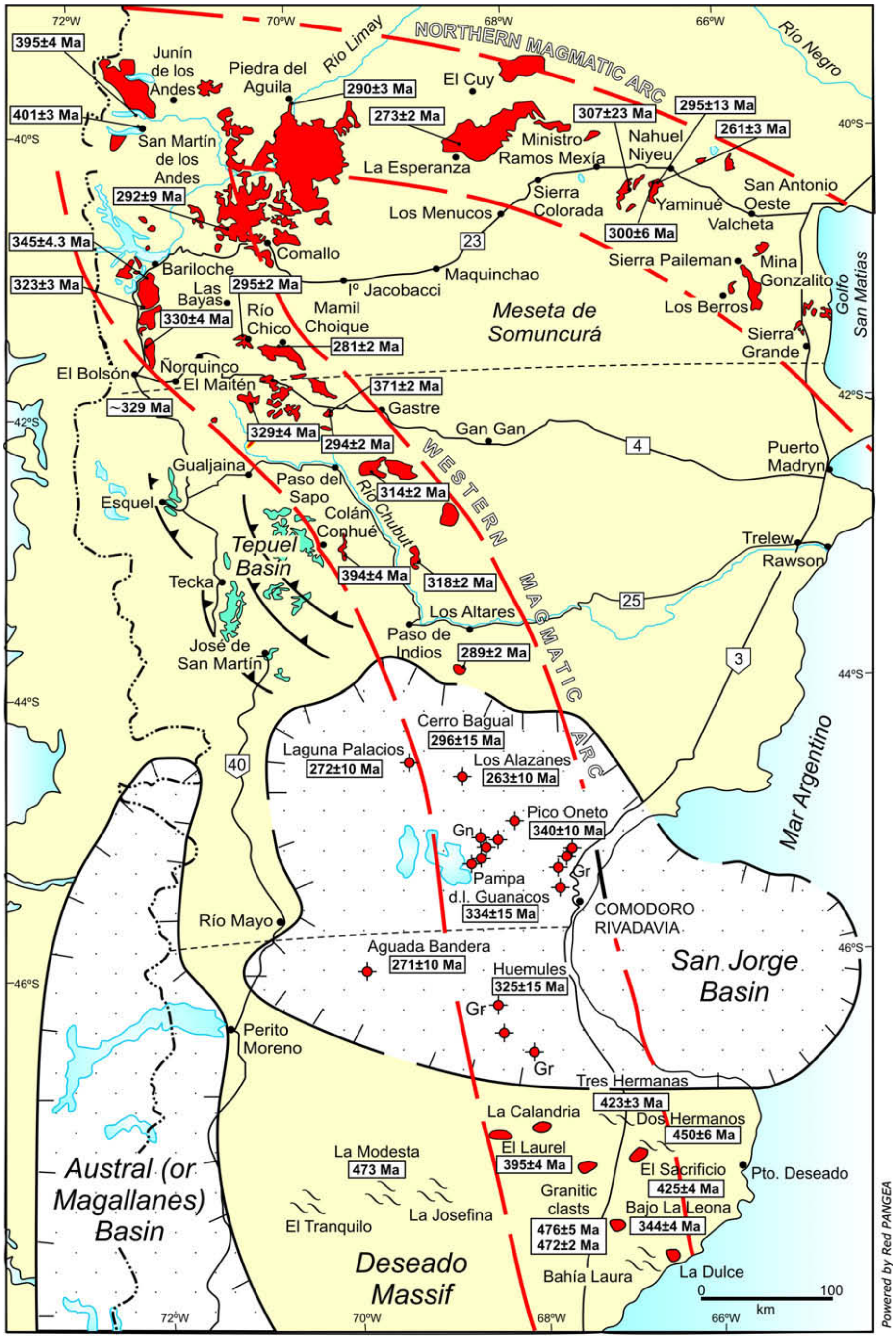

Fig. 5. Exposures of magmatic rocks of the northern and western belts of the Somún Cura Massif based on Cortiñas (1996), and extension of the western belt in the Deseado Massif. U–Pb ages in the northern belt are mainly based on Basei et al. (1999, 2005) and Varela et al. (1998a,b, 1999, 2005, 2007). The U–Pb ages in the western belt are mainly from Varela et al. (2005) and Pankhurst et al. (2003, 2006). The subsurface K–Ar ages from drilling cores are from Lesta et al. (1980), Linares and González (1990), and location of the wells from Sylwan (2001).

A key basin to understand the geologic setting for the Permian in the Deseado Massif is the La Golondrina Basin, best exposed in the proximity of Dos Hermanos, Bajo La Leona and La Dulce (see for location Fig. 5). Continental conglomerates, sandstones, and siltstones up to 2500 m thick, were deposited in half graben systems, with abundant flora that indicates an Early to Late Permian age (Bellosi and Jalfin, 1989). This basin has been interpreted as a rift by Ramos and Palma (1996), an interpretation consistent with the seismic expression depicted by Homovc and Constantini (2001). These authors illustrate an important Permian rift, a Triassic sag sequence and reactivated extension during the Early Jurassic.

4. The passive margin of Gondwana

A stable platformal sequence corresponding to the old passive margin of Gondwana is preserved in the Sierras de la Ventana (Fig. 7). Most of the present reconstructions of Gondwana accept that its southwest margin consisted of a continuous clastic passive margin that extended from Sierra de la Ventana to the Cape System (Milani, 2007, and references herein), and continues further north along the Pacific side through northern Argentina, Bolivia, and Peru (Ramos, 2008).

The continental margin of Gondwana facing Patagonia is partially located beneath the present Colorado Basin. A gravimetric transect across the basin shows an asymmetry between the thicknesses of the two crusts, northern Gondwana being thicker than Patagonia (Ramos, 1996). This difference is interpreted as evidence of a juxtaposition of an old Precambrian continental margin bearing the Río de la Plata craton, with Transamazonian ages of ca. 2.0 Ga (Tohver et al., 2007), against a younger Patagonian lithosphere according to Stern et al. (1990). A series of stages can be recognized in the Gondwana margin in the Sierras de la Ventana, also known as the Ventania System.

An early stage of rifting affecting the Proterozoic basement was postulated by Rapela et al. (2003), based on geochemical characteristics and the age of some 531–524 Ma granites and rhyolites interpreted as a Cambrian rift and correlated with similar rocks in the conjugate margin of South Africa. Depocenters bounded by northwest-trending normal faults have been observed in the seismic lines of the Claromecó Basin, perpendicular to the margin and correlated with this rifting (Ramos and Kostadinoff, 2005).

Sequences of platformal orthoquartzites up to several thousand meters thick of the Curamalal and Ventana Groups were unconformably deposited on metamorphic basement. Paleocurrent analyses of these mature sequences of orthoquartzites indicate a provenance from the northeast. The biostratigraphic control is scarce but is bracketed between Middle-Late Cambrian and Devonian times, based on a well dated basement (Rapela et al., 2003), and an overlying unconformity (Andreis et al., 1989).

A molasse sequence exposed east of the thrust front (see location in Fig. 8), and composed of arkoses and wackes of the Pillahuincó Group, unconformably overlying the Devonian quartzites and associated with glacial deposits in the lower section has a Late Carboniferous to Early Permian age. The age is based on the *Eurydesma* Fauna of the marine deposits (Harrington, 1955) and U–Pb age of 274 ± 10 Ma from a tuff layer in the upper part of the sequence (Tohver et al., 2007). These immature sandstones with volcanic clasts have a southwestern provenance. The changes between the stable clastic platform and these immature deposits indicate an important modification in the transport direction from NE to SW in the base, to SW to the NE in the upper section; an increase of instability in the basin, and the existence of a positive relief to the south (Andreis and Cladera, 1992; López Gamundi and Rossello, 1992). This change indicates the existence of a first uplift

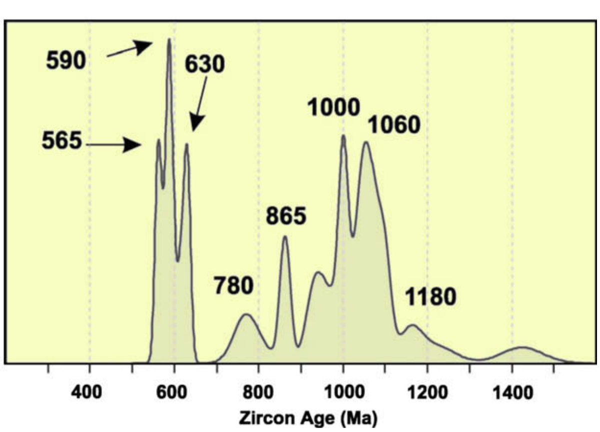

Fig. 6. Relative probability plot for the best-estimated ages derived from the Dos Hermanos phyllites (based on Pankhurst et al., 2003).

event associated with the unconformity between the Devonian orthoquartzites and the Late Carboniferous sequences (Massabie and Rossello, 1984).

The Ventania fold-and-thrust belt of Sierra de la Ventana is characterized by isoclinal folds associated with a high strain in the orthoquartzites, with vergence typically to the northeast (Dimieri et al., 2005, and references therein). The southwestern part of the belt, where the basement is exposed, has evidence of thrusts (see Fig. 7) associated with low grade metamorphism, dated by K–Ar between 282 and 260 Ma (Varela et al., 1986; Buggisch, 1987) constraining the deformation between Lower and Middle Permian. Although there is evidence of strike-slip displacements, the main deformation in this late Paleozoic fold-and-thrust belt is characterized by SW–NE shortening and transport (Tomezzoli and Cristallini, 1998; Dimieri et al., 2005). As a result of the thrust stacking, the Claromecó foreland basin (Fig. 8) was formed by flexural loading of the Gondwana margin with a foredeep more than 10 km thick (Ramos, 1984; López Gamundi and Rossello, 1992). The changes in the sedimentation in the Late Carboniferous predate the low-grade dynamic metamorphism associated with important shortening in the fold and thrust belt of the southwestern sector of Ventania as denoted by the studies of Von Gosen and Buggisch (1989).

These facts, together with the syntectonic sedimentation in the uppermost part of the Lower Permian sequence (López Gamundi et al., 1995), indicate a major episode of deformation along the Gondwana margin at these latitudes. There is no doubt that the main episode is Early Permian in age, but the unconformity between the Devonian and Late Carboniferous deposits indicates that uplift may have started prior to the Late Carboniferous. Deformation lasted at least until Middle Permian, as the complete sequence of Early Permian deposits is folded.

The evolution of the Gondwana passive margin and Patagonia should be tied to the southern Africa counterpart, the Cape fold and thrust belt and the Karoo foreland basin. Since the work of Du Toit (1927) there is a growing consensus that the Ventania fold-and-thrust belt is the continuation of the Cape fold belt and that the Claromecó foreland basin is the western end of the Karoo Basin, both of them with a thickness exceeding 10 km (Milani and De Wit, 2008). Crustal thicknesses have a similar pattern: below the Karoo Basin the crust is about 38 km thick, increasing to 43 km below the Cape fold belt, and abruptly decreasing to the south to 30 km at the southern coast of South Africa, and from there to less than 20 km thick across ~250 km of continental shelf up to the Agulhas Fracture Zone (De Wit et al., 2007). A similar pattern is observed in the Claromecó Basin, with the thickest part below the Ventania belt, and with a new decrease below the Colorado Basin (Introcaso, 2003).

The basal sequence is represented by the Kango Group, the lowermost rift sequence of the Cape Supergroup, which on the basis of U–Pb data on detrital zircons is, in part, Early Cambrian in age (Armstrong et al., 1998). An angular unconformity separates these deposits from underlying Neoproterozoic metasediments intruded by Cambrian A-type granites as young as 520–540 Ma. U–Pb dating and geochemistry of these granites and associated rhyolites below the Cape unconformity, which separates them from the overlying siliciclastics of the Cambrian–Ordovician Table Mountain Group, show that they are equivalent in age and composition to the granites and rhyolites of Sierra de la Ventana (Rapela et al., 2003). The siliciclastic Cape Supergroup ranges in age from mid Cambrian (ca. 500 Ma) to Upper Devonian (ca. 360 Ma) and comprises a number of well-defined marine transgression–regression sequences that match the Curamalal and Ventana Groups. The Pillahuincó Group correlates with the Karoo Supergroup. Both start with an extensive sequence of glacial sediments, but the southern Africa counterpart has up to se-

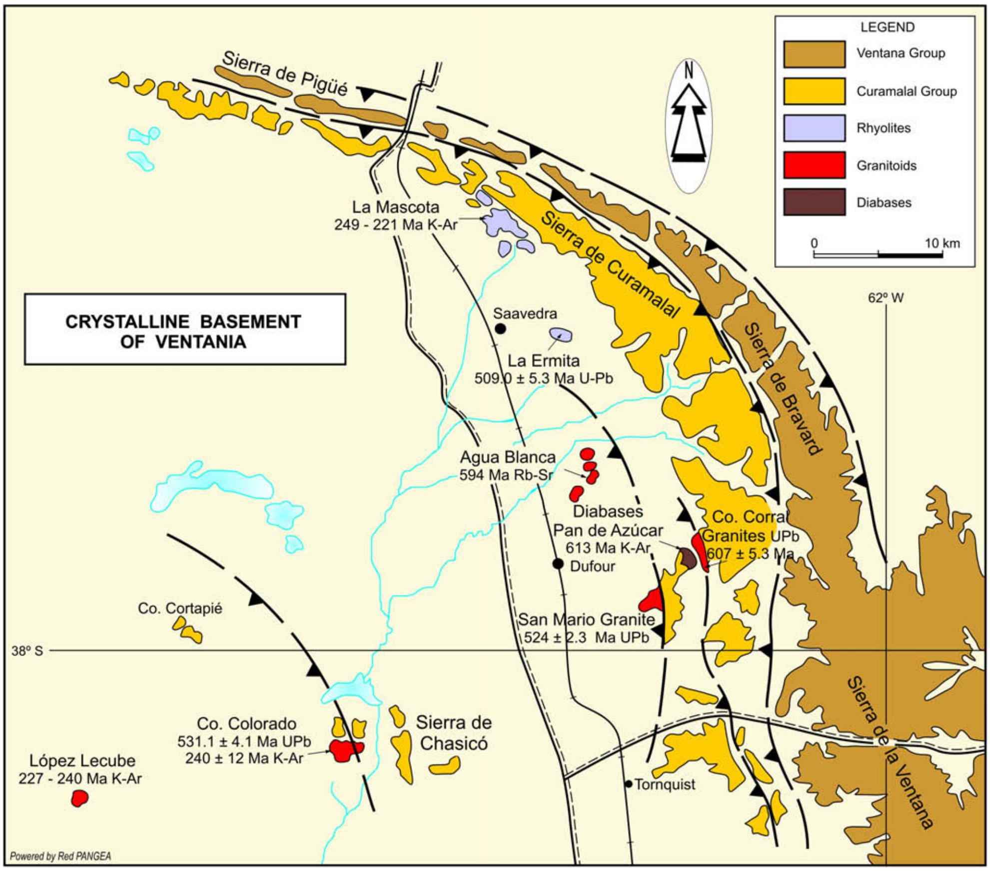

Fig. 7. Basement exposures of Sierra de la Ventana and its early Paleozoic sequences thrust with a dominant northeast vergence (based on Cingolani and Varela, 1973; Rapela and Kostadinoff, 2005). See location in Fig. 8.

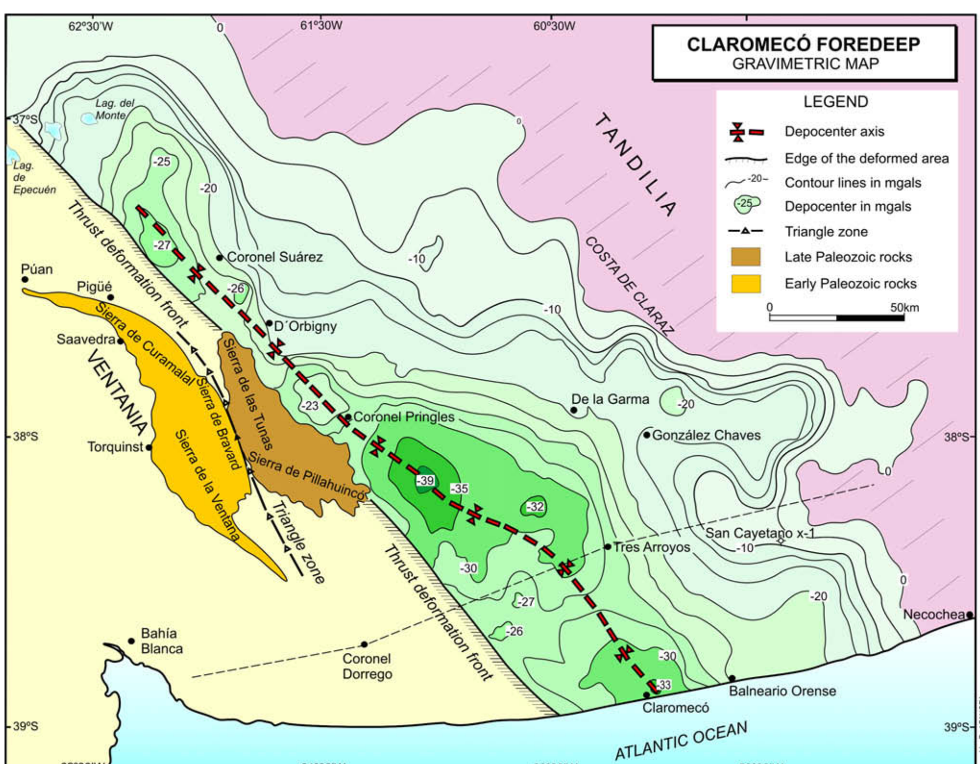

Fig. 8. The different units of the Ventania fold and thrust belt associated with the Claromecó foredeep, formed by crustal loading in Early to Middle Permian. Note the location of the thrust deformation front and the axis of the >10 km foredeep (based on Ramos and Kostadinoff, 2005).

ven major ice advance-retreat episodes representing the Carboniferous–Early Permian Dwyka glaciations (De Wit et al., 2007). Rhyolitic–andesitic volcanic tuffs present in the Dwyka Group have U–Pb dates on zircons from 297 ± 1.8 Ma (Bangert et al., 1999), whereas zircons in the overlying tuffs have U–Pb ages of 288 ± 3 and 289 ± 3.8 Ma. These tuffs are older than the 274 ± 10 Ma tuff found above the glacial deposits in the Pillahuincó Group. Late Early Permian–through Middle Permian (280–260 Ma) tuffs are also detected in the Paraná Basin of Brazil, Paraguay, and Uruguay (López Gamundi, 2006). New SHRIMP data on the Paraná Basin of Brazil constrain the age of the main tuff layer to 278.4 ± 2.2 Ma in close agreement with the Ventania tuffs (Santos et al., 2006).

As can be seen in Fig. 9a, it is evident that in the pre-breakup paleogeography, there is not a simple linear continuation between the Ventania fold and thrust belt and the Cape fold belt. The northern igneous–metamorphic belt described in Fig. 5 has no obvious counterpart in on-land southern Africa, and it has been only detected in the M. Ewing bank (see Fig. 2c) by the ODP dredging and drilling (see Ramos, 1986).

In order to precisely locate the different features between the Agulhas and the Malvinas plateaux, the southern plateau should be contracted at least 20%, in what is the assumed W–E stretching between the M. Ewing Bank and the South American coast based on the continental crustal attenuation (Sandwell and Smith, 1997). Even so, there is a north–south truncation and displacement among the late Paleozoic features of South America and South Africa, larger than 600 km. The structural trend of the Argentine continental platform changes from N70°W to almost north–south in the Valdés and Rawson basins (Fig. 9a), adopting a similar WNW trend in the San Jorge Basin. The region of north–south trend fits with the amount of displacement of the late Paleozoic features.

5. Discussion

In order to explain the different geological features previously described and summarized in Fig. 5, it is necessary to integrate the facts with some other geological evidences. Fig. 10 integrates the western and northern igneous–metamorphic belts with some other structural and geophysical evidence, to the north and south of the previously described study area. The different problems and uncertainties will be discussed from north to south to cover the diverse kind of evidence and topics that are pertinent to the proposed evolution of Patagonia.

5.1. The proposed suture

The ophiolitic belts among different early Paleozoic terranes with north–south trends that separate Chilenia, Cuyania, and Pampia from the Río de la Plata craton (Ramos, 1988) are truncated by an east–west structural fabric in the basement. This fact can be seen in diverse data sets. For example, basement fabrics in the different off-shore basins constrained by seismic reflection profiles and aeromagnetic surveys shows WNW Paleoproterozoic trends, and control the nucleation and orientation of half-graben systems developed in the rift basins (Ramos, 1996). South of the Colorado Basin, a N–S trend dominates the Valdés and Rawson basins (Fig. 9a). Just along this boundary Ghidella et al. (1995) define a magnetic lineament that crosses the entire platform from the mouth of the Colorado river with a NW trend. This Colorado magnetic discontinuity has been interpreted by Max et al. (1999) as the southern boundary of the Precambrian Río de la La Plata craton, a potential suture with the continental crust of the Patagonia platform.

The gravimetric and magnetometric surveys conducted on-land by Kostadinoff et al. (2005) between the city of Neuquén and the coastline recognized a strong contrast of behavior between the Gondwana margin and the Patagonian platform defining a discontinuity just west of the Colorado off-shore feature. This discontinuity coincides with the Huincul fault, a regional transcontinental strike-slip fault defined in this segment by Ploszkiewicz et al. (1984), and separates basement with different characteristics.

The airborne magnetometric surveys combined with the gravimetric data led Chernicoff and Zapettini (2004) to recognize a sharp truncation of the magnetic facies in the Gondwana margin. The ophiolitic belts and the north–south fabrics among Chilenia and Cuyania, as well as between Cuyania and Pampia, are truncated along the Huincul fault, confirming the observations of Kostadinoff et al. (2005) further to the east. The different characteristics between the Gondwana, more specifically the Río de La Plata craton, and Patagonia led Dalla Salda and Francese (1989) to interpret this discontinuity as a suture produced during early Proterozoic times.

The Neuquén Basin is segmented in two parts by the Huincul high, a series of half grabens inverted during the Andean orogeny as a strike-slip fault zone (see for structural details Silvestro and Zubiri, 2008). The half graben system was controlled by the suture of Patagonia with Gondwana according to Franzese and Spalletti (2001). The basement beneath the sedimentary cover has been screened using the available 3D seismic data in different blocks surveyed by the industry along the Huincul fault by Mosquera (2008). These data show more clearly than the other potential geophysical methods (Chernicoff and Zapettini, 2004) that the N–S trend of the basement structural grain is again truncated by an east–west trending fabrics (Mosquera and Ramos, 2006). The Huincul fault continues to the west in a series of conspicuous east–west lineaments first described in Chile by Chotin and Giret (1979).

Based on these data, it is possible to propose that although there is no direct evidence of an ophiolitic belt separating Gondwana from the Patagonia platform, the presence of a crustal discontinuity expressed by a transcontinental fault zone, a first order structural feature related to the Huincul fault zone, the truncation of the basement fabrics and the offshore magnetic anomaly, together with the geological evidence, provide a robust indication of a potential suture between the two continental blocks. Although Chotin and Giret (1979) identified those transversal lineaments between Temuco and Valdivia in Chile, north of Temuco there is a well-known truncation of the late Paleozoic arc front that jumps from the Pacific coast to the water divide of the Andes (Fig. 10).

Independent evidence for the suture is the location of the Cañadón Asfalto rift basin. This basin is developed in the hanging-wall of the potential suture of the western metamorphic belt that coincides with the Chubut high of Cortiñas (1996). The Somuncura Basin of this author is also located in the hanging-wall of the northern belt suture.

5.2. Age of ductile deformation in the northern belt

Ductile thrusting affecting the supracrustal rocks of Yaminué was accompanied by greenschist to lower amphibolite facies metamorphism during peak deformation, forming extensive mylonite and ultramylonite ductile shear zones, including deformation of ~300 Ma old orthogneisses (Llambías et al., 2002; Von Gosen, 2003; Basei et al., 2005). Similar trends and ductile deformation occur in amphibolite grade metamorphic rocks of late Paleozoic age in Cerro Los Viejos (Fig. 10) described on the opposite Gondwana margin by Tickyj et al. (1997). Along this margin in the Sierra de la Ventana area there is clear evidence of low grade metamorphism as well as penetrative deformation between 282 and 260 Ma

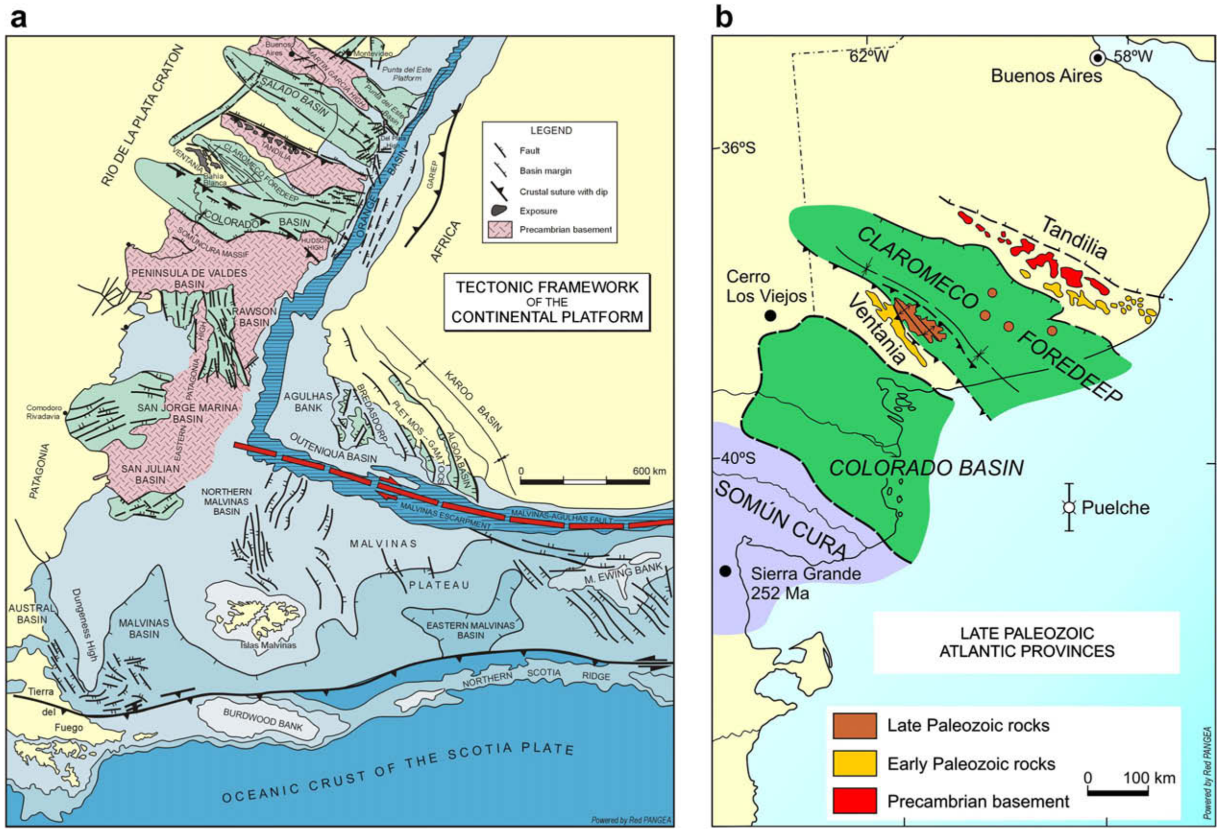

Fig. 9. (a) Structure of the continental platforms of southern South America and southern Africa based on the early fit of Martin et al. (1981) and complemented with new structural features by Ramos (1996); (b) Detail of the late Paleozoic provinces in the South America sides showing that the contact between the northern igneous and metamorphic belt of Somún Cura and the Claromecó foredeep is covered by the Late Jurassic–Cretaceous aulacogenic Colorado basin (De Wit, 1977).

affecting the basement, as well as independent evidence derived from Early Permian syntectonic sedimentation of the Pillahuincó Group of Early Permian age disturbing a 274 ± 10 Ma old tuff layer (Tohver et al., 2007).

All together these data constrain the peak of deformation between Early and Middle Permian, as previously established by many authors (Ramos, 1984; Andreis et al., 1989; López Gamundi et al., 1995; Rapalini et al., 2008).

5.3. A magmatic arc along the northern sector of the Somún Cura Massif

A collision model is supported by magmatic evidence for the postulated subduction and collision phase. Petrological studies performed in the western and central sectors of the northern belt recognized metaluminous granitoids that evolved to peraluminous granites (Llambías et al., 1984; Llambías and Rapela, 1985; Rapela and Llambías, 1985). Geochemical studies recognized an initial tonalitic phase followed by widespread granodioritic facies that evolved from typical calcalkaline subduction related metaluminous granitoids to syncollisional peraluminous granites, followed by postcollisional peralkaline granites and rhyolites (Llambías et al., 1984; Rapela and Caminos, 1987). These authors emphasized that these petrological characteristics can be traced from the La Esperanza area in the western sector to the Yaminué central sector, and even further east.

The main uncertainty of these rocks is the precise age of the older phases with typical subduction related character. For many years these complex systems were dated by Rb–Sr, commonly resulting in conflicts between relative ages and field relationships. Even well defined Rb–Sr isochrones as presented by Caminos et al. (1988) or Pankhurst et al. (1993) were found to be geologically meaningless. The first regional U–Pb dates performed by Varela et al. (2005) in the northern Patagonian Cordillera and in the western sector of the Somún Cura Massif suggest that the late Paleozoic granitoids extend to the east at least up to the Yaminué area. The only precise U–Pb SHRIMP age obtained in the old phases is 273 ± 2 Ma (Pankhurst et al., 2006) should be interpreted as a syn- to late-tectonic phase, due to the age of the deformation recorded at that time in the Sierra de la Ventana region. These authors recognized a 320 Ma inherited zircons in rocks of this area, but no systematic study was performed. More precise ages are needed in this area as well as in the Yaminué region, to confirm the U–Pb ages from 295 to 307 Ma for the orthogneisses and deformed rocks described by Varela et al. (1998b) and Von Gosen (2003).

5.4. The western belt and its southern extension

This late Paleozoic magmatic belt was first recognized on geochronological grounds by the pioneer work of Halpern (1968), and strongly suggested the existence of continental drift along the Samfrau orogenic belt from South America to Australia. Further studies (e.g. Forsythe, 1982; Ramos, 1983) interpreted this belt as to have formed along the Pacific side. Some authors recognized two magmatic cycles by U–Pb dating, one in the Devonian (ca. 390 Ma) and a younger in the late Paleozoic (ca. 280 Ma) with cooling K–Ar ages of 260–250 Ma (Varela et al., 2005). A more comprehensive study based also on U–Pb dating, mainly with SHRIMP ages, constrain the magmatic arc from the Devonian to mid Carboniferous time (ca. 320 Ma) based on the age of some peraluminous granites from Paso del Sapo and Sierra de Pichiñanes

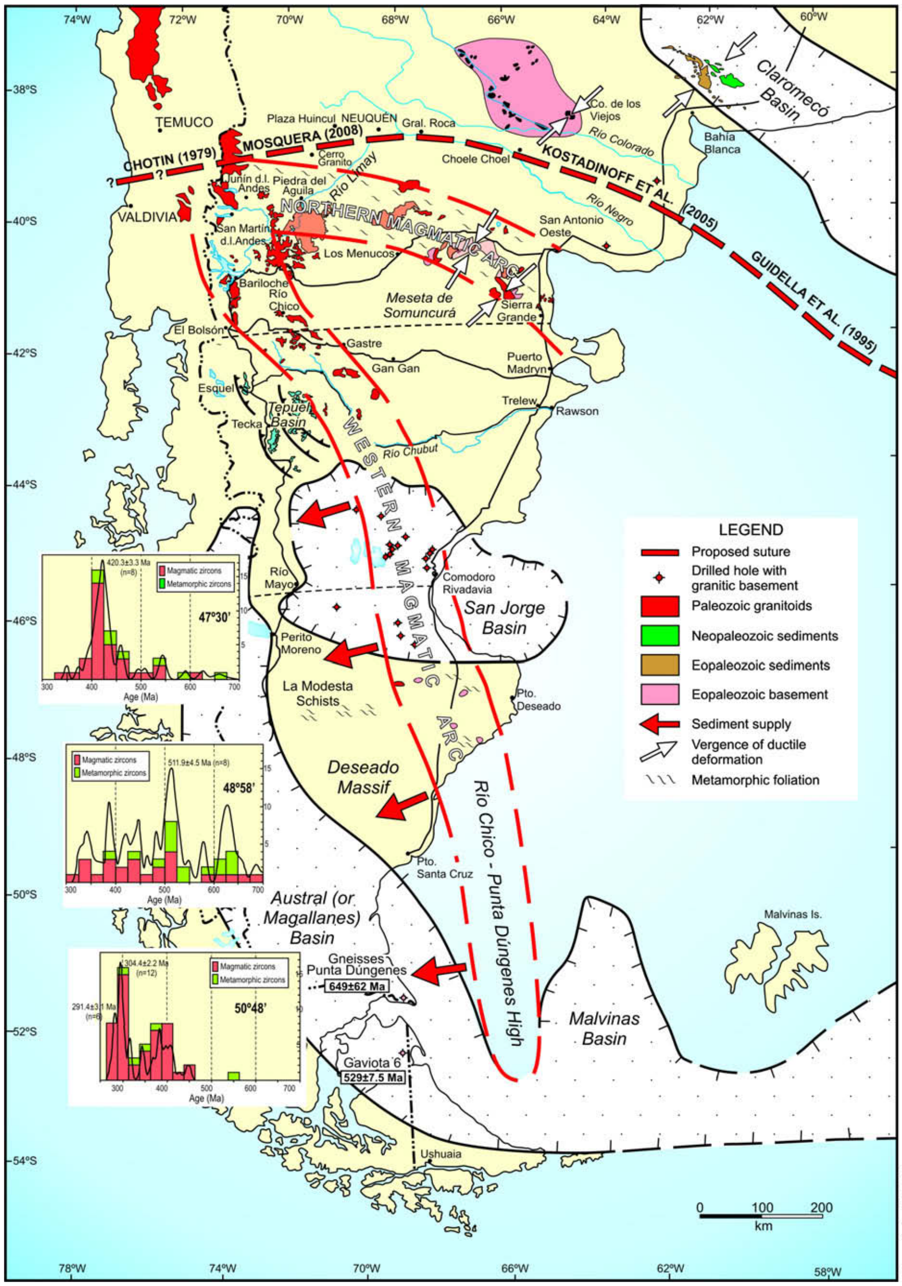

Fig. 10. Location of the two Paleozoic magmatic belts with the main structural features extended from the same source of Fig. 5. The potential suture in the northern sector is based on Chotin and Giret (1979), Mosquera (2008), Kostadinoff et al. (2005), Ghidella et al. (1995); the vergence of ductile deformation from Fortey et al. (1992); the southern extension of the Río Chico–Punta Dúngenes high from Galeazzi (1996); the insets with detrital zircons probability plots along the western regions from Augustsson et al. (2006). See discussion in the text.

(Pankhurst et al., 2006). However, south of Paso de Indios (see Fig. 5), the southern extension of this belt is not well constrained, due to the lack of geochronological data. They interpreted this belt as turning north of the Deseado massif to continue through the middle of San Jorge Basin with a WNW strike (Fig. 1 of Pankhurst et al., 2006). This interpretation is similar to the proposals of Frutos and Tobar (1975) and Gallagher (1990) that imply the Deseado Massif is an allochthonous terrane.

There is robust information from the early works of Lesta (1968) and Lesta et al. (1980) that the granitoids in the subsurface continue with a NNW trend into the Deseado massif and that there are some drilling cores to the east that have intersect amphibolites, the country rock of this belt. It is well known that the San Jorge Basin is interrupted by a NNE feature, known as the Río Chico high, which accompanies the Bernardides fold belt produced by tectonic inversion of the previous NNE trending half-grabens (Fitzgerald et al., 1990). It is interesting to note that the Río Chico high continues eastwards into the offshore in the Punta Dúngenes high, a structural paleo-high that separates the Austral from the Malvinas Basin (Galeazzi, 1996). Based on this structural continuation it is speculated that the western belt continues into the Dúngenes high, and a hint supporting this continuation will be analyzed based on the detrital zircon patterns.

5.5. Detrital zircons from the western belt

As demonstrated by the studies of Hervé et al. (2003) the eastern metamorphic belt records early and late detrital Paleozoic zircons that put some significant constrains in the age of deposition. Recent studies performed between 47° and 50°S in the eastern metamorphic complex of Chile and Argentina based on detrital U–Pb zircon ages, complemented by Lu–Hf isotopic analyses, give further constrain on the isotopic signature of the protolith and information on the crustal residence time (Hervé et al., 2006; Augustsson et al., 2006). These data sets illustrated in the insets of Fig. 10; show two important things: first, there are more abundant detrital zircons of early Paleozoic ages to the north, probably directly derived from the Deseado Massif and from the La Modesta Schists; and second, that the Late Carboniferous and Early Permian zircons are more abundant near 50°S latitude, the latitude of the Dúngenes high, the potential southern extension of the western belt. These authors propose that the change in the frequency of the zircons is related to the diachronous onset of subduction from north to south. The source of the Carboniferous detrital zircons was thought to be in Sierra de la Ventana, southern Africa and Antarctica (Augustsson et al., 2006), and suggested that Patagonia was an autochthonous continent. However abundant magmatic and sedimentary rocks of Carboniferous age occur in central western Patagonia, and some of them presently beneath the San Jorge Basin. A more recent provenance analysis concluded that two different source domains were recorded: metasediments derived from the metasedimentary country rocks of the evolving magmatic arc, and sediments derived from the arc proper (Augustsson and Bahlburg, 2008).

5.6. Collision versus flat slab subduction

The western late Paleozoic magmatic belt developed almost parallel to the continental margin, but the arc trench-gap distance varies from 400 to 600 km from the present trench. The simplest interpretation, recently presented by López Gamundi (2006), is to assume a trench parallel to the magmatic arc obliquely crossing the entire southern Patagonia from north to south, west of the Deseado massif, as previously proposed by Forsythe (1982), Uliana and Biddle (1987), and many others. The main drawback of this model requires that most of the Patagonian Cordillera and adjacent foothills should have been formed by sedimentary accretion since late Paleozoic times. However, drilling performed in the Austral Basin shows a granodiorite of Early Cambrian age (529 ± 7.5 Ma, Söllner et al., 2000; Charrier et al., 2007), emplaced in a Precambrian basement underlie the basin (see Fig. 10). Recent precise U–Pb SHRIMP zircon data from this basement show ages from 536.8 ± 3.3 to 527.2 ± 5.2 Ma (Hervé et al., 2008). Based on the previous data and the geologic setting of the western magmatic belt, two alternative hypotheses may be possible: a collision of the southernmost Patagonia against the Deseado Massif and/or a period of shallow subduction during the late Paleozoic.

–*Collisional model*: several authors studying the late Paleozoic metamorphism of the northern Patagonian Cordillera recognized a collisional deformation in the P–T paths of the metamorphic rocks (Dalla Salda et al., 1994; Heredia et al., 2006). The best time constraints indicate a mid Carboniferous age for this event (Pankhurst et al., 2006). However, if the present extension of the magmatic belt is accepted, only the Madre de Dios terrane in the present continental margin is a candidate for the block that could have collided with the continental margin (Heredia et al., 2006). However, time constraints for the sedimentation of the fussuline-bearing carbonate rocks indicate a Late Carboniferous–Early Permian age, and the youngest zircons of the metasedimentary sequence are Early Permian (272 Ma, Hervé et al., 2003), indicating that the Madre de Dios Terrane cannot account for the mid Carboniferous collision. Recent studies performed with U–Pb and Hf–Lu isotopes between southern Patagonia and Antarctic Peninsula (Hervé et al., 2006) support the close correlation between these two areas and confirm their relative proximity, as was proposed by plate reconstruction of the Weddell Sea based on magnetic anomalies, topography and gravity by Ghidella et al. (2002, 2007). If this is accepted, the southern Patagonian Cordillera was attached to the Antarctic Peninsula until Early Jurassic times, and therefore a potential larger mass could have impacted during a late Paleozoic collision. The main uncertainty with this model is the requirement of a suture that could be speculated was between these two contiguous blocks, a weakness zone later reactivated during the opening of the Weddell Sea.

–*Flat slab model:* this hypothesis could explain the expansion to the foreland of the magmatic arc rocks, and some Paleozoic K–Ar ages found in Lago Puelo (42°S, Lizuaín, 1981) and in Lago Mogotes (47°S, Ramos, 1983), west of the present magmatic arc, that could be interpreted as the magmatic front. The episode of thickening in mid Carboniferous time could indicate the maximum shallowing of the subducted slab, with consequent attenuation and widespread Late Carboniferous–Early Permian granitic melts, associated with injection of hot asthenosphere and melting of the crust during the steepening of the oceanic slab.

However, if the Antarctic Peninsula was located as proposed by Ghidella et al. (2007), the distance from the potential trench to the magmatic arc would be too great to develop the important magmatism of the western belt. In that case it will be necessary to combine shallow subduction with a collisional episode.

5.7. One or two collisions

The collision of the Deseado massif against Gondwana in the mid Carboniferous times interrupted an exceptional magmatic arc activity and generated a compressive regime that lasted up to the Early Permian (Pankhurst et al., 2006). According to this model, this compression produced dynamic metamorphism in intraplate regions as in the Ventania System, located about 1000 km inboard of the Deseado massif. The La Golondrina rift basin in this model would be located in the foot-wall of the suture and extension should be coeval with the deformation peak in the Ventania System.

The existence of two magmatic arcs requires two orogenic episodes and two sutures, one north of the northern belt and another west of the western belt, in order to explain the localized deformation that stopped subduction-related magmatism. The western belt, according to Pankhurst et al. (2006), produced important deformation and metamorphism in Mid to Late Carboniferous times, and extensional collapse began in Early Permian times, as seen by the rifting of the La Golondrina Basin in the hanging-wall of the suture. Most of the rift systems associated with sutures are always in the hanging-wall as seen in Jeann d'Arc in Canada, in Newark Basin in the Appalachian, North Sea rift in Scotland, Cuyo rift in the Precordillera of Argentina, among many others (Ramos, 1999). Meanwhile, deformation in the northern magmatic belt started in the Late Carboniferous and its climax in the Early Permian is represented by the dynamic metamorphism along southwestern Sierra de La Ventana. By analogy with Cenozoic orogens, the rhyolitic flare-up in the Somún Cura was probably linked to the slab break-off that triggered deformation in the Gondwanan margin of Ventania.

5.8. Paleomagnetic constraints for Patagonia

Most of the paleomagnetic data from Patagonia were analyzed by Rapalini (2005). Available paleomagnetic poles are presented in Fig. 11. As concluded by Rapalini (2005) four out of six paleomagnetic poles for Patagonia, between the Devonian and Permian are consistent with the Gondwana path. One of the anomalous poles has been interpreted as a local block rotation and the remaining one has been considered unreliable. All these data belong exclusively to the Somún Cura massif and the uncertainties in some of the poles are large enough to allow displacement between Patagonia and Gondwana. These uncertainties permit a separation up to about 1000 km orthogonal to the northern boundary of Patagonia in the Middle to Late Carboniferous (Fig. 11). Undoubtedly, new paleomagnetic data are needed. Rapalini (2005) proposes a para-autochthonous origin of Patagonia, involving rifting away from southwest Gondwana (*circa* 1000 km) in the late Proterozoic or early Paleozoic to collide again with southwest Gondwana in the late Paleozoic. This seems to be the model most compatible with most lines of evidence.

On the other hand, paleomagnetic studies performed by Tomezzoli and Vilas (1999) demonstrate syntectonic sedimentation during the Early Permian in the Pillahuincó Group of Sierra de la Ventana, in the same sequence where López Gamundi et al. (1995) have demonstrated coeval deformation based on syngrowth strata.

6. Concluding remarks

All published models fail to explain all the existing data. Nevertheless, some specific points to contribute to a better comprehension of the geologic history of Patagonia should be taken in consideration (Fig. 12).

The basement of Patagonia is not exotic to Gondwana, as indicated by the inheritance of the zircons observed in the magmatic and metamorphic rocks of both the Somún Cura and the Deseado massifs (Figs. 4 and 6). There is robust evidence of Brasiliano ages, which indicate that the Patagonian block participated in the amalgamation of Gondwana. This implies as stated by Rapalini (2005), that Patagonia is a para-autochthonous terrane, which was probably detached during the rifting episode recorded by Armstrong et al. (1998) and Rapela et al. (2003), in the Cape System and the Ventania province, respectively. The Somún Cura and Deseado massifs have also inherited zircons with common Grenville-age peaks, which point out a potential provenance from the Namaquá metamorphic belt in southern Africa, the closer and larger source for such detritus. The rifting was followed by the formation of a passive margin sequence dominated by clastic rocks, that characterized southwestern Gondwana from Northern Argentina to the Cape Fold Belt and further east (Rapela et al., 2003; Ramos and Kostadinoff, 2005; De Wit et al., 2007).

The eastern sectors of the Somún Cura and Deseado massifs preserved good evidence of Ordovician metamorphism and magmatic activity ca. 470 Ma. This deformational episode has not been recorded in the early Paleozoic stable platform sequence of the Sierra de la Ventana. In the Cape System, there is an interruption in the continuous and homogeneous sand deposition of the Peninsula Formation in the lower Table Mountain Group. This has been interpreted by Tankard et al. (1982) and Compton (2004) as a general regression that gave place to the coarse conglomerates and diamictites of the Parkhuis Formation related to a Late Ordovician glacial episode. Even if a soft collision could be invoked for the Middle Ordovician to produce the metamorphism and the uplift in both basement massifs, there is no supporting evidence in the known adjacent margins. The reconstruction of western Gondwana prior to the South Atlantic opening as depicted in Fig. 9a indicates that both eastern sectors were facing a north–south margin segment along a 600 km length. Either an early collision with Kalahari craton, or a collision along its western margin (as proposed by Dalla Salda et al., 1990), is needed to account for this deformation, but evidence for such episodes is missing. A third alternative is that a collision between the two massifs occurred in the early Paleozoic to form the Patagonia terrane as proposed by Ramos (2004b). Independent of these models, an important fact is that in Silurian–Devonian times a general subsidence took place in the north and northeast margins of the Somún Cura Massif developing a quartzitic platform in a passive margin setting. These quartzites, known as Sierra Grande Formation, have similar Malvinokafric fossils as coeval units in the Malvinas islands (Manceñido and Damborenea, 1984). Similar fauna have been described at the same latitudes along the Pacific coast from the Pizarras de Buill (42°S) in the accretionary prism by Fortey et al. (1992).

The tectonic setting of the Carboniferous to Early Permian Tepuel Basin, and its prolongation beneath the western sector of the San Jorge Basin, has weak or no metamorphism, paleocurrents from east to west, and a westerly vergence. These facts are consistent with a forearc basin environment on continental crust (Fig. 12a), east of the accretionary prism as proposed by Forsythe (1982). A similar conclusion was obtained by Augustsson and Bahlburg (2008) based on the provenance of the metasediments. Further south (48°58'S inset at Fig. 10), sedimentation younger than

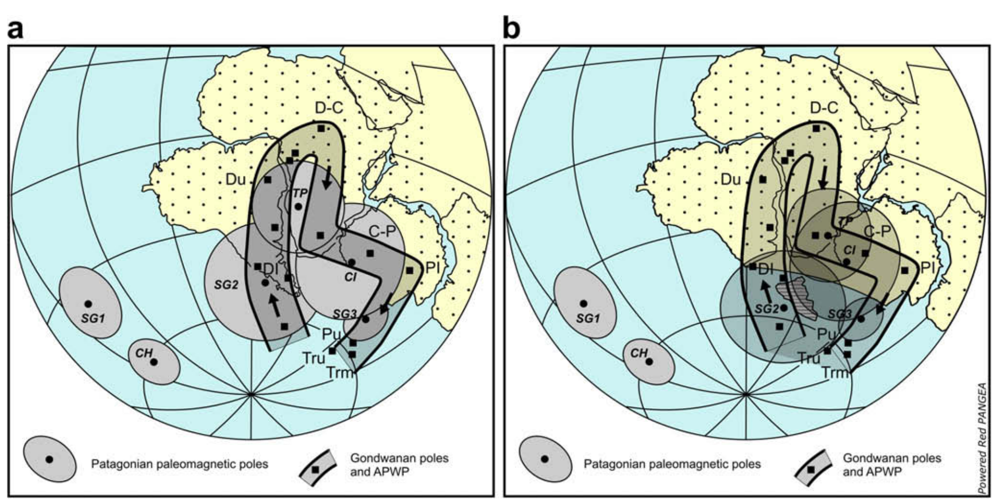

Fig. 11. Paleomagnetic data from Patagonia and the apparent polar wandering path of Gondwana. (a) Autochthonous Patagonia; (b) displaced Patagonia (based on Rapalini, 2005).

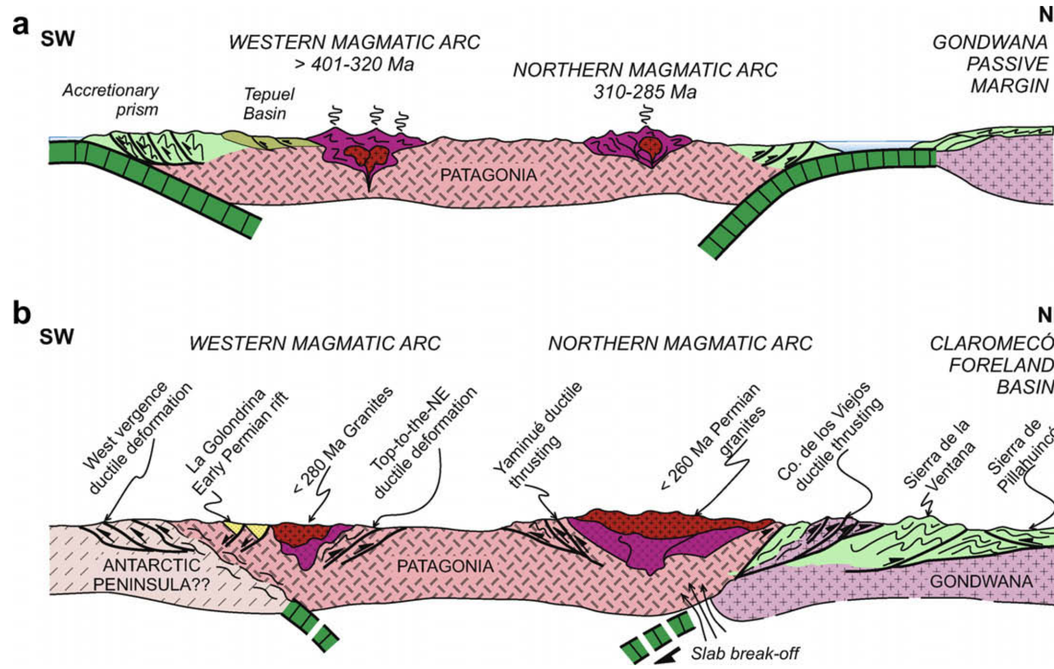

Fig. 12. Tectonic evolution of Patagonia during the late Paleozoic. (a) Oblique schematic structural section showing the western and northern magmatic belts under subduction; (b) sequence of collisions: first with Antarctic Peninsula (?) during mid to Late Carboniferous, and second with the Gondwana margin during Early–Middle Permian. Note that the Deseado massif is extensionally collapsing in La Golondrina rift, while new compression acquired its deformation peak in the Ventania System.

mid Carboniferous as established by Augustsson et al. (2006) in Bahía La Lancha, formed the eastern low grade metamorphic belt of Hervé et al. (2003).

The two late Paleozoic magmatic and metamorphic belts imply that Patagonia was an independent plate since the Devonian. Subduction-related magmatism ends first in the western belt during mid Carboniferous times according to Pankhurst et al. (2006). Evidence of strong deformation in the northern Patagonian Cordillera (Heredia et al., 2006) is difficult to explain by a collision along its western margin. Further south, a hypothetical collision with the basement of Antarctic Peninsula may explain the higher metamorphism of the eastern metamorphic complex in comparison with the Tepuel Basin deposits (Fig. 12b). However, there are many uncertainties about the location of a potential suture or crustal discontinuity along the Pacific side of the western belt. The proposed western magmatic belt, as well as the one proposed by Pankhurst et al. (2006), fails to explain the length of the gap between the present trench and the arc, although an episode of flat subduction will reduce that problem at least in the northern segment.

Southward subduction of the Gondwana clastic passive margin stopped after the Carboniferous in the northern magmatic belt. First, contact between Patagonia and Gondwana may have started during the Carboniferous, but collision, deformation and uplift took place in Early Permian times. The compressive stress regime lasted in this sector of South America to the Late Permian, when a generalized extension took place. The implication and consequence of this model are that the Cape fold belt would be a collisional orogen that resulted from the amalgamation of the Malvinas plateau during Permian and younger times. The dissimilar deformation in the Gondwana margin north of Patagonia can be easily explained by a combination of hard and soft collisions associated with the paleogeography of the colliding margins.

Any viable model must account for successive periods of breaking and rifting in the Early-Middle Cambrian, subsequent amalgamation in the mid Ordovician, renewed rifting in Silurian and Devonian times and final re-accretion in the late Paleozoic. This plate tectonic history of the Pacific margin of west Gondwana is inherent to the evolution of the Terra Australis orogen (Cawood, 2005), controlled by absolute displacements of the Gondwana supercontinent guided by successive plate reorganization as first order controls.

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