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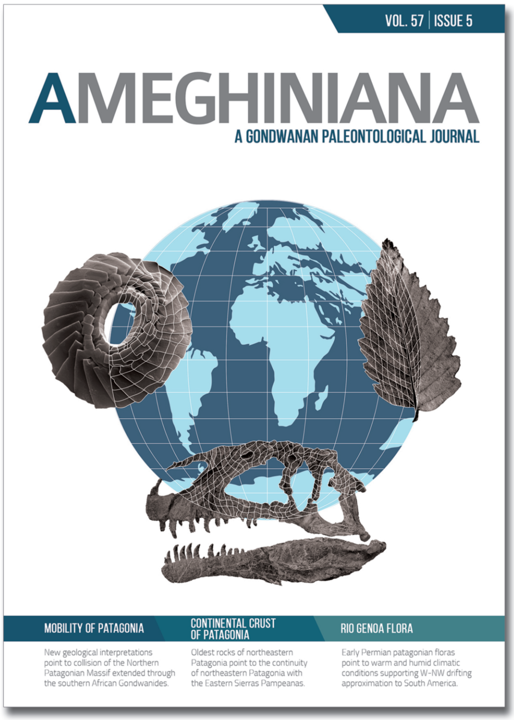

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THE COLLISION OF PATAGONIA: GEOLOGICAL FACTS AND SPECULATIVE INTERPRETATIONS

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Abstract. The Paleozoic evolution of Patagonia was the focus of controversies between its allochthonous or autochthonous origin. The arrival of plate tectonics supported new allochthonous alternatives and from an initial fixist resistance, different mobilistic hypotheses have made their way. There is currently some consensus about its allochthony, but there is no agreement on collision times or in the configuration of the continental blocks involved. Based on the present data an alternative is developed that fits better with existing information. The northeast-vergent deformation in Ventania System, the Hespérides Basin, its wide longitudinal and transverse distribution, show that collision occurred in the northern sector of Northern Patagonian Massif, and extended through the southern African Gondwanides. Their similar metamorphic and tectonic patterns identified a previous southward subduction with a Permian climax, characteristic of a continent-continent collision. The associated magmatic arc has been partially obliterated by slab-breakoff and delamination in the Late Permian–Triassic. The western magmatic belt along the Pacific margin is older, spanning from Devonian to mid-Carboniferous. The Chaitenia island arc collision in Upper Devonian produced an episode of exhumation and uplift. This western belt extends into Tierra del Fuego island and its contour allows tentatively to recognize a Southern Patagonian terrane. It is speculated that this block may have included the Antarctic Peninsula, although more data is needed to characterize its composition and areal development. However, it is concluded that the dimensions of this southern terrane cannot justify the broad regional deformation of the Gondwanides.

Key words. Gondwanide. Hespérides Basin. Late Paleozoic deformation. Synorogenic deposits. Delamination.

Resumen. LA COLISIÓN DE PATAGONIA: EVIDENCIAS GEOLÓGICAS E INTERPRETACIONES ESPECULATIVAS. La evolución paleozoica de la Patagonia fue motivo de controversias entre su origen alóctono o autóctono. La llegada de la tectónica de placas apoyó nuevas alternativas alóctonas y, a partir de una resistencia fijista inicial, surgieron diferentes hipótesis movilistas. Actualmente existe cierto consenso acerca de su aloctonía, pero no hay acuerdo sobre los tiempos de colisión o sobre la configuración de los bloques continentales involucrados. Con base en datos actuales se desarrolla una alternativa que se ajusta mejor a la información existente. La deformación vergente al noreste en el Sistema Ventania, la cuenca Hespérides, su amplia distribución longitudinal y transversal, muestran que la colisión ocurrió en el sector norte del Macizo Patagónico Norte y se extendió a través de los Gondwanides al sur de África. Sus patrones metamórficos y tectónicos similares identifican una subducción anterior hacia el sur con un clímax pérmico, característico de una colisión continente-continente. El arco magmático asociado ha sido parcialmente obliterado por *slab-breakoff* y la delaminación en el Pérmico tardío–Triásico. El cinturón magmático occidental a lo largo del margen pacífico es más antiguo, desde Devónico hasta Carbonífero medio. La colisión del arco islándico Chaitenia en el Devónico Tardío produjo un episodio de exhumación y levantamiento. Este cinturón se extiende hasta Tierra del Fuego y su contorno permite tentativamente reconocer un terreno Patagonia Sur. Se especula que este bloque puede haber incluido la Península Antártica, aunque se necesitan más datos para caracterizar su composición y desarrollo regional. Se concluye que las dimensiones de este terreno sur no pueden justificar la amplia deformación regional de los Gondwánides.

Palabras clave. Gondwánides. Cuenca Hespérides. Deformación paleozoica tardía. Depósitos sinorogénicos. Delaminación.

THE IDEA THAT PATAGONIA WAS AN INDEPENDENT CONTINENT from the rest of the Gondwana made by Ramos (1984), has originated controversies and discussions for more than 35 years. This resulted into two lines of interpretation among geoscientists that persisted for several decades. On the one hand were those who argued that Patagonia as a whole or in part had collided with the continent of Gondwana, while on the other hand were those who argued that this collision did not exist and that Patagonia was an indissoluble part of South America.

In order to understand its evolution, a brief review will be made of the main alternatives that over the years have led to a relative consensus on its geological history. However, there are still discrepancies regarding its limits, its temporal evolution, and the identification of those sectors that would be certainly allochthonous.

The first proposal to consider Patagonia as an independent continent of Gondwana corresponds to Windhausen (1924). In a paper published in a Special Supplement of the newspaper *"Diario del Plata"*, he identified the Gondwanides of northern Patagonia, as a Permian orogen that sutured this continent with the Brasilia Massif (see Fig. 1). This proposal remained largely unknown given its means of publication, although Storni (1946) transcribed it in one of the first issues of the *Revista de la Sociedad Geológica Argentina*.

Windhausen's proposal was based on a fragmentary data of the geology of Patagonia and a poor understanding of the mechanisms of the continental drift. However, a similar conclusion was obtained by Keidel (1925: 299–300), who identified Patagonia as *"a region that has long remained independent of the rest of South America [...] it is presented as a remnant of a former continent of greater extent, whose main fragment is the current Antarctic continent"*. This Antarctic connection was also followed by Windhausen (1931). The development of the terrane concept by Coney *et al.* (1980) and Monger *et al.* (1982) raised some new ideas about the origin of Patagonia. Although some authors preferred an autochthonous origin of the Patagonian block as part of Gondwana (Forsythe, 1982), others supported Patagonia as an accreted terrane (Ramos, 1984, 1987). This hypothesis had few followers in the first years, among which stands out von Gosen (2002, 2003).

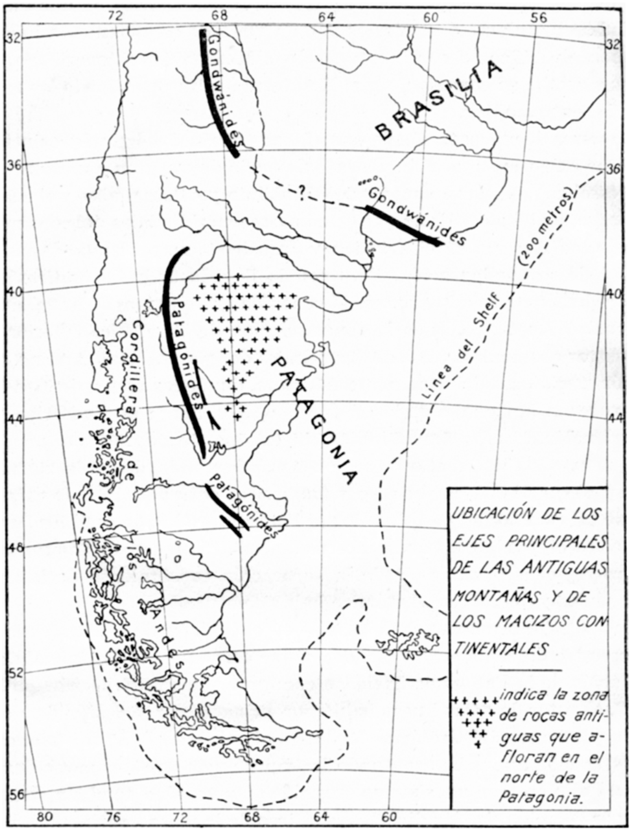

Figure 1. Outlines of the two old massifs, the Brasilia as part of Gondwana, and Patagonia, separated by the Gondwanides, an orogen formed in the Permian that continued in the Cape Belt in southern South Africa (Windhausen, 1924).

The mainstream postulated numerous evidences that seemed to indicate that Patagonia was part of the continent of Gondwana during the Paleozoic, among them (besides Forsythe, 1982), the contributions of Rapela and Kay (1988), Rapela and Pankhurst (2002), Rapela *et al.* (2003), Gregori *et al.* (2008, 2013), among others.

Another fixist alternative was to explain the Gondwanide fold and thrust belt, by an intra-plate episode of contractional deformation, related to a flat slab episode of subduction, as early proposed by Lock (1980). This early model could explain the deformation along the Ventania and Cape belt systems, but not the important magmatism located in the North Patagonian (or Somún Cura) Massif. To solve this problem, Dalziel *et al.* (2000) used the Murphy *et al.* (1998) model proposed for western United States Laramide orogeny. The model combines a flat slab geometry with the subduction of an active oceanic plume. This model when applied to Patagonia (Dalziel *et al.*, 2000) could explain the existence of magmatic rocks, but not the composition and characteristics of this magmatism. In recent years, the orogenic model associated with flat slab and subduction of active oceanic plume has gained adherents and has been widely applied in China (Li & Li, 2007). A variation of this model has been recently used by Navarrete *et al.* (2019) in Patagonia, which is going to be discussed later.

However, most of these fixist models have failed to explain the strong contrast between the Patagonia basement and the rest of South American shelf. It has been difficult for decades to associate the basement of Patagonia with the crustal evolution of the Brazilian or South American platform (Fig. 2) as Marques de Almeida *et al.* (1976) recognized it, among many others.

Several models that partially combine both alternatives

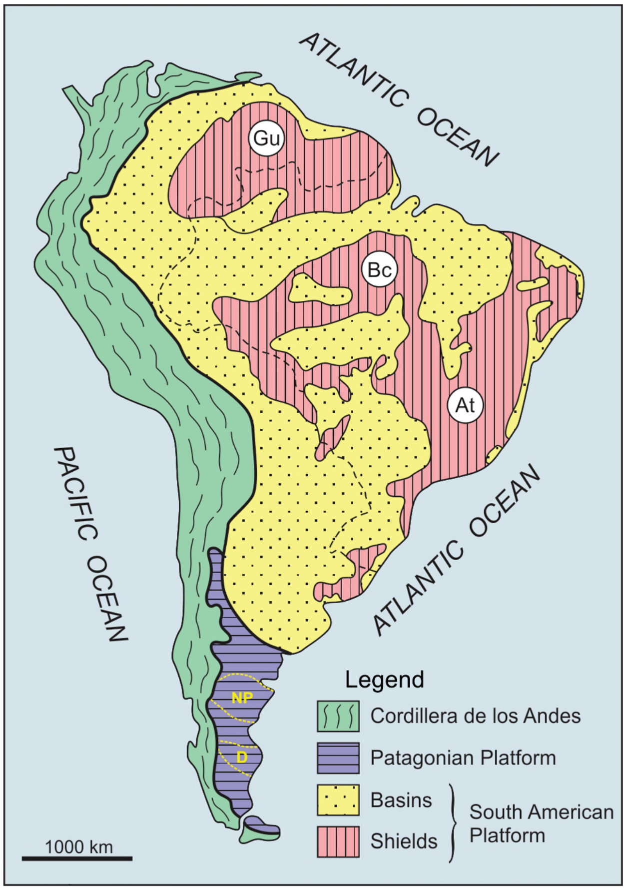

Figure 2. Regional location of the Patagonia Platform showing the most important basement massifs: The Deseado (**D**) and North Patagonian (or Somún Cura) (**NP**) massifs. **Gu,** Guyana; **Bc,** Brasil Central; **At,** Atlántico (based on Marques de Almeida *et al*., 1976).

were developed in recent years, such as the work of Rapalini (2005), Pankhurst *et al.* (2006), López de Luchi *et al.* (2010), Rapalini *et al.* (2010), González *et al.* (2018), among others. However, there are significant differences in the proposed models regarding their tectonic evolution. To analyze the different alternatives, the main geological observations and known facts, which the different models must explain, will be hereafter introduced to assess their consistency of the available hypothesis.

The structural vergence of the Gondwanides

Since the early descriptions of Holmberg (1884), there is consensus that the direction of transport of the Ventania fold and thrust belt (Fig. 3), as well as the deformation of the metamorphic basement north of Patagonia, has a northern vergence. This fact has been confirmed by Keidel (1916), Du Toit (1927, 1937), Harrington (1962), Tomezzoli and Cristallini (2004), and many others. The metamorphic grade in the area varies between greenschists and higher metamorphic grade rocks in the northern Patagonian basement, to prehnite-pumpellite facies in the southern Ventania belt (von Gosen & Buggisch, 1989; von Gosen *et al*., 1991; von Gosen, 2002; González *et al*., 2008, 2018). This observation confirms that the inner orogen is to the south, where the late Paleozoic magmatic arc rocks are exposed and preserved as orthogneisses (Chernicoff *et al*., 2013).

The structural studies carried out in the Ventania System (Fig. 4) indicate that both the ductile deformation of the basement and those of the lower units present a clear northeast vergence (Cucchi, 1966; Japas, 1989; von Gosen & Buggisch, 1989; von Gosen *et al*., 1990; Sellés Martínez, 2001; among others). Seismic interpretation of the Claromecó Basin and the adjacent offshore platform to the east, clearly indicates a northeast vergence of the late Paleozoic deformation for hundreds of kilometers (Pángaro *et al*., 2016).

The importance of establishing the regional vergence of the strain associated with an orogen such as that of the Gondwanides, is that it allows identifying the polarity direction of the subduction prior to the collision. As can be seen in the Himalayas, the main transport direction of the thrust sheets of the Cenozoic fold and thrust belt is to the south, consistent with a previous subduction to the north.

The deformation observed in the Ventania System as well as in the adjacent offshore platform requires a subduction polarity to the southwest beneath the North

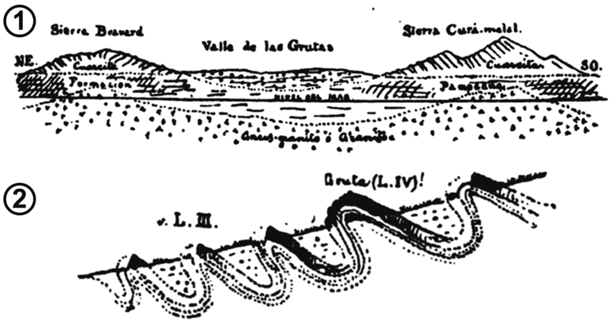

Figure 3. Pioneer illustration of Holmberg (1884) of the Sierra de Curamalal. **1,** General structural scheme of the Sierras de Curamalal and Bravard; note the unconformity interpreted with the gneiss-granitic basement; **2,** detailed structure of the quartzites of Sierra de Curamalal showing northeast vergence (note that north is on the left side of the figure).

Figure 4. 1, Regional view of the general northeast vergence of the deformation at Sierra de la Ventana; **2,** detail of a conglomerate of La Lola Formation, early Paleozoic of the Sierra de Curamalal, Ventania System. Note the ductile deformation of the clasts with top-to-northeast. For further details, see Cucchi (1966).

Patagonian Massif prior to the collision. The fold and thrust belt synthetic with the subduction polarity always has a greater development than antithetic belts. The northeast-verging deformation north of the North Patagonian Massif, which constitutes the Gondwanides, is by far greater to that existing in the south with a southwestern vergence (Rapalini *et al.*, 2010; Mosquera *et al.*, 2011; Pángaro *et al.*, 2016).

The synorogenic basins

The existence of an important sedimentary basin between the Tandilia and Ventania systems was based on gravimetric data (Kostadinoff & Font de Affolter, 1982). These data allowed to confirm the existence of a 10.5 km thick sedimentary depocenter by Introcaso (1982), developed along the western sector of the Gondwanides. This depocenter has been interpreted as a foredeep, the Claromecó's foredeep, associated with the fold and thrust belt of Ventania (Ramos, 1984). Similar conclusions came from López Gamundi and Rosello (1992), who recognized the importance of this foreland basin; new gravimetric studies showed the broad development of the basin in the province of Buenos Aires (Ramos & Kostadinoff, 2005).

Studies on the adjacent continental shelf led to identify one of the largest late Paleozoic basins of Argentina, the Hespérides Basin (Fig. 5), which in its proximal part is more than 7,000 m thick (Pángaro *et al.*, 2016). This large offshore basin has an inland depocenter represented by the Claromecó Basin, but their late Paleozoic deposits are relics of a broader basin that covered most of the Buenos Aires Province, including the Tandilia system (Harrington, 1962). The vitrinite data of the late Paleozoic sediments in Claromecó Basin, and hydrothermal studies in the Tandil rocks, show a thickness over 2,000 m of sediments of this age above the Tandilia basement, which has been eroded away along the Buenos Aires continental margin during the opening of the Atlantic Ocean (Pángaro *et al.*, 2016). Moreover, a telodiagenetic stage was determined at 254±7 Ma (K-Ar in alunite) in the Neoproterozoic cover of the Tandilia System that demonstrates a burial and exhumation stage of the Tandilia area during the Permian (Zalva *et al.*, 2007).

The basin extends north of Buenos Aires where it reaches a thickness of near 1 km at the latitude of Punta del Este Basin in Uruguay, and connects to the Parana/Chacoparana Basin. The paleogeographic reconstruction shows a large foreland basin where the Hespérides and the Karoo basins where part of the same synorogenic system with an area of 2,100,000 km^2. This basin displays large turbiditic lobes during the Late Permian spanning for more than 700 to 800 km north of the orogenic front of the Gondwanides, almost the same order of magnitude as the lobes of the Hindus and Bengal megafans south of the Himalayas orogenic front (Fig. 6). This fact is typical of collisional-related basins where, as seen in the Hindus or the Bengal megafans, giant turbiditic lobes are developed (see Miall, 1995, fig. 11.21).

The petrographic provenance studies of the sedimentary sequences preserved in the the Ventania System and

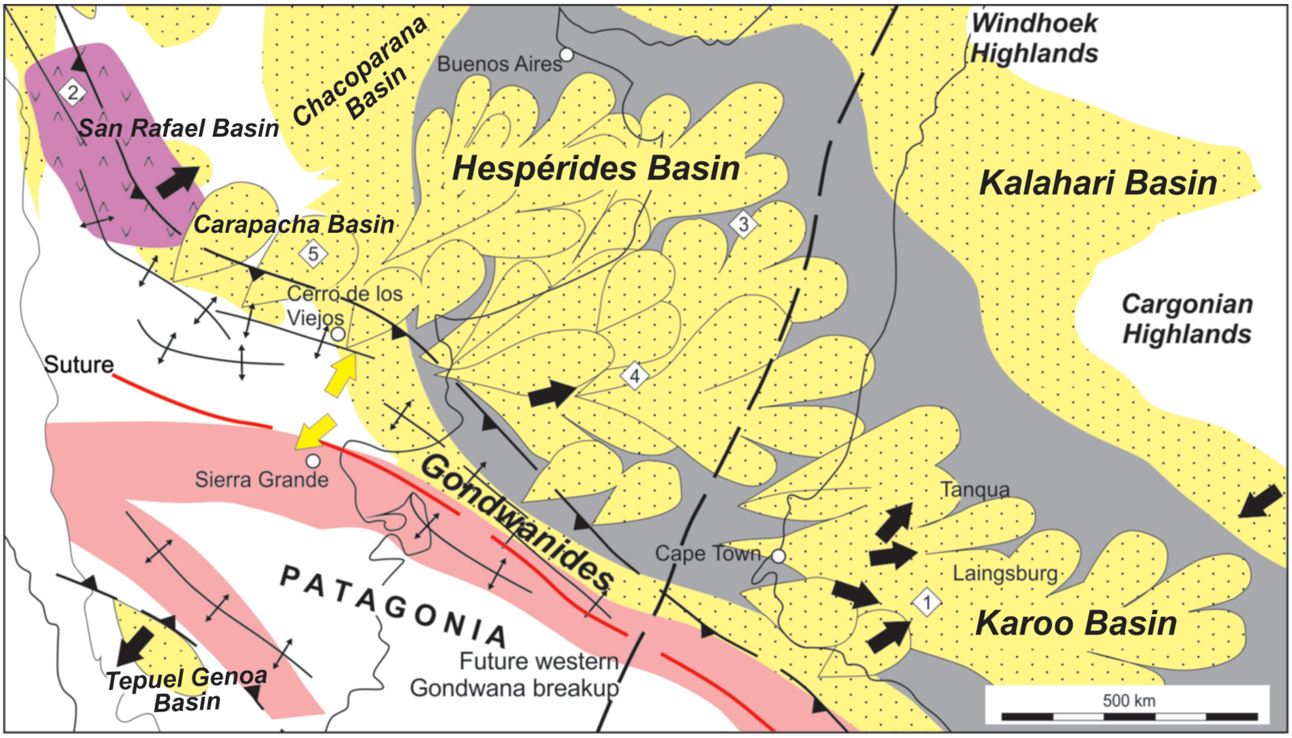

Figure 5. The Hespérides Basin associated with the Gondwanides showing the regional importance of the collision and development of the synorogenic deposits at during Middle–Late Permian (based on Pángaro *et al.*, 2016). Note that most of the Buenos Aires Province was covered by late Paleozoic deposits. Romboedrons denote control points based on wells or outcrop data; see Pángaro *et al.* (2016) for details.

the Claromecó Basin, together with the paleocurrent analyses done by Andreis *et al.* (1987, 1989), and Andreis and Cladera (1992) have shown two different areas of provenance. The early Paleozoic series were deposited in a stable platform with a northern provenance, while the late Paleozoic deposits are molassic sediments, sourced from the south. This polarity change in the provenance has been confirmed by geochronological U-Pb **LA-ICP-MS** (laser ablation-inductively coupled plasma-mass spectrometry) analyses in detrital zircons of both series in the Ventania System (Ramos *et al.*, 2014), as well as by geochemical studies of the different sedimentary units by Alessandretti *et al.* (2013).

A foreland basin as described here with a minimum length of 1,000 km in the north-south direction, and extended over 2,000 km parallel to the Gondwanides in South America and southern Africa (Fig. 5), indicates following Miall (1995), a large collisional-related foreland basin. The volume of sediments of this basin can be estimated in approximate 9,500 km^3. If an almost orthogonal dispersion of the sediments is assumed (Pángaro *et al.*, 2016), this basin could be the result of orogenic uplift of a high mountain system, with a synorogenic topography of several thousand meters distributed across 300 km north-south. These values agree with an exhumation of more than 10 km as indicated by the high grade metamorphic rocks exposed in the North Patagonian Massif and in the Chadileuvú Block at the Cerro de los Viejos orthogneiss (Fig. 5). Exhumation of such a thick sedimentary pile is further supported by the measurement of some 14 km of deformed sedimentary rocks in the offshore extension of the frontal Gondwanide orogen some 350 km east of Cerro de los Viejos locality (Pángaro & Ramos, 2012), which displays structures with a structural relief in excess of 5 km.

This group of evidence would point to the occurrence of a Late Permian continent-continent collision after a period of southwards subduction (present coordinates) as inferred by the dominant vergence of the structures that in the Ventania and Cape foldbelts have top-to-the-north vergence. Similar conclusions have been achieved in the Cape Belt of South Africa by Miller *et al.* (2016). The final stage of this collision is interpreted as Lower Triassic or younger

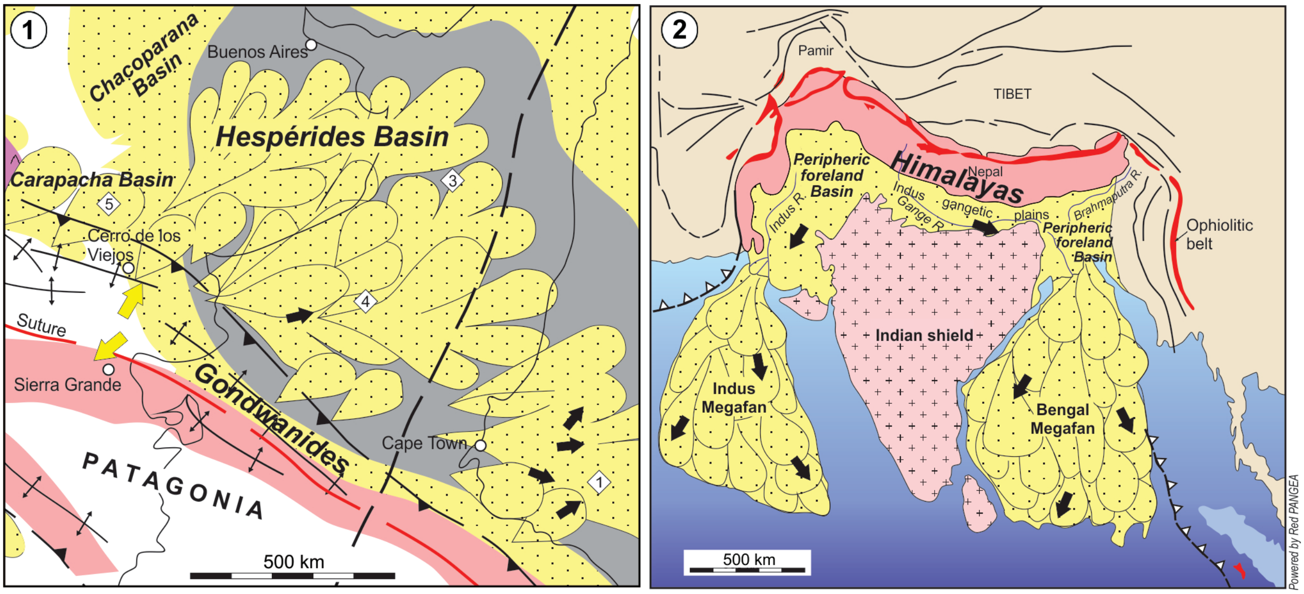

Figure 6. Comparison of the synorogenic deposits of the Hespérides Basin (**1**) with the synorogenic deposits of the Himalayas collision (**2**) (based on Ingersoll *et al.*, 1995, and Pángaro *et al.*, 2016).

(post 250 My) in the Argentinean offshore, on the basis of the observation of deformed strata correlated to the Lainsburg Formation of the Karoo Basin and younger units (Pángaro *et al.*, 2016).

The roots of the late Paleozoic magmatic arcs

There are several proposals for the location of a magmatic arc during the late Paleozoic in Patagonia. The classic Pacific margin magmatic arc, corresponding to the western belt, and a more controversial east-west belt along northern Patagonia.

a) The northern magmatic belt. The pioneer interpretations of Windhausen (1924) and Keidel (1925), followed by Marques de Almeida *et al.* (1976), among others, were based on the crustal differences between the Brazilian (and Río de La Plata) Craton and Patagonia. These authors note a contrasting geologic evolution between the cratonic area of the Brazilian Platform and the Paleozoic history of the North Patagonian Massif. This contrasting difference led Harrington (1962) to coin the term Northpatagonian Nesocraton, to highlight its Paleozoic instability.

The abundant magmatism of this region was described by Llambías *et al.* (1984), who characterized late Paleozoic plutonic rocks with a characteristic metaluminous calc-alkaline trend in tonalities and granodiorites, which in the younger granites become peraluminous with transitions to peralkaline in the more differentiate types (Caminos *et al.*, 1988). However, the geochronological data that these authors presented were based on Rb-Sr ages, not accurate enough to present day standards.

The original allochthonous Patagonia hypothesis by Ramos (1984, 1987), was based on the supposedly Carboniferous granites in the North Patagonian Massif. These granites were later dated as Permian to Triassic by Pankhurst *et al.* (1992).

New petrologic studies carried out in the northern part of the North Patagonian Massif show the complexity of the relations between magmatic rocks and the age of metamorphism (López de Luchi *et al.*, 2010; Rapalini *et al.*, 2010; Chernicoff *et al.*, 2013; Luppo *et al.*, 2019; among many others). The study of Chernicoff *et al.* (2013) postulates that the deformation and metamorphism of the metasedimentary unit of the Yaminué Complex, occurred around 261 Ma coevally with the syn-kinematic intrusion of the tonalitic orthogneisses of the Yaminué Complex. According to these authors a strong Permian deformational event took place in northern Patagonia independently of the mid-Carboniferous event of the western belt. This deformation was attributed to the frontal collision of the Patagonia (composite terrane) against Gondwana (Chernicoff *et al.*, 2013).

The occurrence of a frontal collision in northern Patagonia was also proposed by Rapalini *et al.* (2010), but with an older age for the deformation. This deformation was based on the magnetic fabrics, where plutonic rocks older than the Navarrete granodiorite of 281±3 Ma, have a strong tectonic foliation, which is absent in younger rocks. These authors related the strong deformation to a major NNE–SSW thrusting event. However, based on the apparent continuity of the crustal basement of Patagonia with Gondwana, assumed a parautochthonous origin for Patagonia, which collided after a short period of subduction of the Colorado Ocean, a temporary ocean no more than 1,000 km wide in a southwest to northeast direction. The paleomagnetic data presented by Luppo *et al.* (2019) is coherent with this hypothesis.

The thermobarometric studies show important changes in the emplacement depth of these rocks in the Yaminué area (Rapalini *et al.*, 2010). The metamorphic basement records a depth of 18±2 km, similar to the Navarrete granodiorite of 19±2 km, while the tonalitic rocks vary from 11 to 10±1 km, indicating a rapid uplift. The main problem is the lack of an adequate amount of good quality dating, to specify the ages of the different facies to know the uplift time. The studies in the basement of Cerro Los Viejos, located further to the north (see location in Fig. 5) recognized several events at 280.4±2.3, 265±13, and 261±13 Ma (Tickyj *et al.*, 1999), which indicate a complex history of deformation.

On the other hand, it is important to remark the excellent review and study of Martínez Dopico *et al.* (2017) in a region further to the west, which after a meticulous petrologic study of the La Esperanza plutono-volcanic complex, concluded that between 273 and 246 Ma these rocks did not record deformation associated with an active collision during its crystallization and cooling.

Despite the discrepancy between the ages of deformation between these studies, it is clear that there was a strong event in the Early Permian, which may have reached the Middle Permian, associated with an uplift of 8 to 9 km. There is consensus that all this northern part of the North Patagonian Massif was affected by important rhyolitic magmatism that postdated the Early Permian deformation, interpreted by Pankhurst *et al.* (2006) as produced by slab-breakoff. These rhyolitic rocks could be also an expression of lower crustal delamination after collision.

b) The western magmatic belt. The early proposal that the Paleozoic magmatic arc was located from north to south in an oblique northwest trend across Patagonia was advanced by Halpern (1972, fig. 2b), and Halpern *et al.* (1972), who indicated a Paleozoic subduction south of Buenos Aires province, which was confirmed by Forsythe (1982). The magmatic arc in this interpretation was developed parallel to the west of the Deseado Massif basement and due to the growth of the accretionary prism evolving in the present Pacific continental margin. This proposal was challenged by Ramos (1983), mainly based on the observation that in the Fuegian Andes the Jurassic deposits in the Bahía Arenal have a basal conglomerate with large garnet-bearing-gneiss clasts, which indicated the occurrence of a thick basement (see Caminos *et al.*, 1981). This magmatic arc was developed on continental crust without a large sedimentary accretion postulated by Forsythe (1982) and it was recognized along the western sector of the North Patagonian Massif and in the subsurface of the San Jorge Basin (Ramos, 1983). Based on the late Paleozoic ages presented by Bekinsale *et al.* (1977) in the Malvinas Plateau, its southern end was extended by some authors to cover the plateau (Forsythe, 1982; Ramos, 1983).

New U/Pb ages in the western sector of the North Patagonian Massif were presented by Varela *et al.* (2005) and Pankhurst *et al.* (2006), which improved the outline of the belt and constrained a mid-Carboniferous collision at 320 Ma. This interpretation postulates that subduction has a northward polarity, where the Deseado massif subducted beneath the North Patagonian Massif. The N–NW trend of the magmatic arc and associated collisional zone, according to Pankhurst *et al.* (2006), bends to the east beneath the San Jorge Basin (Fig. 7).

However, the industrial data of the subsurface of the San Jorge Basin indicate that the basement in the eastern sector of the basin is composed by metamorphic rocks, and the granitoids continue to the south into the eastern Deseado Massif (Renda *et al.*, 2019). This reconstruction of a Devonian to Carboniferous northwest trending magmatic arc and associated collisional belt coincides with the data analyzed by Varela *et al.* (2005), Chernicoff *et al.* (2013), and Ramos and Naipauer (2014). The precise location of the magmatic arc, based on new geochronological data and an

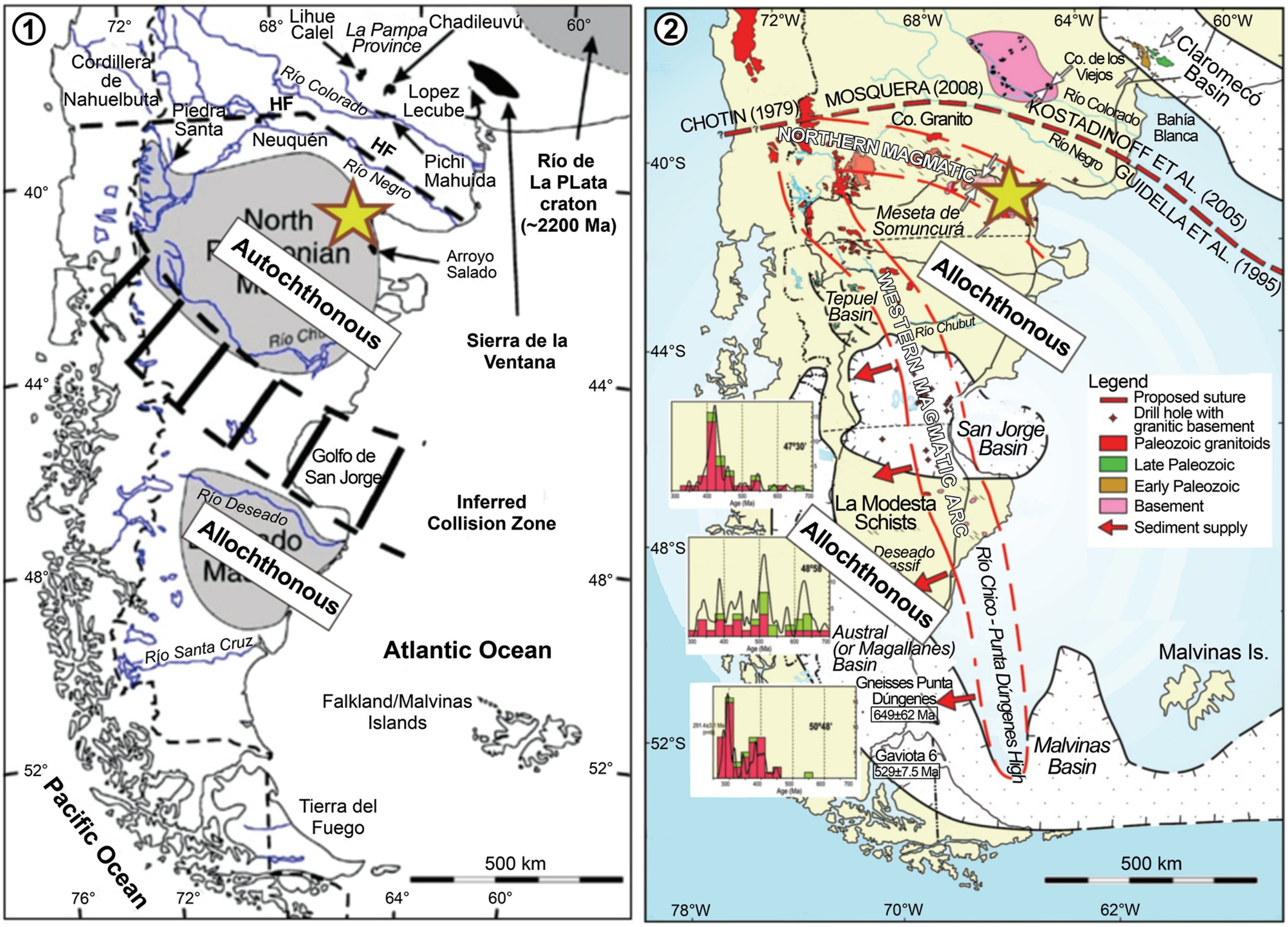

Figure 7. Alternative proposals for the late Paleozoic magmatic arc in Patagonia: **1,** based on Pankhurst *et al.* (2006); **2,** after Ramos (2008). The stars indicate the location of the fossil locality with Cambrian archeocyathids. The autochthonous and allochthonous sectors are based on Ramos (2015).

aeromagnetic dataset of Renda *et al.* (2019, figs. 1–2) confirms the location of the northern and central part proposed by Ramos (2008).

Recent studies of Oriolo *et al.* (2019) indicate along the western magmatic belt of Patagonia at the latitude of Bariloche, that amphibolite facies of a prograde metamorphism at near 300 Ma, were not related to a collisional event, disregarding the proposal of Martínez *et al.* (2012). These last authors proposed that the Chilenia terrane collided at these latitudes south of the Huincul-High boundary of Patagonia, although most of previous studies showed that the collision of this terrane is only recognized north of that boundary (see Mosquera & Ramos, 2006, and cites therein). The studies of Oriolo *et al.* (2019) clearly indicate that Devonian–Carboniferous deformation and metamorphism in the northern Patagonian Cordillera, was coeval with the deformation in the accretionary prism during an important crustal thickening estimated at about 70 km and an exhumation episode in the order of 20 km.

Data from several oil wells in northern Argentinean Tierra del Fuego, led to the recognition of late Paleozoic granitoids through K-Ar dating, which can be correlated to a Permian high temperature metamorphic event described by Hervé *et al.* (2010) and Castillo *et al.* (2016). New data in the adjacent Chilean sector recognized through U-Pb dating in zircons Permian granitoids in three wells with an age between 254 and 258 Ma by Castillo *et al.* (2017). Based on these new dating the magmatic front of the late Paleozoic arc in the southern sector should be along eastern Tierra del Fuego, modifying the early proposal of Ramos (2008). On the other hand, in Tierra del Fuego the unconformity between high-grade metamorphic rocks and the Tobífera volcanic rocks indicates a post-Permian exhumation of 8–12 km (Hervé *et al.*, 2010; Lovecchio *et al.*, 2019), compatible with the collision with a continental block, such as the Antarctic Peninsula (see Ramos, 2008).

Although Pankhurst *et al.* (2006) proposed a collision in mid-Carboniferous times, the new data of Renda *et al.* (2019) indicate that plutonism and high grade metamorphism could be as old as Late Devonian, outlining a Devonian–Carboniferous arc as the one proposed by Chernicoff *et al.* (2013) and Ramos and Naipauer (2014). The increased complexity of the Devonian setting is shown by the collision of an island arc terrane, as Chaitenia, now preserved in the accretionary prism at these latitudes (Hervé *et al.*, 2018).

Based on the previous discussion, there seems to be some consensus in the northern sector of the western magmatic belt of Patagonia along the latitude of the North Patagonian Massif. This sector was a regular Andean-type margin with no collision, except for a minor island arc, during Devonian times, which could be related with the deformation described at 350 Ma by Renda *et al.* (2019).

The southern sector of this belt might have had a collision with the Antarctic Peninsula as proposed by Ramos (2008), but more petrologic studies should be carried out to identify its precise evolution and potential sutures.

The collision of the Deseado Massif

Since the early and fragmentary interpretation of Frutos and Tobar (1975), who have proposed an early Paleozoic subduction zone across Patagonia beneath the San Jorge Basin, north of the Deseado Massif, this hypothesis has been brought back over the years. A second attempt was done by Gallagher (1990) who proposed that the Deseado Massif was accreted to Gondwana during Carboniferous–Permian times, in a similar way to that proposed more recently by Pankhurst *et al.* (2006).

There is no doubt that the presence of two independent massifs in Patagonia, the North Patagonian and the Deseado massifs, separated by a Mesozoic rift basin as the San Jorge, indicates a conspicuous first-order discontinuity in the crustal structure of Patagonia, as pointed out by Renda *et al.* (2019) on geophysical grounds. The occurrence of early Paleozoic igneous and metamorphic rocks in the Deseado Massif led Ramos (2004) to speculate that a possible collision between the two blocks could have happened in Devonian times. However, the new geochronological data makes this somewhat unlikely.

On the other hand, the lack of a well dated and continuous magmatic arc in the northern belt of Patagonia as proposed by Winter (1984) and Ramos (1987) favored the idea that a potential late Paleozoic orogen underlies the San Jorge Basin (Pankhurst *et al.*, 2006). As previously discussed, these authors fail to explain the location of the late Paleozoic magmatic arc, which crosses the basin with a north-northwest trend as depicted recently by Renda *et al.* (2019).

In recent years, many authors followed the hypothesis of Pankhurst *et al.* (2006). Among them, the work of González *et al.* (2018) interpreted the North Patagonian Massif as a composite terrane derived from Antarctica, which collided with Gondwana in Late Cambrian–Early Ordovician times. This early collision is difficult to reconcile with the evolution of Ventania in a passive margin setting as described by Ramos and Kostadinoff (2005) and Ramos *et al.* (2014), who describe an Ordovician to Devonian passive margin with dominant paleocurrents to the south. The change in the paleocurrents pattern and the uplift of the southern sector was identified from the Carboniferous to the Permian by many studies (Andreis *et al.*, 1987, 1989; Alessandretti *et al.*, 2013; Ramos *et al.*, 2014).

González *et al.* (2018) suggested that after the early Paleozoic collision of the North Patagonian Massif with Gondwana, the Deseado Massif, together with the basement of the Magallanes Basin, would approach to end up colliding in the late Paleozoic. This hypothesis fails to explain two first order facts that invalidate the proposed interpretation.

The first is that the magmatic belt of late Paleozoic rocks does not turn eastward in the San Jorge Basin (Ramos, 2008; Renda *et al.*, 2019), but on the contrary, it maintains almost a north-south trend that continues to Tierra del Fuego (Hervé *et al.*, 2010). If the magmatic arc has an almost north-south direction, the collision of this margin would produce structures parallel to it (see the structures described by Renda *et al.*, 2019), and not in an orthogonal direction that dominates the northern sector of the North Patagonian Massif.

The second fact is that both precollisional and postcollisional magmatism is located in the northern sector of the North Patagonian Massif, more than 600 km from the late Paleozoic suture proposed along the northern end of the Deseado Massif. The deformation of Ventania fold belt is

Figure 8. A new proposed location for the western magmatic arc of the late Paleozoic and tentative outline of the Southern Patagonia block that collided south of 42° S latitude. Based on Ramos (2008), Hervé *et al.* (2010), and Renda *et al.* (2019).

more than 1,000 km away, and the resulting synorogenic basin is even farther. The slab-breakoff and associated delamination is also far away of the magmatic arc.

The Carboniferous collision

The collision identified by Pankhurst *et al.* (2006) in the southwestern part of the North Patagonian Massif was based on the pattern of subduction-related magmatism, metamorphism and crustal melting at about 320 Ma. These authors interpreted a short period of ocean-floor subduction with north-eastern polarity followed by crustal anatexis during the mid-Carboniferous. However, they fail to explain the longer period of subduction, which started in the Devonian (Renda *et al.*, 2019). Although, if a collision is accepted, it is necessary to identify the boundaries of the terrane that has collided and its characteristics. The new basement ages obtained from drilling cores in the subsurface of Tierra del Fuego (Castillo *et al.*, 2017), modify the location of the magmatic arc. This allows, accepting a polarity towards the east-northeast according to Pankhurst *et al.* (2006), to outline the form and dimensions of this crustal block (Fig. 8).

A collision on the Argentinian side of the Andes would have started in the Cordón del Serrucho area, north of El Bolsón (Fig. 8) at about 42°S (Pankhurst *et al.*, 2006), in coincidence with the change in the direction of the magmatic arc. With this new outline, only the western sector of the Deseado Massif is involved in the colliding block, together with the basement of the Magallanes Basin as proposed by González *et al.* (2018). Ghidella *et al.* (2002) have proposed that at about 160 Ma the Antarctic Peninsula crustal block was detached from Patagonia. The previous location of this crustal block should be more to the north than suggested, near the Present Chiloé Island, to match the outline of the western magmatic belt. If the Antarctic Peninsula was not involved in the collision, the remaining Southern Patagonia block would be too small to produce the proposed major collision. With this configuration of the Southern Patagonia block, it is not feasible to produce the deformation and uplift of the North Patagonian Massif, the Ventania System, and the extensive synorogenic turbiditic lobes that are recorded in the Hespérides and Karoo basins.

Based on the present outline of the magmatic belt there are two alternatives to explain this configuration.

The first alternative could be a Carboniferous shallowing of the subduction zone, the flat-slab proposed of Navarrete *et al.* (2019), but for the late Paleozoic and not during Triassic as these authors suggested. Flat slab subduction between 42 and 48°S should have ceased in the Late Permian–Early Triassic to allow the development of the rift systems of El Tranquilo and the Malvinas Basin recently dated as Triassic by Lovecchio *et al.* (2019). On the other hand, this alternative would not explain the deformation, uplift, and melting described by Pankhurst *et al.* (2006) at 42°S, with an exhumation that could reach 8 to 12 km in Tierra del Fuego (Hervé *et al.*, 2010). This hypothesis explains the easterly migration of the arc in the 42–48°S segment between the North Patagonian and Deseado massifs.

The second alternative, which is favored in this work, is the collision of a block, the Southern Patagonia terrane that may include the Antarctic Peninsula. This collision would explain the deformation, metamorphism, melting, and important uplift observed.

DISCUSSION AND CONCLUDING REMARKS

The analysis of the different processes that have been used to explain the origin and evolution of Patagonia shows that none of the alternatives proposed above are suitable to explain all the geological features described. However, each of the alternatives analyzed contains partial successes, which can be integrated into a more holistic interpretation that tends to explain as reasonably as possible the Paleozoic evolution of Patagonia.

One of the most outstanding features of this geological evolution is the development of the Hespérides Basin, hundreds of kilometers of longitudinal extension, which if integrated with the evolution of the Karoo Basin (Pángaro *et al.*, 2016), allows us to recognize a continent-continent collision with a development of thousands of kilometers parallel to the margin (Fig. 9). In support of this hypothesis, the new data described in the basement south of the Cape Belt of South Africa have recognized a Permian metamorphism at 253 Ma (Miller *et al.*, 2016), consistent with that observed in the northern sector of the North Patagonian Massif. A deformation as widespread and as important on a continental scale (Fig. 9) cannot be explained by a small collision, such as that of a piece of the Deseado Massif as suggested by Pankhurst *et al.* (2006) and González *et al.* (2018).

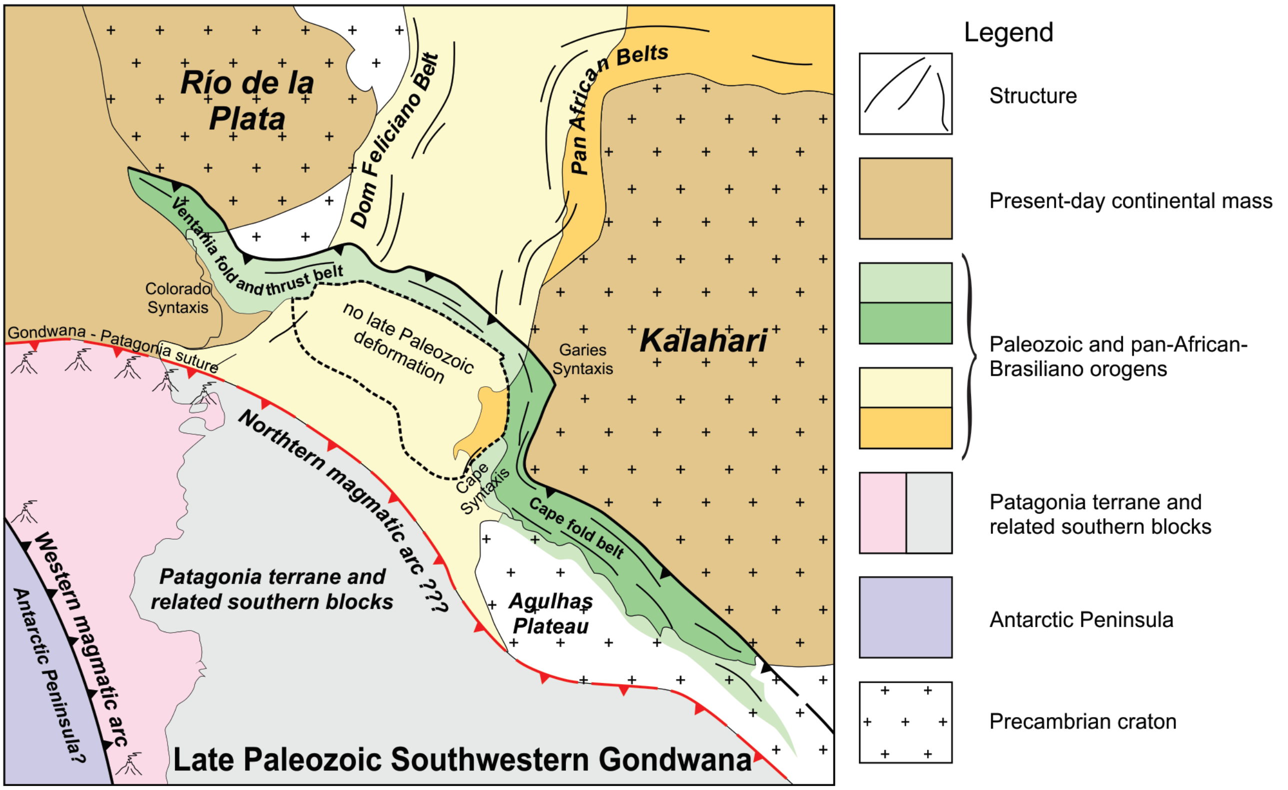

Figure 9. Reconstruction of the South Atlantic during Late Permian–Triassic times. The Colorado syntaxis after Pángaro *et al.* (2016); the Garies syntaxis after Paton *et al.* (2016) and the general paleogeography based on Pángaro and Ramos (2012), Pángaro *et al.* (2016), Miller *et al.* (2016), partially modified based on Ramos *et al.* (2017). The suture between South Africa, Patagonia and related southern terranes should continue in Antarctica. For location of the Malvinas (Falkland) Islands see Ramos *et al.* (2019).

The northern sector of the North Patagonian Massif recorded an intense magmatic activity, part of which is not related to a collisional activity as evidenced by Martínez Dopico *et al.* (2017), with the development of extensive Permo–Triassic rhyolitic plateaux (Llambías *et al.*, 1984). This activity is characteristic of a postcollisional magmatic setting, either associated with a slab-breakoff or a major crustal delamination, or both (Pankhurst *et al.*, 2006). These magmatic processes are linked from a structural point of view to an extensional collapse of the late Paleozoic thrusts developed after the compressive stage, as identified by Lovecchio *et al.* (2018). This intense magmatism partially obliterated the previous late Paleozoic magmatic arc, of which there are some relics such as the Yaminue orthogneiss, or some inherited zircons in the younger rhyolites (Chernicoff *et al.*, 2013).

The presence of archeocyathids in the North Patagonian Massif, whose analysis and paleontological study shows a clear correspondence with those of the Shackleton Limestone of Early Cambrian age (González *et al.*, 2011, 2013), further confirms the allochthonous nature of this massif. The tectonic setting of the unit bearing this archeocyatids was widely discussed by Ramos and Naipauer (2014). Attempts to associate them with other archeocyathids do not resist taxonomic screening.

The intense deformation described both in the North Patagonian Massif, by the continental collision, the structure of the fold and thrust belt, and the involvement of the basement of the massif in the internal sector south of the orogenic front with a dominant northeast vergence is illustrated in Figure 10. It is important to highlight that the subsurface basement structures of the Neuquén Basin show an orthogonal intersection of the structures that reinforces the important discontinuity between Gondwana and Patagonia as described by Mosquera and Ramos (2006).

The conceptual section presented in Figure 10 is based on the longitudinal seismic lines of the adjacent offshore shelf (Ramos *et al.*, 2014; Pángaro *et al.*, 2016). This structure

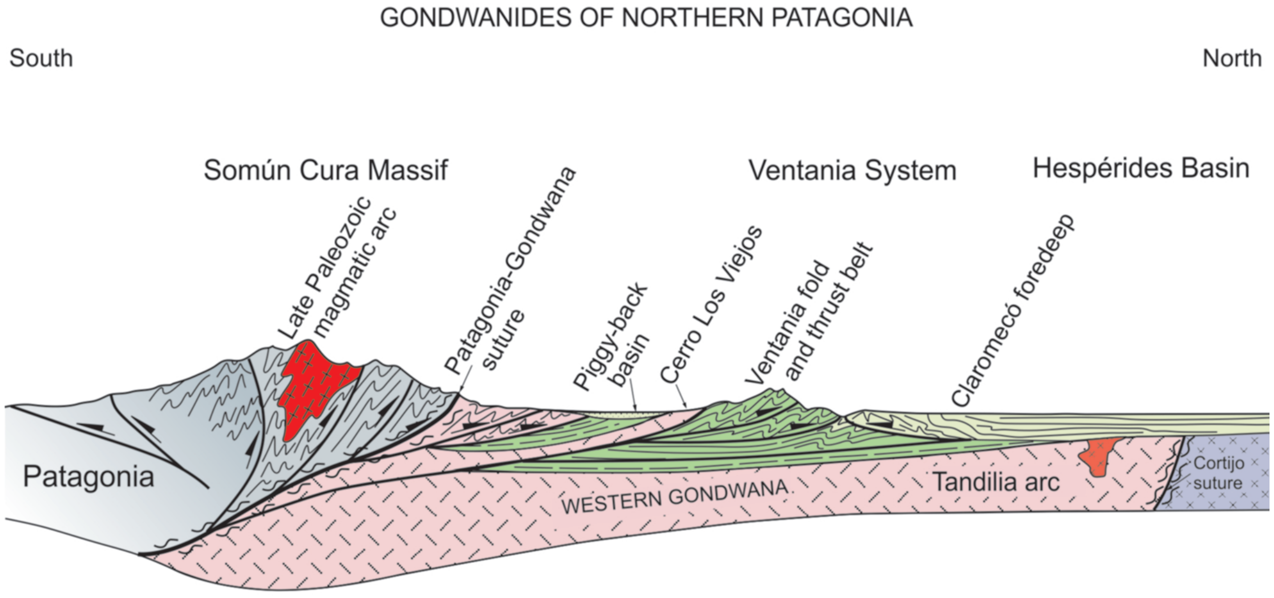

Figure 10. Schematic structural cross section of the Gondwanides of northern Patagonia restored for the end of the Paleozoic. The hinterland region developed in present Somún Cura Massif with exhumed late Paleozoic arc-granitoids is shown as well as the Ventania System with the fold and thrust belt and associated Claromecó foredeep as proximal part of the Hespérides Basin (based on Ramos *et al.*, 2014, and Pángaro *et al.*, 2016). Note that Tandilia is covered by thick Permian to Triassic deposits. Southern vergence thrusts in the Somún Cura Massif based on Rapalini *et al.* (2010), and López de Luchi *et al.* (2010).

is complemented by the south vergence thrusts described by Rapalini *et al.* (2010) and López de Luchi *et al.* (2010) in the central part of the North Patagonian (or Somún Cura) Massif. The hypothesis that suggests that the Deseado Massif in the Carboniferous was subducting towards the northeast (Pankhurst *et al.*, 2006) fails to explain this double verging thrust system, where the northern vergence is much more developed than the south as seen in continent-continent collision as the Himalayas.

In relation to the western magmatic belt, there is greater consensus that extends with a north-northwest trend from the north of the North Patagonian Massif to the south, to at least the island of Tierra del Fuego (Hervé *et al.*, 2010). However, there is no consensus on the dimensions and outline of the block that collided south of the 42°S along the Pacific margin, which has been called Southern Patagonia by Ramos (2008), which may include the Antarctic Peninsula. An alternative interpretation was proposed by Navarrete *et al.* (2019) invoking a flat-slab subduction, which if existed must have developed in the late Paleozoic and not in the Late Triassic–Early Jurassic as suggested by the authors, because the Mesozoic was an era of generalized extension in the southwestern margin of Gondwana (Lovecchio *et al.*, 2020).

It can be concluded that of all the hypotheses presented, the one that advocate a continent-continent frontal collision of Patagonia, which encompass the development of the Gondwanides along the southern margin of South Africa, is the one that contains the greatest coincidences with the observed geological data. However, research should continue to try to understand the eastward expansion of the southern sector of the western Devonian–late Paleozoic magmatic belt, which requires more structural data of its poorly exposed basement.

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