Chapter 5

The Pre-Andean phases of construction of the Southern Andes basement in Neoproterozoic-Paleozoic times

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Abstract During the late Neoproterozoic and Paleozoic times, the Southern Andes of Argentina and Chile (21º-55º S) formed part of the southwestern margin of Gondwana. During this period of time, a set of continental fragments of variable extent and allochtony was successively accreted to that margin, resulting in six Paleozoic orogenies of different temporal and spatial extension: Pampean (Ediacaran-early Cambrian), Famatinian (Middle Ordovician-Silurian), Ocloyic (Middle Ordovician-Devonian), Chanic (Middle Devonian-early Carboniferous), Gondwanan (Middle Devonian-middle Permian) and Tabarin (late Permian-Triassic). All these orogenies culminate with collisional events, with the exception of the Tabarin and a part of the Gondwanan orogenies that are subduction-related.

Keywords Paleozoic, Southern Andes, Pampean orogen, Ocloyic orogen, Famatinian orogen, Chanic orogen, Gondwanan orogen, Tabarin orogen.

1 Introduction

In the southern part of the Andean Cordillera (21º-55º S, Fig. 1A) and nearby areas, there are Neoproterozoic (Ediacaran)-Paleozoic basement relicts of variable extension. This basement has been involved in orogenic events prior to the Andean orogeny, which is related to the current configuration of the Andean chain (active since the Cretaceous).

The Paleozoic orogens were developed in the SW Gondwana paleomargin by the docking of different continental fragments, named, from N to S: Antofalla, Chi-Cu, Eastern Patagonia, Western Patagonia and Western Antarctica (Fig. 1A). These continental fragments have different extension, lithology and origin (allochthonous and parautochthonous). Some of them could be exotic and therefore considered as terranes: Chi-Cu and Western Antarctica. All these different fragments were formed by Neoproterozoic rifting of the Rodinia supercontinent. After separation, these fragments traveled forming part of lithospheric plates and subplates such as Chilenia and Cuyania, included in Chi-Cu, and Atacama belonging to the Antofalla continental fragment (Heredia et al. 2016). The Paleozoic orogens were formed, in some cases, by a subduction event prior to collision (non-collisional type) and in other cases by direct continental fragment/terrane collision with the SW Gondwana paleomargin (collisional type). All these orogenic events were sequential in time, non-collisional followed by collisional ones, or overlaped in space or time (Ramos et al. 1986; Ramos 1988a, b, 2009; Rapela et al. 2001; Ramos and Naipauer 2014; Heredia et al. 2016; among others).

The orogenies that ended with a collision event were (Figs. 1 A and B): 1) “Pampean” (Neoproterozoic-early Cambrian), produced by the accretion/collision of the Antofalla continental fragment. 2) “Ross” (late Cambrian-Early Ordovician), caused by the accretion/collision of the Eastern Patagonia continental fragment. 3) “Famatinian” (Ordovician-late Silurian), generated by the accretion/collision of two continental fragments at different paleogeographic locations: Chi-Cu (Cuyania subplate) and Western Patagonia. 4) “Ocloyic” (Middle Ordovician-Devonian), caused by a subduction/collision in the Atacama subplate. 5) “Chanic” (Middle Devonian-early Carboniferous), formed by the accretion/collision of the Chilenia subplate (western part of the Chi-Cu fragment). 6) “Gondwanan” or “San Rafael” (Middle Devonian-middle Permian), produced by the accretion/collision of the Western Antarctica fragment. This orogeny has a clear non-collisional part to the North of 38º S latitude, where the Western Antarctica fragment would not have reached those latitudes. Apart from these collisional events, Heredia et al. (2016) have recently proposed a new non-collisional type orogen located in the Patagonia and the Antarctic Peninsula, which was named “Tabarin” (late Permian-Triassic). It was formed by a subduction event underneath the SW margin of the Pangea supercontinent, prior to its breakup. Among all of these orogenic events, we do not refer to the "Ross" orogeny, because it is not recognized in the cordilleran territory, but only in the northtern part of the Atlantic Patagonian coast (González et al. 2011; Ramos and Naipauer 2014).

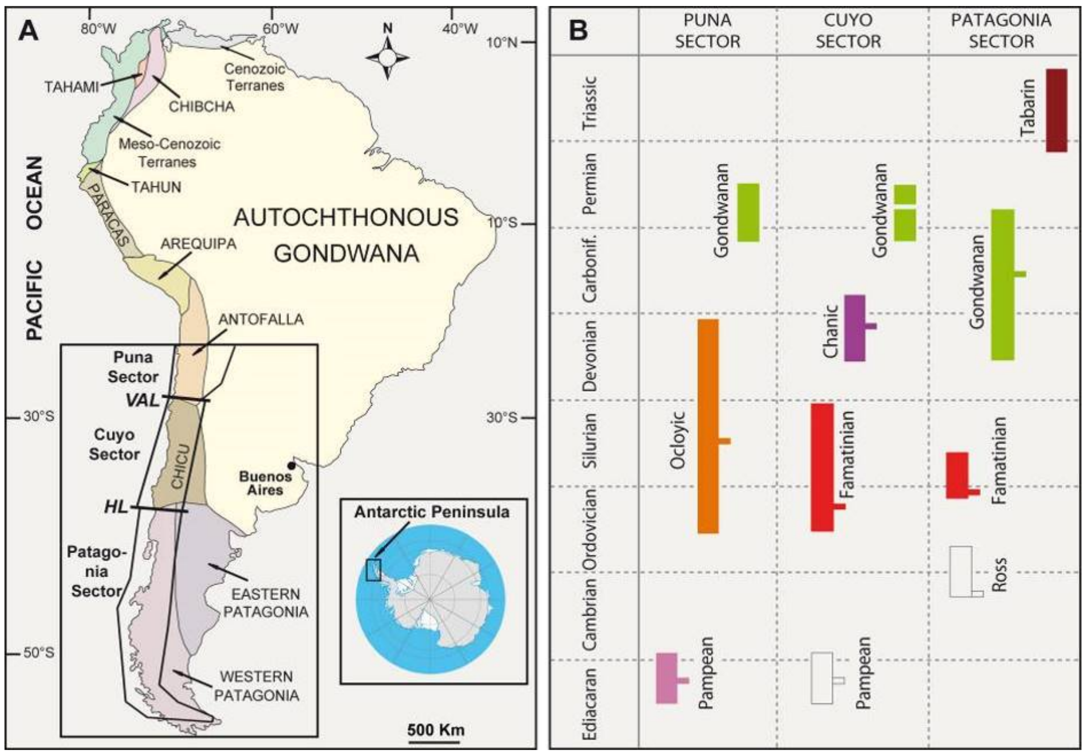

Fig. 1 A) Paleozoic terranes and continental fragments of South America and location of the Puna, Cuyo and Patagonia sectors. Modified from Ramos (2009). The Western-Antarctica fragment is mainly preserved in the Antarctic Peninsula. Lineaments: VAL- Valle Ancho, HL- Huincul. **B)** Sketch with the time distribution of the Paleozoic Andean orogenies. Uncolored bars, orogenies outside the Andes: Pampean in the Cuyo Sector and Ross in the Patagonia Sector. The small rectangles mark the beginning of collisions.

2 Main features of the Paleozoic orogenies in the Southern Andes

The imprints of the different Paleozoic orogenies are not ubiquitous along the Argentinean-Chilean Andes; only the Gondwanan orogeny had a widespread effect, although with significant variations from North to South, both in age and type (ie. collisional or non-collisional) (Fig. 1B). These observations led Heredia et al. (2016) to separate three distinct sectors in the Paleozoic basement of the Southern Andes, whose boundaries are approximately coincident with important tectonic lineaments: the Valle Ancho lineament (28º S, VAL in Fig. 1A) (Ramos 1999) and the Huincul lineament (38º S, HL in Fig. 1A) (Ploszkiewicz et al. 1984). Therefore, to the north of 28º S, the Puna Sector was affected by the Pampean, Ocloyic and Gondwanan (non-collisional) orogenies. Then, between 28º and 38º S, the Cuyo Sector records the

Famatinian, Chanic and Gondwanan (non-collisional) orogenies. Finally, south of 38º S the Famatinian, Gondwanan (collisional) and Tabarin orogenies are identified in the Patagonia Sector.

3 The Pampean orogeny

The Pampean orogeny has been a source of deep debate about its age, spatial distribution and characteristics since its initial proposal (Aceñolaza and Toselli 1976). The key geological units identifying the first order discordance that separate the Pampean orogeny of the following tectonic or orogenic cycle (i.e. Ediacaran-lower Cambrian Puncoviscana Formation/Complex and middle to upper Cambrian Mesón Group, characterized by Turner 1960; Turner and Mon 1979; Aceñolaza and Aceñolaza 2005) crop out extensively in the Eastern Cordillera and not in the nearby Pampean Ranges (see discussion in Sureda and Omarini 1999). The main records of the Pampean orogeny are broadly represented from the Argentina-Bolivia border (Puna and Eastern Cordillera) up to the Pampean Ranges showing a progresive deepening of the exposed cortical levels southward (Rapela et al. 1998; Ramos 2008). The Puncoviscana basin was originally interpreted as a passive margin basin (Jezek et al. 1985) but lately it is interpreted as a basin related to an active margin linked to variable geotectonic scenarios (Keppie and Bahlburg 1999; Zimmermann 2005; Escayola et al. 2011).

The subduction along this active margin followed by the collision of the Antofalla continental fragment (Fig. 1A) against the western border of the Gondwana continent (Pampia block, previously amalgamated to the Río de la Plata craton) generated the complex structure of the Puncoviscana Complex, showing superposed deformations with fold interferences and related cleavages. The available data are abundant but not enough for getting an unequivocal characterization of the structural evolution of the Puncoviscana Complex. Regional variations of structural data, like vergence and fold plunge, gave place to proposals of internal unconformities (e.g. Mon and Hongn 1991). Although recent studies on the age and provenance of detrital zircons are also consistent with the existence of internal discontinuities in the Puncoviscana Complex (Adams et al. 2011; Aparicio González et al. 2014) there is no still consensus about such internal unconformities. Lower to middle Cambrian granitoids, such as Cañani and Tastil batholiths, are part of the Pampean arc, although at least one of the facies of the Tastil batholith postdated the deposition of the shelf clastic sedimentary sequences filling the early Cambrian-Lower Ordovician basins (Hongn et al. 2010b).

Outcrops of units preserving the Pampean metamorphic and magmatic events at low crustal levels are very sparse in the Puna and Eastern Cordillera. In contrast, they are largely reperesented in the Pampean Ranges (Grissom et al. 1998; Rapela et al. 1998).

4 The Ocloyic orogeny

The Ocloyic deformational phase was defined by Turner and Méndez (1975) for identifyng the deformational events that generate the discontinuity between Ordovician and Silurian successions in the Eastern Cordillera. New researches strongly improved the knowledge of the Paleozoic rocks in NW Argentina by recognizing and characterizing deformational, magmatic, metamorphic and stratigraphic features related to Paleozoic orogenic events. However, the original definition of the Ocloyic phase has lost its identity and it was used in several senses in order to define orogenies or deformational phases at different areas and times between the Ordovician and the Devonian (Ramos 1986, 1988b, 1999; Mon and Hongn 1987; Bahlburg and Hervé 1997; Astini and Dávila 2004; Collo et al. 2008; Heredia et al. 2012; Moya 2015).

Here we describe the main events related to the Ocloyic orogeny in the sense of Heredia et al. (2016). Based on the age, geotectonic evolution, paleogeographic situation and deformational features, these authors propose to restrict the use of Ocloyic orogeny to the Puna Sector. The Ocloyic orogeny started in the Middle Ordovician and ended in the Late Devonian (Fig. 1B), however in this chapter we also describe ductile pre-orogenic extensional deformations, developed in Early Ordovician times, which can be confused with some contractional deformations related to subsequent orogenic processes.

After the accretion of the Antofalla terrane to the Gondwana continent during the early Cambrian (Pampean orogeny), a subduction zone was installed along the new western Gondwana margin. The western border of the Puna preserves the related magmatic arc (WP in Fig. 2A), where the oldest components probably are of late Cambrian age (Moya 2015), although the arc achieved its climax during the Early Ordovician (Tremadocian-Floian) (Coira et al. 1999; Zimmermann et al. 2010, Niemeyer et al. 2014) reaching the middle Silurian (ca. 431 Ma) in the Chilean Andes (Vergara 1978) (see Chapter 6).

Changes in plate dynamics have led to major tectonomagmatic events in the Puna and surrounding areas during the upper Tremadocian and lower Floian times. The thermal anomaly related to the back-arc extension gave place to metamorphic, magmatic and deformation processes well defined along the eastern border of the Puna (Hongn et al. 2014). Imprints of these processes are well-preserved mainly in the Ordovician units northward of 24° S and also in the Pampean basement southwards of this latitude. The Ordovician magmatic belt along the eastern border of the Puna (EP in Fig. 2A) (Méndez et al. 1973) is currently thought as a result of the back-arc thermal anomaly (Coira et al. 2009; Sola et al. 2010) in contrast to some proposals interpreting these rocks as a magmatic arc related to a second subduction zone (Ramos 2008). A high-T and low-P metamorphism transformed the Puncoviscana Complex in schists, gneisses and migmatites, mainly in the eastern border of the southern Puna, the SW area of the Eastern Cordillera (Sola et al. 2013; Hongn et al. 2014) and their southern prolongations in the Northern Pampean Ranges (Finch et al. 2015) (Fig. 2A). The Early Ordovician metamorphic and magmatic complexes display well-defined structures, such as folds of several orders with related minor structures (foliations and lineations) and mylonitic belts, at different scales and with different kinematics (Hongn and Riller 2007; Hongn et al. 2014; Finch et al. 2015). Most of these structures are contemporary to the late Tremadocian-Floian magmatic-metamorphic events according to most of the available ages.

The Early Ordovician extensional process resulted in a thinned continental crust under the back-arc basin that allows individualizing the Atacama subplate, which approximately coincides with the old Antofalla plate (Heredia et al. 2016).

In the westernmost Puna and the Eastern Cordillera, Hongn and Vaccari (2008) and Moya (2015) describe internal unconformities between sedimentary successions of Tremadocian and Floian ages that record the Early Ordovician deformation at shallower crustal levels. Therefore, the intensity of the deformational, metamorphic and magmatic events of late Tremadocian-Floian age decreased eastward and westward from the eastern border of the Puna. Becchio et al. (1999) and Lucassen et al. (2000), among others, proposed that the early Paleozoic events in the Puna could reflect processes of crustal reworking in a mobile belt related to a protracted thermal anomaly.

The analysis of Ordovician deposits of the Puna and Eastern Cordillera, reveals changes in the basin setting from extensional to compressional conditions in Middle Ordovician times (Bahlburg 1990; Bahlburg and Hervé 1997; Astini and Dávila 2004; Moya 2015) indicating the start of the subduction-related Ocloyic orogeny.

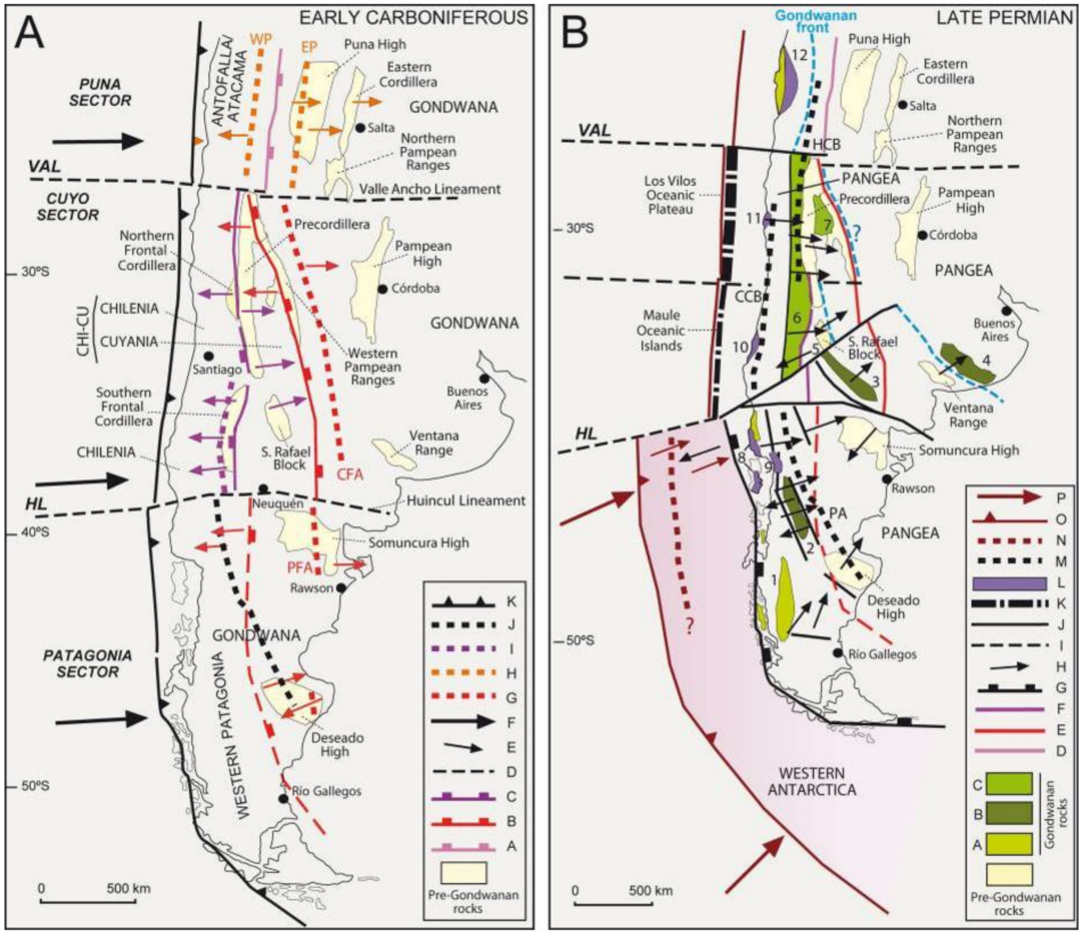

Fig. 2. Main geotectonic features in the Paleozoic basement of the Argentinean-Chilean Andes and their foreland in: **A)** Early Carboniferous times. Sutures (little rectangles mark the upper plate): A- Pampean, B- Famatinian, C- Chanic. D- Limits between the Paleozoic Andean sectors that coincide with Andean lineaments: VAL- Valle Ancho, HL- Huincul. E- Vergences of Paleozoic structures (Pink: Pampean, Orange: Ocloyic, Red: Famatinian, Purple: Chanic). F- Displacement sense of the proto-Pacific lithosphere to Gondwana margin. Magmatic Arcs: G- Famatinian magmatic arcs: CFA- Cuyo Famatinian arc (late Cambrian-Middle Ordovician), PFA- Patagonian Famatinian arc (Ordovician), H- Ocloyic magmatic arcs: EP- Eastern Puna arc (Ordovician), WP- Western Puna arc (late Cambrian-middle Silurian), I- Chanic magmatic arc (Devonian), J- Gondwanan magmatic arc of the Patagonia Sector (late Silurian-late Carboniferous). K- Gondwanan subduction zone (Orange triangle: former Ocloyic subduction in the Puna Sector). **B)** Late Permian times. Main Gondwanan rocks outcrops: A- Fore-arc pre- and synorogenic rocks: 1- Eastern Andes metamorphic complex, 8 to 12- Eastern Series of the Coastal Cordillera (same names as the Western Series described in L). B- Back-arc pre-orogenic rocks and peripheral foreland basin synorogenic rocks: 2- Tecka-Tepuel, 3- Southern San Rafael, 4- Claromecó, 5- Northern San Rafael. C- Retrowedge pre-orogenic rocks and retroarc foreland basin synorogenic rocks: 6- Río Blanco, 7- Paganzo. Pre-Gondwanan sutures: D- Pampean, E- Famatinian, F- Chanic. G- Gondwanan suture (little black rectangles mark the upper plate). H- Vergences of Paleozoic structures (Black- Gondwanan, Maroon- Tabarin). I- Limits between the Paleozoic Andean sectors that coincide with Andean lineaments: VAL- Valle Ancho, HL- Huincul. J- Trace of Gondwanan structures. K- Oceanic reliefs accreted to Gondwana. L- HP metamorphic rocks related to the Gondwanan basal accretionary prism (Western Series) emplaced over the fore-arc basin (Eastern Series): 8- Puerto Montt-Chiloé, 9- Bariloche, 10- Pichilemu-Constitución, 11- Los Vilos, 12- Antofagasta. M- Gondwanan magmatic arcs: PA- Gondwanan magmatic arc of the Patagonia Sector (late Silurian-late Carboniferous), CCB- Coastal Cordillera batholith (late Carboniferous), HCB- High Cordillera batholiths (early Permian). N- Tabarin magmatic arc (Triassic?). O- Southwestern margin of Pangea: triangles mark the position of the Tabarin subduction. P- Displacement sense of the last proto-Pacific lithosphere to Pangea margin.

This change in tectonic regime is imprinted at deeper crustal levels in the Cachi Dome of the Eastern Cordillera (Tubía et al., 2012), where migmatite and granitoids allow precisely date the extensional event at ca. 475 Ma, but not the subsequent shortening event (Hongn et al. 2014), which was dated by Ramos (1972) at ca. 465 Ma (age of the first Ocloyic synorogenic deposits). The magmatic activity starts to vanish after this first compressional event.

The thick turbidites successions exposed in the central Puna were deposited in a compressional setting, related to subduction, during the Middle Ordovician and early Silurian times (Ramos 1986; Bahlburg and Hervé 1997; Heredia et al. 2016). These levels are strongly folded and metamorphosed at very low-grade metamorphic conditions (Mon and Hongn 1987; Astini 2008) during latter phases of the Ocloyic deformation.

The Ocloyic subduction probably ends in the middle Silurian (ca. 431 Ma), when the magmatism was drastically reduced or disappeared and the inversion of the back-arc basin starts, as a result of the approach and later collision of the Atacama subplate with Gondwana (Heredia et al. 2016). This last orogenic episode finally forms a N-S and double-vergent orogenic belt (Fig. 2A) with scarce internal zones and clear east-vergences in the Eastern Cordillera (Alonso et al. 2012), to the east of the older Pampean suture (Fig. 2A). In the Puna and the Chilean Andes (western branch of the Ocloyic orogen), the structures related to the Ocloyic orogeny do not show a clear vergence in the late Ordovician levels. This allows identifying two well-defined segments, the northern one without a clear generalized vergence and a southern portion (Salta and Catamarca provinces) with a marked west-vergence (Fig. 2A). These variations argue for models including superposed deformations (subduction- and collision-related), structural systems with main and secondary vergences (retro-vergent structures), transpression and, probably, a lack of systematic research. The Ocloyic orogeny finished with the accretion of the Atacama subplate to Gondwana in the Late Devonian (Fig. 1B), although some authors, like Díaz-Martínez (1996), consider that reached the early Carboniferous.

The dominant N-S structural trend of the Ocloyic structures enhaced their reactivation during the following orogenies (Hongn et al. 2010a; Alonso et al. 2012). Thus, the Ocloyic eastern front seems to coincide with the Eastern Cordillera Andean front and the western orogenic front probably coincides with the eastern border of the Coastal Cordillera (Heredia et al. 2016) (Fig. 2A).

5 The Famatinian orogeny

The Famatinian orogeny (Aceñolaza and Toselli 1973) can be recognized in the Cuyo and Patagonia sectors (Fig. 1B) and in both areas it ends with a collisional event. This orogeny can be related to the accretion/collision of two fragments with a different paleogeographic and allochthonous position: Chi-Cu and Western Patagonia (Fig. 1A). According to some authors, the Chi-Cu continental fragment (Cuyo Sector) is an allochthonous fragment, a terrain with a peri-Laurentic origin (Ramos et al. 1986; Dalla Salda et al. 1992; Astini et al. 1995; Keller 1999; Thomas and Astini 2003; Ramos 2004, among others). For some other authors, this same fragment could not be considered a terrain but could be attributed to a peri-Gondwanic origin (Baldis et al. 1989; Aceñolaza et al. 2002; Finney et al. 2003; López and Gregori 2004; Finney 2007; González-Menéndez et al. 2013). As regards the Western Patagonia (Patagonia Sector), it seems to be a peri-Gondwanic fragment (Heredia et al. 2016).

Although this orogeny presents N-S variations in age, it could be considered as Ordovician-Silurian (Fig. 1B). In the Cuyo Sector, east-vergent structures suggest a relationship to a non-collisional orogen (Andean Type), generated in the Middle Ordovician (Fig. 1B) close to the active margin of Gondwana (ca. 460 Ma) (Astini and Dávila 2004), where the subduction was already active since the late Cambrian (ca 500 Ma). The collision between Chi-Cu (Cuyania subplate) and Gondwana took place from the Late Ordovician (ca. 460 Ma) (Astini et al. 1995; Pankhurst et al. 1998) and extended up to the Silurian-Devonian limit (ca. 420 Ma) (Mulcahy et al. 2011) (Fig. 1B). In the Patagonia Sector there is no evidence of precollisional contractional deformation related to the subduction that was originated underneath the Gondwana margin. The Famatinian deformation in Patagonia affects pre-orogenic granitoids related to the Famatinian magmatic arc (PFA in Fig. 2A), which reach the Upper Ordovician (ca 452 Ma), according Loske et al. (1999). Thus, the Famatinian orogeny was generated by the subsequent collision of the Western Patagonia continental fragment in the Late Ordovician (Heredia et al. 2016) (Fig. 1B). This orogeny ends in this sector in the Wenlock (Middle Silurian, ca 430 Ma), the age of the fossils from the postorogenic sequence (Müller 1965; Manceñido and Damborenea 1984).

The Famatinian orogenic belt has an N-S trend that rotates towards NNW-SSE in its northern part (Fig. 2A). This belt presents a double vergence, though only its western branch, developed over Cuyania (Fig. 2A), developed on the surroundings of the Cordillera de los Andes (Astini et al. 1995; Astini and Dávila 2004). In this sense, Famatinian structures can be recognized in the Cuyo Sector in a broad part of the northern border of the Precordillera range, while towards the south, these structures are restricted to the Eastern Precordillera (Heredia et al. 2016). Furthermore, no Famatinian structures can be seen in the San Rafael Block (Heredia et al. 2016) (Fig. 2A), which constitutes the extension of the Precordillera towards the south. In the Patagonia Sector, these structures can be recognized in most part of the Argentinean side of the Patagonia.

This orogen presents some quite well developed internal zones in which high-grade metamorphic conditions can be seen, especially in the Patagonia Sector (Loske et al. 1999; Giacosa et al. 2002, 2010; Serra-Varela et al. 2016) in which up to three penetrative cleavages are developed (Serra-Varela et al. 2016; Heredia et al. 2016). These cleavages seem to be related to both folds and shear zones. In the internal zones of the Cuyo Sector, close to the Famatinian suture (northern Precordillera, Fig. 2A), the Grenvillian Mesoproterozoic basement (Varela et al. 2011) and mid-crustal fragments of the Famatinian magmatic arc (CFA in Fig. 2A) are involved in the Famatinian deformation (Otamendi et al. 2009). However, in both areas, scarce synorogenic granites were identified. As regards the external zones and foreland basins, they are only well preserved in the western branch of the Cuyo Sector (Precordillera).

6 The Chanic orogeny

The Chanic orogeny (Ramos et al. 1986) has a Middle Devonian to early Carboniferous age (Davis et al. 1999, 2000; Willner et al. 2011; Heredia et al. 2012, 2016; Colombo et al. 2014). It is only recognized in the Cuyo Sector (Fig. 1B), where it has been related to the accretion/collision of the westernmost Chi-Cu subplate (Chilenia) with Gondwana (Fig. 2A).

This orogeny shows different characteristics from N to S. In the north, due to the lack of oceanic crust separating the Cuyania and Chilenia sub-plates, subduction was not required to produce its collision (González-Menéndez et al. 2013; Heredia et al. 2012, 2016). In the south, related to the Devonian Chanic subduction, an incipient magmatic arc was developed (Fig. 2A) and also pre-collisional contractional deformations took place in high-pressure metamorphic conditions (Massonne and Calderón 2008; Willner et al. 2011; García-Sansegundo et al. 2016). This processes only affecting the eastern Chilenia margin in Devonian (Tickyj et al. 2011) and Middle Devonian times (ca. 390 Ma, according to Willner et al. 2011). During the subsequent collision of Chilenia with Gondwana (western margin of the previously accreted Cuyania subplate) in Late Devonian times (ca. 374 Ma, according to Heredia et al., 2016), the high-pressure rocks were exhumed and emplaced over Chilenia. Moreover, remains of the ancient oceanic crust that separated the two sub-plates (ophiolitic klippes described by Davis et al. 2000) and some fragments of Chilenia were emplaced over the Gondwana margin (Giambiagi et al. 2014; Farias et al. 2016), marking the Chanic suture (Fig. 2A). In this southern part of the Chanic orogen the internal zones are well developed, mainly on the eastern Frontal Cordillera and the western part of the Precordillera. In these zones the deformation is developed in medium-grade metamorphic conditions, recognizing shear zones, up to two pervasive cleavages related to folds and some synorogenic granites (Heredia et al. 2012; Giambiagi et al. 2014; Giacosa et al. 2014; García-Sansegundo et al. 2014b, 2016; Farias et al. 2016). By contrast, the northern part of the Chanic orogen is produced by inversion of the rift that separated Cuyania and Chilenia (Fig. 2A), resulting in a marine basin developed over a thin continental crust. This rift inversion produced a less intense deformation, which resulted in a narrower orogen with barely internal zones, where a locally pervasive cleavage, associated with very low metamorphic conditions (von Gosen 1997), has been developed. In this context, thrust and related folds are the main structures, which form a well-preserved fold and thrust belt in the eastern branch of the Chanic orogen, located on the Precordillera (Álvarez-Marrón et al. 2006). The foreland areas of the Chanic orogen are only well preserved in this eastern branch (over Cuyania/Gondwana), and their main synorogenic basins have been dated as Tournaisian-Visean (Gallastegui et al. 2014; Colombo et al. 2014).

The Chanic orogenic belt trends N-S and shows a double vergence (Fig. 2A), to the east in the eastern branch, developed on Cuyania, and to the west in the western one developed on Chilenia. The western branch is recognized throughout the High Andes (Alta Cordillera de los Andes) between 28º-38º S, while the structures associated with its eastern branch are recognized in the Central Precordillera and in the San Rafael Block (Heredia et al. 2016). Both the Chilean Coastal Cordillera and the Eastern Precordillera are not affected by this orogeny, which suggests that the current western boundary of the High Cordillera (Alta Cordillera de los Andes) at this latitude is a Chanic heritage and it can be correlated with the western limit of this Paleozoic orogen.

7 The Gondwanan orogeny

The Gondwanan orogeny (Ramos 1988b) can be recognized in all the pre-Andean basement of the Argentinean-Chilean Andes, but shows significant variations from N to S. In the Patagonia Sector this orogeny is related to the accretion-collision of Western Antarctica with Gondwana (Heredia et al. 2016) (Figs. 1B and 2B). In the Cuyo and Puna sectors it is related to subduction developed under the Gondwanan margin (Figs. 1B and 2B), which started in the early Carboniferous (Hervé 1988; Rebolledo and Charrier 1994), specifically in the Visean (ca. 337 Ma) (Heredia et al. 2016). In the Puna Sector the Gondwanan subduction is a reactivation of the Ocloyic subduction. Therefore, in those sectors the Gondwanan orogeny took place from the late Carboniferous to the middle Permian (Fig. 1B).

The Gondwanan orogen is very wide and shows an arcuate shape (Fig. 2B), so that in the northern part it is oriented N-S and in the southern part almost E-W (Giacosa et al. 2012). In the Patagonia Sector, the subduction process that allowed the accretion of Western Antarctica to Gondwana began in the late Silurian and probably led to the development of an Andean-type orogenic belt from the Middle Devonian (ca. 391 Ma) to the early Carboniferous (335 Ma) (Fig. 1B) as proposed by Heredia et al. (2016) based on a reinterpretation of data provided by Pankhurst et al. (2006) and Martínez et al. (2012). This orogenic belt shows the characteristic double vergence of the collisional orogens. So, in the branch developed over the Gondwanan margin, the vergence of the structures is to the internal (concave) part of the Gondwanan arc (Fig. 2B), while the structures of the branch developed in the Western Antarctica (less preserved) show a vergence pointing to the external (convex) arc. However, the entire Patagonian region is located in the Gondwanan branch, as the branch developed on Western Antarctica has moved to the south since the Mezosoic and it can be only recognized in the Antarctic Peninsula (Fig. 1A).

The internal zones of this orogen show evidence of up to three deformational episodes; two of them developed up to high-grade metamorphic conditions accompanied by shear zones and anatectic synorogenic granites. In these zones, the remains of a basal accretionary prism, previously deformed under HP-LT metamorphic conditions (Willner et al. 2004), are also preserved (Fig. 2B). These rocks were thrusted and placed over the margin of Gondwana, hundreds of kilometers away from the original subduction zone (García-Sansegundo et al. 2009) (Fig. 2B). In the Antarctic Peninsula (Western Antarctica plate), Loske et al. (1990) dated the Gondwanan metamorphism as late Carboniferous-early Permian (ca. 315-291 Ma).

The external zones and foreland basins of the Gondwanan collisional orogen in the Gondwanan branch are well preserved away from the Andean Cordillera, for all the Patagonian territory, and the orogenic front is located close to the Sierra de la Ventana, to the north of the Huincul lineament (38º S) (Fig. 2B), where the deformation would have a late early Permian age (López-Gamundi et al. 1995).

In the non-collisional part of the Gondwanan orogen (north of 38º S), three different segments can be distinguished (Fig. 2B) according to (i) the variation of the subduction angle through the time and (ii) the characteristics of the oceanic reliefs that reached the trench at the end of the orogenic process. Thus, in the Puna Sector and in the southern part of the Cuyo Sector the subduction angle remained fairly inclined during all the orogenic process, while in the northern part of the Cuyo Sector the subduction was a flat-slab type (Ramos and Folguera 2009) during the late Carboniferous-early Permian (ca. 300-280 Ma) (Alonso et al. 2005, 2014; García-Sansegundo et al. 2014a). The development of the flat-slab subduction allowed migration of the deformation, the arc magmatism (Parada 1990; Hervé et al. 2014; Sato et al. 2015) and the synorogenic retroarc depocenters (Busquets et al. 2005, 2013) to far more eastwards positions than in the two other segments, so that the deformation reached the western Pampean Ranges, nearby the Famatinian suture (Fig. 2B). In the flat-slab segment the Gondwanan orogeny ended in the middle Permian (ca. 265 Ma, Fig. 1B) when an "oceanic plateau" reached the Gondwana continental margin (Fig. 2B) and forced the migration of the deformation to the trench (García-Sansegundo et al. 2014a). The approach of this submarine relief to the continent led to the steepening of the subduction slab and its final docking led to the exhumation of the Gondwanan basal accretionary prism. This accretionary prism was thrusted for tens of kilometers over the fore-arc basin, reaching the vicinity of the volcanic arc (García-Sansegundo et al. 2014a).

In the southern part of the Cuyo Sector the Gondwanan orogeny ends earlier, in the early Permian (ca. 280 Ma, Fig. 1B) (Ramos et al. 2011; Giacosa et al. 2014), with the arrival of oceanic islands to the Gondwanan margin (Hyppolito et al. 2014) (Fig. 2B). This process also led to the exhumation of the basal accretionary prism, although it is not placed so near of the arc as in the central segment (Heredia et al. 2016) (Fig. 2B). The Gondwanan deformation in this segment does not seem to have surpassed eastwards of the San Rafael Block.

In the Puna Sector, the Gondwanan deformation also ended in the middle Permian (Fig. 1B). Here the basal accretionary prism was also exhumed and placed far away from the old margin (after Lucassen et al. 1999 and Tomlinson et al. 2012), suggesting that some sort of oceanic relief could have docked to this region of the Gondwana margin. However, the Gondwanan deformation is practically limited to the Chilean Andes (Fig. 1B), indicating that (i) this subduction was the steepest of all of them, and/or (ii) the relief that approached the Puna margin did not exist or was smaller than those accreted in the adjacent Cuyo Sector. Furthermore, the late Carboniferous and Permian sediments of the eastern Argentinean Andes at this latitude (Eastern Cordillera) have been related to extensional basins.

The internal zones of the Gondwanan subduction orogen (named Western Series by the Chilean authors) are restricted to the exhumed remains of the basal accretionary prism, where four deformation events can be recognized, mainly represented by tectonic foliations. The first of these foliations developed in the basal accretionary prism under HP-LT metamorphic conditions and is preserved as relictic into albite and/or garnet porphyroblasts (Willner et al. 2004). The other three, were developed in relation to the exhumation of the basal accretionary prism (García-Sansegundo et al. 2014a) and, excluding the last one, they are pervasive. As in all the Andine-type orogens, this orogen shows a single vergence (Fig. 2B), in this case to the east, although the presence of structures with an opposite vergence is common near the accretionary prism zone.

8 The Tabarin orogeny

The Tabarin orogeny is only recognized in the Patagonia Sector and has been related to an early Permian-Triassic subduction episode (Heredia et al. 2016). The subduction zone was located along the western margin of the Western Antarctica continental fragment (Heredia et al. 2016), previously accreted to Gondwana during the Gondwanan cycle, which is now part of the Pangea supercontinent (Fig. 2B). The Tabarin orogeny is late Permian-Triassic in age (ca. 265-208 Ma) (Hervé 1992; Heredia et al. 2016) and is best preserved in the Antarctic Peninsula. In this area, several authors reported compressive deformations of this age (Thomson 1975; Smellie 1991; Hervé 1992, Muñoz et al. 1992; del Valle et al. 2007) as well as the presence of retroarc synorogenic deposits, typical of subduction-related orogens (del Valle et al. 2007). In the surroundings of the Antarctic Peninsula, the main structures related to the Tabarin orogeny are folds and thrusts with NW-oriented trend and NE vergence (Fig. 2B), developed under very low grade to non-metamorphic conditions (Muñoz et al. 1992; del Valle et al. 2007). However, these structures and deposits were initially attributed to the Gondwanan orogeny.

Since the late Permian (ca. 265 My, Tickyj et al. 1997) and especially during the Triassic, the entire Patagonian territory, including the Andes, changed from a post-Gondwanan extensional regime to a new setting in which compressional stresses are transmitted from a new subduction zone developed to the W and SW, underneath the margin of the new Pangea supercontinent (Heredia et al. 2016) (Fig. 2B). In this context, probably transpressive, the Tabarin orogeny resulted in several NW-SE sinistral shear zones (Coira et al. 1975; Proserpio 1978; Nullo 1978; Volkheimer and Lage 1981; Llambías et al. 1984; von Gosen 2003; von Gosen and Loske 2004; Pankhurst et al. 2006, among others), which overlapped the subparallel Gondwanan structures, affecting also some post-Gondwanan plutons with ages up to ca. 208 Ma (Rapela et al. 1992).

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