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# Three stages in the Late Paleozoic to Triassic magmatism of southwestern Gondwana, and the relationships with the volcanogenic events in coeval basins

Ana María Sato [a,*], Eduardo J. Llambías [a], Miguel A.S. Basei [b], Carlos E. Castro [c]

[a] *Centro de Investigaciones Geológicas (UNLP-CONICET). Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Calle 1 N° 644, B1900TAC, La Plata, Argentina*

[b] *Centro de Pesquisas Geocronológicas (Instituto de Geociências, Universidade de São Paulo), Rua do Lago 562, CEP 05508-080, São Paulo, SP, Brazil*

[c] *Departamento Ingeniería de Minas, Facultad de Ingeniería, Universidad Nacional de San Juan, Av. Libertador San Martìn 1109 Oeste, 5400 San Juan, Argentina*

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ABSTRACT

The intermediate to acid Choiyoi Magmatic Province is the most conspicuous feature along the Late Paleozic continental margin of southwestern Gondwana, and is generally regarded as the possible source for the widespread ash fall deposits interlayered with sedimentary sequences in the adjacent Gondwana basins. The Choiyoi magmatism is geologically constrained between the early Permian San Rafael orogenic phase and the Triassic extensional Huarpica phase in the region of Argentine Frontal Cordillera, Precordillera and San Rafael Block. In order to better assess the Choiyoi magmatism in Argentine Frontal Cordillera, we obtained 6 new LA-ICPMS U–Pb ages between 278.8 ± 3.4 Ma and 252.5 ± 1.9 Ma from plutonic rocks of the Colangüil Batholith and an associated volcanic rock. The global analysis of age data compiled from Chilean and Argentine Late Paleozoic to Triassic outcrops allows us to identify three stages of magmatism: (1) pre-Choiyoi orogenic magmatism, (2) Choiyoi magmatism (286–247 Ma), and (3) post-Choiyoi magmatism related to extensional tectonics. In the Choiyoi stage is there an eastward shift and expansion of the magmatism to the southeast, covering an extensive region that defines the Choiyoi magmatic province. On the basis of comparison with the ages from volcanogenic levels identified in the coeval Gondwana basins, we propose: (a) The pre-Choiyoi volcanism from the Paganzo basin (320–296 Ma) probably has a local source in addition to the Frontal Cordillera region. (b) The pre-Choiyoi and Choiyoi events identified in the Paraná basin (304–275 Ma) are likely to have their source in the Chilean Precordillera. (c) The early stage of the Choiyoi magmatism found in the Sauce Grande basin (284–281 Ma) may have come from the adjacent Las Matras to Chadileuvú blocks. (d) The pre-Choiyoi and Choiyoi events in the Karoo basins (302–253 Ma) include the longest Choiyoi interval, and as a whole bear the best resemblance to the age records along the Chilean and Argentine Frontal Cordillera.



## 1. Introduction

The extensive intermediate to acid magmatism along the Permian continental margin of southwestern Gondwana is widely known as the "Choiyoi magmatism". The large volcanic and plutonic outcrops in Argentine territory were first gathered into the "Cuyano Nordpatagonica magmatic province" (Rapela and Llambías, 1985), and then included in the currently more accepted "Choiyoi province" (Kay et al., 1989), a name derived from those established by Groeber (1946), Stipanicic et al. (1968), and Rolleri and Criado Roque (1968). The areal extension of this magmatic province in Argentina is depicted in Fig. 1. According to Llambías and Sato (2011), the Choiyoi magmatism is constrained by the San Rafael orogenic phase of Early Permian age –which causes the folding and thrusting of pre-Early Permian rocks–, and the Huarpica extensional phase of Triassic age (see tectonomagmatic synthesis in Fig. 2, discussed below in section 5; Azcuy and

* Corresponding author. Centro de Investigaciones Geológicas Geológicas (UNLP-CONICET), Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Calle 1 N°644, B1900TAC La Plata, Argentina.

*E-mail addresses:* sato@cig.museo.unlp.edu.ar (A.M. Sato), llambias@cig.museo.unlp.edu.ar (E.J. Llambías), baseimas@usp.br (M.A.S. Basei), cecastro@unsj.edu.ar (C.E. Castro).

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Caminos, 1987; Llambías and Sato, 1990, 2011; Sato and Llambías, 1993; Llambías et al., 1993, 2005, 2007; Leanza, 2009). The importance of the Late Paleozoic magmatism stems from the fact that it represents not only the active margin of southwestern Gondwana, but also the volcanic source for the pervasive ash fall deposits interlayered in coeval, retroarc to intracontinental basins of southwestern Gondwana, such as Paganzo, Chaco-Parana, Sauce Grande and Parana basins in South America, and even Karroo basin in South Africa and its extension in the Falkland Islands (López-Gamundí, 2006; Limarino and Spalletti, 2006; Matos et al., 2001; Holtz et al., 2010; Rocha-Campos et al., 2011; Trewin et al., 2002; Catuaneanu et al., 2005; Tankard et al., 2009). The widespread ash fall deposits help constrain the timing of basin fill as well as the correlation of glacial and explosive volcanic events involved in western Gondwana.

The Choiyoi magmatism in Argentina is mostly exposed in the western region (Frontal Cordillera and San Rafael Block), and spreads towards the central (Precordillera, Sierras Pampeanas, Las Matras and Chadileuvú Block) and southern regions (Principal Cordillera, Neuquén basin, Patagonia) (Fig. 1). It is also recognized in the underground of eastern regions, along the base of Meso-Cenozoic sedimentary successions. Toward the west, it is extensively exposed along the Chilean Frontal Cordillera and Chilean Precordillera (see Fig. 1b for locations), as recorded by numerous contributions (*e.g.* Mpodozis and Cornejo, 1988; Charrier et al., 2007; Hervé et al., 2014; Maksaev et al., 2014).

In this contribution we attempt a review of published age data from the Late Paleozoic to Triassic magmatism in Argentina and Chile, and interpret them within the geologic and tectonic scheme of the Gondwana continental margin. Additionally, we compare them with the ages from volcanogenic events in the above mentioned Gondwana basins, in order to contribute to regional correlations from the point of view of the Gondwana magmatism.

With the above purpose, we first present six new LA-ICPMS U–Pb ages from a representative area of the Choiyoi magmatism in Frontal Cordillera of Argentina –Colangüil area between 29° and

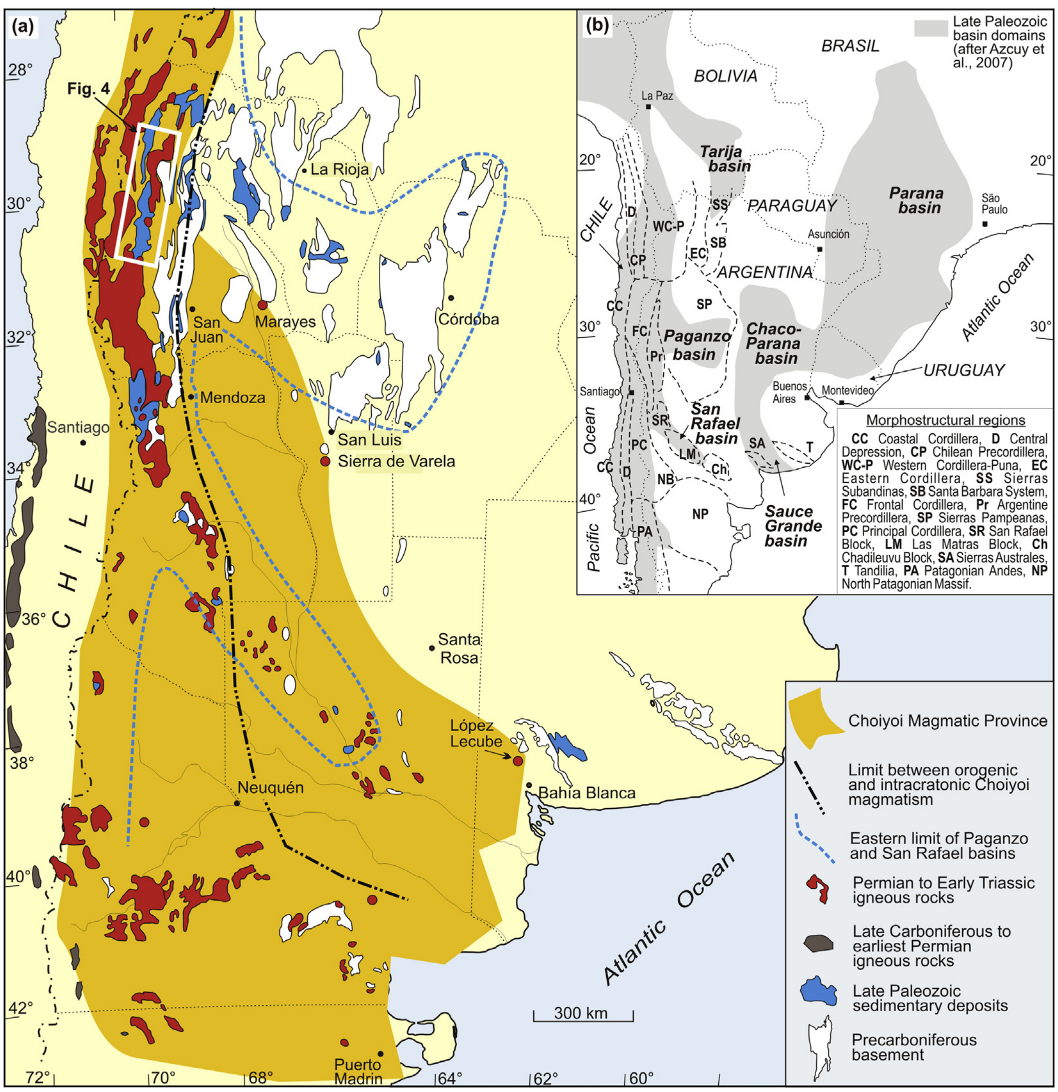


**Fig. 1.** (**a**) Possible extension of the Choiyoi Magmatic Province in Argentina, including outcrops from Frontal Cordillera, southwestern Precordillera, San Rafael Block, Principal Cordillera and Neuquén basin and Northpatagonian Massif, representing orogenic magmatism. An eastern belt with intracratonic magmatism includes the Sierras Pampeanas, Las Matras and Chadileuvú blocks and the López Lecube outcrop in western Sierras Australes. To the north, the Choiyoi province extends along the western margin of south Puna and Western Cordillera, and Chilean Precordillera. Modified from Llambías and Sato (2011). Late Paleozoic sedimentary outcrops are enclosed in the Paganzo and San Rafael basins, and to the west in the Rio Blanco, Uspallata and Calingasta basins. The location of the area in Fig. 4 is indicated. (**b**) Map of the southern South America, with the morphostructural regions in Chile and Argentina. Also indicated the areas of Late Paleozoic basins discussed in the text.

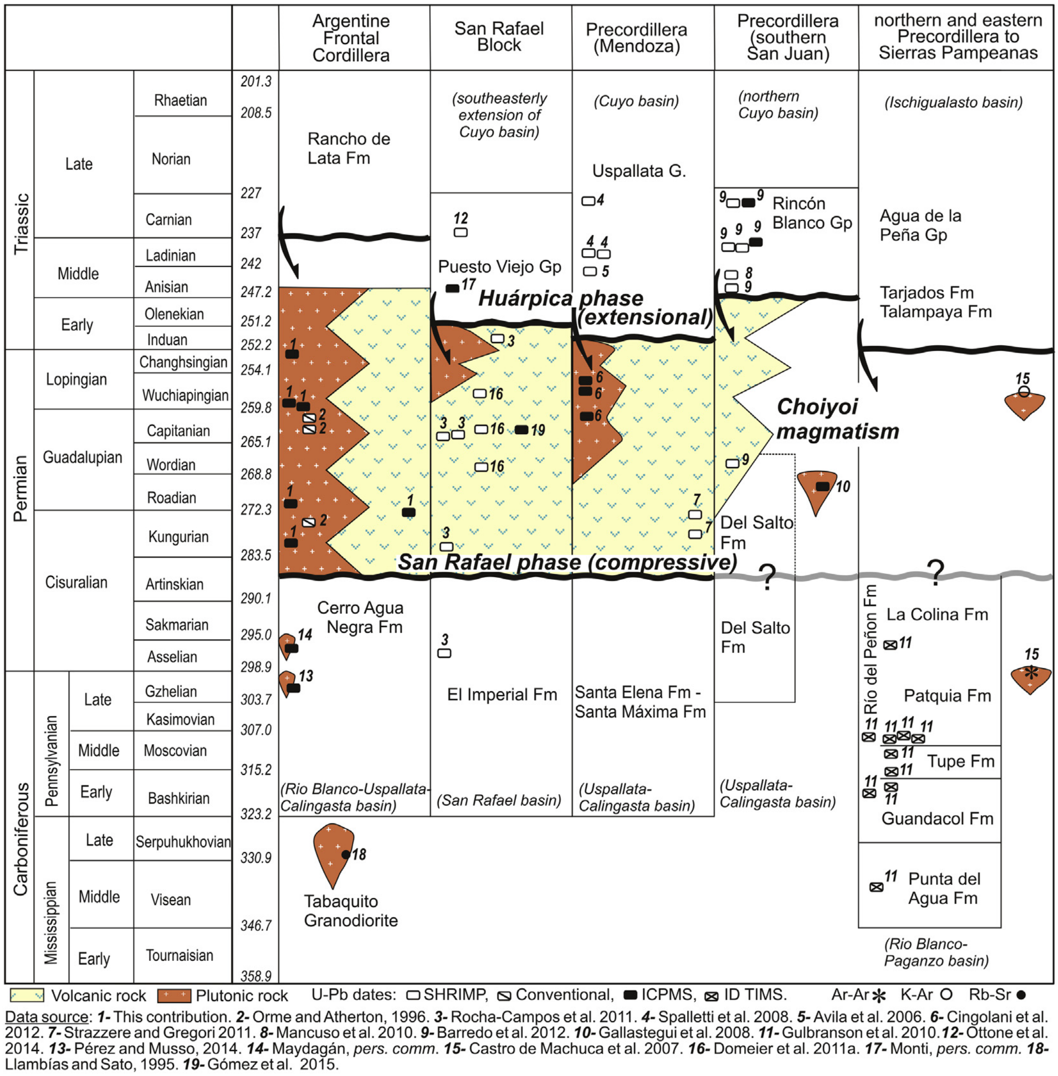


**Fig. 2.** Late Paleozoic to Triassic tectonomagmatic evolution and age constraints for the Choiyoi magmatism in Argentine Frontal Cordillera, San Rafael Block and part of the Argentine Precordillera to Sierras Pampeanas between 28° and 35°S. See Fig. 1 for location of morphostructural provinces. The early Permian San Rafael compressive phase affects the Carboniferous to earliest Permian strata in the Rio Blanco–Uspallata–Calingasta and San Rafael basins and marks the initiation of the Choiyoi magmatism. The effect of the San Rafael phase seems to be uncertain in the Paganzo basin of Sierras Pampeanas region. The end of the Choiyoi magmatism is marked by a generalized extensional event (Huarpica phase) that causes the rift stage during the Triassic. In this way, the Choiyoi magmatism in this region is constrained between the Cisuralian and Early Triassic. Stratigraphically below and above, magmatism is found mostly interlayered in sedimentary sequences, as tuffs, pyroclastic flows and lavas, and in minor degree, as intrusive bodies. Time Scale used: International Chronostratigraphic Chart v2014/02.

31°S–, which essentially confirm previous K–Ar and Rb–Sr age constraints (*e.g.* Llambías and Sato, 1995). We then characterize the tectonomagmatic evolution of the Choiyoi magmatism and its age constraints in key regions of Argentina (Frontal Cordillera, San Rafael Block and Precordillera) and draw a comparison with information from Chilean outcrops. All the age data will be contrasted with those from the ash fall deposits in the Gondwana basins.

## 2. Regional geology of Argentine Frontal Cordillera

The Frontal Cordillera is a morphostructural province involved in the Andean orogeny, located to the west of Precordillera and stretching between 27° and 34°45′ S in Argentina (Caminos, 1979), and farther between 27°S and 31°S in Chile (Maksaev et al., 2014; see locations in Fig. 1b).

As depicted in the stratigraphic synthesis of Fig. 3, the Argentine Frontal Cordillera consists of (1) pre-Carboniferous basement units, (2) sedimentary and igneous sequences belonging to the Gondwanide orogen of Carboniferous to Triassic age, and (3) sedimentary and igneous sequences of the Andean orogeny. From these, the upper Paleozoic units are areally the most significant.

Within the metamorphic basement units (Caminos, 1993), Mesoproterozoic orthogneisses (Ramos and Basei, 1997; Basei et al., 1998) and an Ediacaran to Cambrian sequence affected by Middle Devonian HP metamorphism (López de Azarevich et al., 2009; Willner et al., 2008, 2011) are recognized.

An Ordovician siliciclastic and turbiditic sequence of Las Lagunitas Formation, bearing *Climacograptus bicornis* fauna crops out at the southernmost Frontal Cordillera without stratigraphic contact with the metamorphic basement (Volkheimer, 1978; Tickyj et al., 2009), and is affected only by very low-grade metamorphism even though they are no more than 100 km apart. Tightly folded, Devonian marine strata with very low-grade metamorphism, such as the Chinguillos and Cienaga del Medio groups, scatter along the

eastern region shared with the Precordillera (Caminos, 1979; Baldis and Peralta, 1999). The tectonism and incipient metamorphism affecting both units might be the result of the Middle to Late Devonian Chañica phase, as Carboniferous to Permian marine strata lies unconformably over them (Scalabrini Ortiz, 1973; Baldis and Sarudiansky, 1975; Azcuy et al., 1999; Heredia et al., 2002).

Upper Paleozoic rocks formed during the Gondwanide orogenic cycle begins with the Carboniferous to Permian, marine and transitional siliciclastic strata of the western area of the Rio Blanco–Calingasta–Uspallata basin shared with Precordillera, from which the Upper Carboniferous to Lower Permian Cerro Agua Negra Formation (Polanski, 1970) is the most widespread unit between 29° and 32°S (Figs. 2–4). The biostratigraphic constraints for this 2000 m-thick retroarc sequence are based on marine invertebrates (*Balakhonia–Geniculifera* and *Tivertonia–Streptorhynchus* associations), paleoflora (NBG and *Kraeuselcladus – Astherotheca* fitozones) as well as palynological remains (*Raistrickia densa–Convolutispora muriornata* Biozone) (see synthesis in Azcuy et al., 2007). The major part of this sequence is considered preorogenic (Caminos, 1979; Azcuy and Caminos, 1987; Heredia et al., 2002), with sediment source from Precordillera and Sierras Pampeanas highlands located to the east (Spalletti et al., 2012). The uppermost part cropping out around 31°S (Heredia et al., 2002) is considered a synorogenic succession, with main source area from the volcanic arc to the west, as evidenced by dense gravity flow deposits with volcanic and sedimentary pebbles, in sharp erosional contact over the previous sequence (Heredia et al., 2002; Busquets et al., 2005, 2013a, b). Lacustrine carbonate microbialites are intercalated in the top of the succession, together with lava and pyroclastic flows, where a fossil forest of Late Pennsylvanian – early Permian cordaitaleans is preserved (Busquets et al., 2007; Cesari et al., 2012). The Cerro Agua Negra Formation and the time equivalent beds in Frontal Cordillera, such as Las Balas and Loma de los Morteritos formations (Polanski, 1958) and El Plata Formation (Caminos, 1965), are folded and thrust in an E-verging thin-skinned tectonics as a result of the compressive action of the Early Permian San Rafael phase (Caminos, 1979; Azcuy and Caminos, 1987; Heredia et al., 2002).

The activity of the Choiyoi magmatism begins after the development of a regional erosion surface (Fig. 2). Basal layers of the

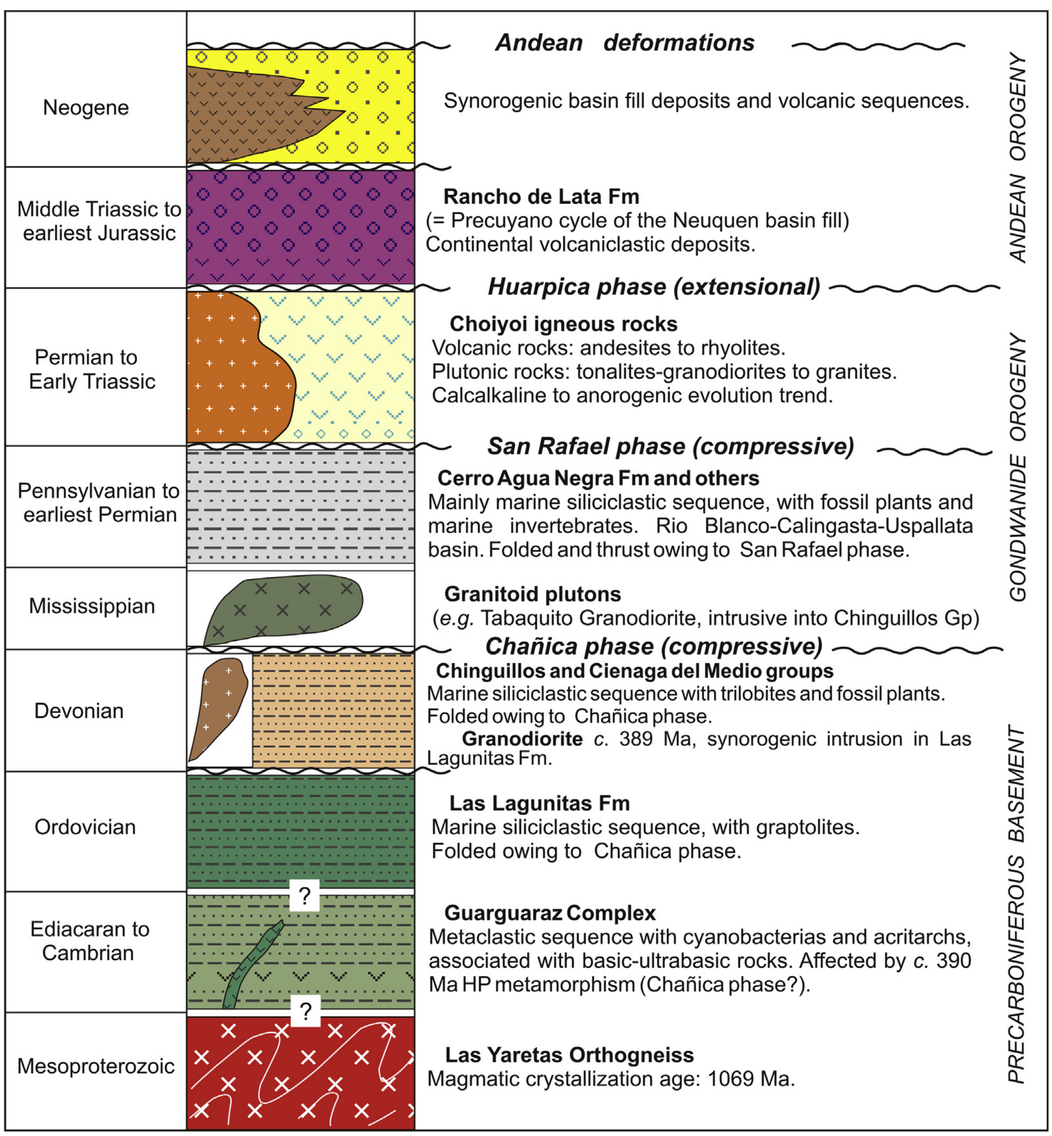


**Fig. 3.** Stratigraphic synthesis of the Argentine Frontal Cordillera. Mesoproterozoic to Cambrian igneous and metamorphic basement is followed by early Paleozoic units, Upper Paleozoic to Early Triassic igneous and sedimentary units of the Gondwanide cycle, and igneous and sedimentary units of the Andean cycle.

extrusive rocks are well exposed to the west of the Colanguil Batholith at around 30°S (Fig. 4a,c), where an angular unconformity surface is preserved subhorizontally at altitudes between 4000 and 4760 m (Sato and Llambías, 1993), over the folded Cerro Agua Negra Formation. Equivalent unconformity surfaces are now exposed at different altitudes across the Frontal Cordillera, dislocated by Tertiary faults. The volcanic strata of the Choiyoi magmatism consist of two sections, a lower section of intermediate compositions (andesites to dacites), with thin sedimentary lenses scattered along the base, and an upper section of acid compositions (rhyolites) (Llambías et al., 1993; Sato and Llambías, 1993). Basic compositions are also mentioned along the base (Poma and Ramos, 1994). The lower section covers the erosional surface carved following the San Rafael tectonism and uplift, after isolated topographic lows have been filled with conglomerates, breccias, sandstones and minor mudstone and limestone lenses that turn upwards to volcanic agglomerates (Caminos, 1965; Dessanti and Caminos, 1967; Sato and Llambías, 1993; Caballé, 1990; Cortés, 1985; Caminos, 1965;

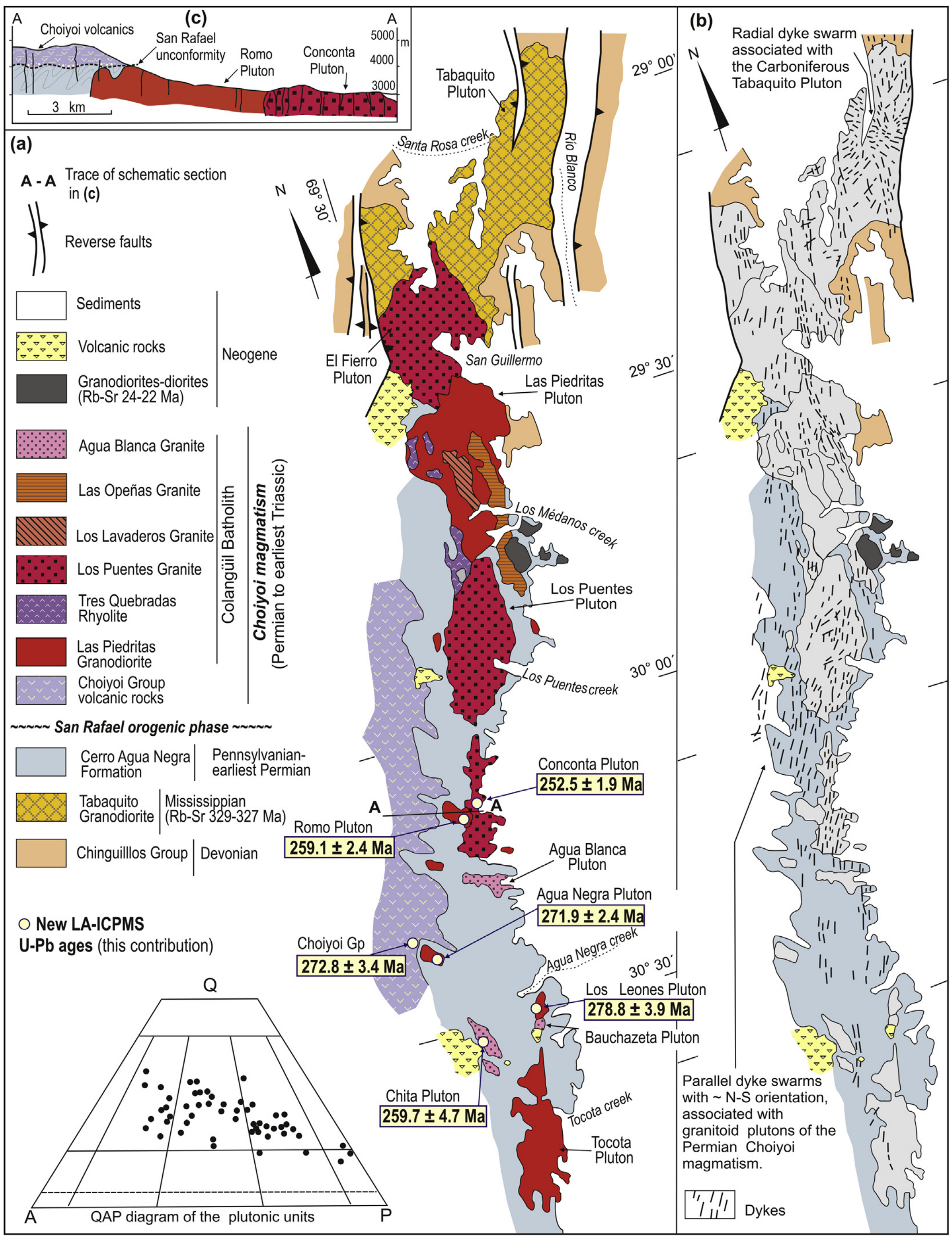


**Fig. 4.** (**a**) Geological map of the Colangüil area, depicting the relationships between the sedimentary country rocks, the volcanic rocks of the Choiyoi Group and plutonic rocks of the Colangüil Batholith. Modified from Llambías and Sato (1995). LA-ICPMS U–Pb ages obtained in this contribution are indicated. The modal QAP diagram shows the compositions of Carboniferous and Permian plutonic rocks. (**b**) The same map base, showing the radial dyke swarm associated with the Carboniferous Tabaquito Granodiorite and the N–S dyke swarm associated with the Permian plutons of the Colangüil Batholith. (**c**) E–W profile at around 30°S, showing the effects of the San Rafael orogenic phase on the Cerro Agua Negra Formation, and the relationships with Choiyoi volcanic rocks and the Romo granodiorite and Conconta granite of the Colangüil Batholith.

Volkheimer, 1978). These fluvial and lacustrine deposits contain clasts with increasing volcanic origin toward the top, suggesting equivalence to those synorogenic layers described by Busquets et al. (2005; 2013b). The thickness of this lower section is estimated in around 800 m in the area of Colangüil (Sato and Llambías, 1993). The acid upper section is more widely extended, covering the lower section or direct and unconformably older rocks, with greater thicknesses between 1500 m and 2500 m in southern San Juan Province, Mendoza Province and in Chilean territory (Caminos, 1965; Mirré, 1966; Quartino, 1969; Coira and Koukharstky, 1976; Volkheimer, 1978; Cortés, 1985; Mpodozis and Cornejo, 1988; Strazzere et al., 2006).

The plutonic rocks were referred to as Frontal Cordillera Composite Batholith (Polanski, 1958), and Variscide Plutonic Association (Caminos, 1979). The batholiths are mainly emplaced into the already folded and thrust Cerro Agua Negra Formation, as well as coeval and older sequences. Tonalitic to granodioritic and minor gabbroic components are older, whereas granitic ones are younger and predominant (Caminos, 1965, 1979; Llambías and Sato, 1995; Gregori et al., 1996; Gregori and Benedini, 2012).

Both the volcanic and plutonic emplacement of the Choiyoi magmatism are associated with an extensional regime, with volcanic deposits controlled by normal faults (Heredia et al., 2002; Giambiagi and Martinez, 2008), and highly elongated plutons with parallel dyke swarms related to the extensional collapse of the Gondwanide orogen (Llambías and Sato, 1995).

The top of the volcanic sequence is marked by sedimentation of coarse grained, Triassic clastic and volcaniclastic deposits, such as Rancho de Lata Formation along the western side, and Sorocayense and Uspallata groups in the eastern side of Frontal Cordillera. The Triassic deposits are separated from the Choiyoi volcanics through angular unconformity and normal faults (Stipanicic, 1979; Rolleri and Fernández Garrasino, 1979; Alvarez, 1996), ascribed to the extensional Huarpica phase (Figs. 2 and 3). The Rancho de Lata Formation is one of the so called Precuyano depocenters (Gulisano, 1981) that initiate the Mesozoic retroarc basin fill in the Principal Cordillera and Neuquen basin in the Andean cycle.

Tertiary volcanic rocks partly interlayered with synorogenic sedimentary deposits complete the stratigraphy of Frontal Cordillera (Fig. 3), which is involved in the thick-skinned fold and thrust belt of the Andes (Pérez, 2001; Heredia et al., 2002; Kay and Mpodozis, 2002; Litvak et al., 2007).

## 3. The Colangüil Batholith and associated volcanic rocks (29°–31°S)

Following brief descriptions by Groeber (1951), the name of Colangüil Batholith was given by Quartino and Zardini (1967) to the extensive exposures of mainly acid plutonic rocks between the Santa Rosa (29°S) and Agua Negra (30° 20′S) creeks (Fig. 4). They revealed a variety of local granitoid facies, their petrography and contact effects on the country rocks.

On the basis of integral mapping of the plutons between 29° and 31°S, their crosscutting relationships and whole rock-biotite Rb–Sr ages supporting the internal igneous stratigraphy (Table 1), Llambías and Sato (1990, 1995) and Sato et al. (1990) distinguished an Early Carboniferous granodioritic pluton (Tabaquito Granodiorite, 329–326 Ma) and mainly Permian granodioritic and granitic plutons (several units, 272–247 Ma) (Fig. 4). Host rocks are the Devonian Chinguillos Group for the Carboniferous Tabaquito Granodiorite, and the Late Carboniferous to Asselian, Cerro Agua Negra Formation for the younger plutons. Therefore, only the younger set of plutons belongs to the so-called Choiyoi magmatic province. A synthesis of pluton size, morphology and mineral composition is shown in Table 1, together with Rb–Sr age data and the new LA-ICPMS data obtained in this contribution.

The Carboniferous Tabaquito Granodiorite consists of one large pluton with 896 $km^2$ of exposure, partly covered by recent sediments. Its southern border is intruded by a pluton of Los Puentes Granite, and the eastern and western borders are truncated by Neogene Andean tectonic structures. A radial dyke swarm is emplaced in the eastern sector, covering an area of around 14 km by 14 km (Fig. 4b). With a thickness up to 15 m, the dykes are of intermediate composition (andesites, porphyritic diorites and scarce rhyolites), and are cut by a late set of ~N–S, longitudinal dykes associated with the younger group of plutonic rocks. According to the Rb–Sr age, the emplacement of this granodiorite should have predated the San Rafael orogeny. However, the effect of this tectonism on the pluton is not noticeable as is on the Late Carboniferous to Early Permian Cerro Agua Negra Formation.

The first post–San Rafael phase plutonic unit, the Las Piedritas Granodiorite (Fig. 5a,c,d), is emplaced into the already folded Cerro Agua Negra Formation, and consists of the following plutons: Los Leones, Tocota, Romo, Agua Negra and Las Piedritas. From 12 $km^2$ (Agua Negra Pluton) to 472 $km^2$ (Las Piedritas Pluton), they totalize 694 $km^2$ (Fig. 4). A cluster of small subvolcanic stocks of rhyolitic composition intrudes the western part of Las Piedritas Pluton and is in turn intruded by Los Puentes Pluton of the succeeding Los Puentes Granite. This biotite–granite unit consists of three main plutons (Fig. 4), Los Puentes, Conconta (Fig. 5b,e) and El Fierro, from which the last one is the largest, with 413 $km^2$. The Conconta Pluton cuts the eastern side of the small Romo granodioritic pluton (Fig. 4c). The succeeding Los Lavaderos Granite consists of a single elongated pluton with axial ratio 3.5 and equigranular to porphiritic texture, which is composed of amphibole granites with allanite. This granite is entirely intrusive into the Las Piedritas Pluton. We consider that the maximum extensional stage is reached with the emplacement of the cordierite-bearing Las Opeñas Granite (102 $km^2$, axial ratio 8.5), intruded into the Las Piedritas Pluton and the Cerro Agua Negra Formation. The last group of granites is the Agua Blanca Granite, consisting of small plutons, such as Chita (Figs. 4 and 5f), Agua Blanca and Bauchazeta, preserving their greisenized cupola and associated with fluorite veins. The Bauchazeta Pluton is intrusive into the Los Leones granodioritic Pluton, while the other two plutons are emplaced into the sedimentary host rock.

Numerous dykes are associated with the granitoids. The Carboniferous Tabaquito Granodiorite is the only one intruded by a radial dyke system. All the succeeding granodioritic and granitic units up to Las Opeñas Granite are affected by a system of ~N–S longitudinal dykes (Fig. 4b) with 90% rhyolitic and 10% mafic compositions (Llambías and Sato, 1995). The Agua Blanca Granite is associated with cone sheets, rather than N–S dykes, which is well observed in the Chita Pluton.

The Choiyoi Group volcanic strata in Colangüil area crop out in an N–S belt to the west of the Colangüil Batholith, generally separated by a strip of folded Cerro Agua Negra Formation (Fig. 4). The Romo Pluton belonging to the Las Piedritas Granodiorite shows one of the closest relationships with the clastic base of the andesitic lower section (Fig. 5c,g), with an apophysis of the Romo Pluton almost punctuating the roof (Fig. 4c). The volcanic layers in the area are mainly andesitic to dacitic lavas and pyroclastic flows containing mostly plagioclase and showing devitrification and variable degree of propylitic alteration that makes difficult the identification of the primary features. The rhyolitic upper section is scarcely represented in the area. The best outcrops are in the Cerro Pata de Indio, between the creeks of Agua Blanca and Agua Negra (Fig. 4). Here, a subvolcanic rhyolite is associated with ignimbrites, and rhyolitic sills and microgranites intrude into the Cerro Agua Negra

**Table 1**
Synthesis of the igneous stratigraphy of the Choiyoi magmatism in the Colangüil area, Frontal Cordillera of Argentina, with information about size and morphology of plutons, mineral compositions, and previous Rb–Sr data as well as the new U–Pb ages obtained in this contribution.

| Choiyoi Group volcanics | Colangüil Batholith plutonic units | Pluton | Size ($km^2$) | Axial ratio | Major phases | Minor phases | Rb–Sr wr isochron (Ma) | Initial $^{87}Sr/^{86}Sr$ | Rb–Sr wr-Bt isochron (Ma) | LA-ICPMS U–Pb age (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|
| Rhyolite (dykes) | | | | | | | 247.3 ± 3 | 0.70811 | | |
| | Agua Blanca Granite | Chita | 22 | | Bt | Ms-Fl-Op-Zm-Ap | 247.6 ± 3.0 | 0.7045 | | 259.7 ± 4.7 |
| | | Bauchazeta | 8 | | Bt | Ms-Fl-Op-Zm-Ap | | | | |
| | | Agua Blanca | 24 | | Bt | Ms-Fl-Op-Zm-Ap | | | | |
| | Las Opeñas Granite | | 102 | 8.5 | Bt-Ms | Crd-And-Fl-Ap-Zm | | | 254–258 | |
| | Los Lavaderos Granite | | 39 | 3.5 | Amp-Bt | Aln-Op-Ap-Zm | 258.7 ± 1.9 | 0.70716 | | |
| | | Conconta | 96 | | Bt | Op-Zm-Fl-Ap | | | | 252.5 ± 1.9 |
| | Los Puentes Granite | El Fierro | 413 | 1.6 | Bt | Op-Zm-Ap | 274.2 ± 3.2 | 0.70544 | 257–256 | |
| | | Los Puentes | 330 | 2.3 | Bt | Op-Zm-Ap | | | 257–249 | |
| | Tres Quebradas Rhyolite | | | | | | | | | |
| | | Romo | 18 | | Bt-Amp-Op | Px-Ttn-Ap-Zm | | | 264 | 259.1 ± 2.4 |
| | | Las Piedritas | 472 | | Bt-Amp-Ttn | Op-Px-Ap-Zm | 255.9 ± 37.5 | 0.70645 | 262–253 | |
| | Las Piedritas | Tocota | 192 | 3.2 | Bt-Amp-Op | Px-Ttn-Ap-Zm | 259.2 ± 28 2 | 0.70582 | 269–267 | |
| | Granodiorite | Agua Negra | 12 | | Bt-Amp-Op | Px-Ttn-Ap-Zm | | | | 271.9 ± 2.4 |
| | | Los Leones | 15 | | Bt-Amp-Px-Op | Ttn-Ap-Zm | | | 272–268 | 278.8 ± 3.9 |
| Andesites | | | | | | | 289.2 ± 19.3 | 0.70569 | | 272.8 ± 3.4 |
| *San Rafael orogenic phase* | | | | | | | | | | |
| | Tabaquito Granodiorite | | 896 | | Bt-Amp | Op-Ap-Zm | | | 329–326 | |

Formation (Sato and Llambías, 1993). In addition, frequent rhyolitic dykes are pervasively emplaced into the lower section andesites and the Cerro Agua Negra Formation.

The plutonic rocks of the batholith and the associated volcanic rocks show equivalent evolutions, from calcalkaline intermediate compositions (andesites to dacites and tonalite to granodiorites) to highly differentiated acid ones (rhyolites and granites). Their geochemical characterization (Sato and Llambias, 1993; Llambías and Sato, 1995) suggests an evolution from magmatic arc in transition to anorogenic setting, which is also observed in the San Rafael Block region (Kleiman and Japas, 2009).

As the granitoid plutons generally represent shallow intrusions, and their roofs are partly preserved together with the volcanic cover (Sato, 1987; Yoshinobu et al., 2003), a considerable number of mineral deposits are found in association with their hydrothermal evolution. The deposits and manifestations are: breccia-pipes with Bi–Cu mineralization in Tocota granodiorite, polimetallic veins associated with the volcanic rocks and El Fierro granite, W, Mo and fluorite veins and Mo-greisens in Agua Blanca granite and Cerro Pata de Indio rhyolites (Llambías and Malvicini, 1966, 1969; Oliveri et al., 1971; Sato, 1987; Simon and Cardinali, 1990; Cardó, 1999).

## 4. Geochronology

### 4.1. Previous study

Previous geochronological data include a K–Ar date from Tocota Granodiorite (283 ± 15 Ma, recalculated from Linares and Llambías, 1974), Rb–Sr whole rock and whole rock-biotite isochrones (Table 1) from plutonic (329–326 Ma from Tabaquito granodiorite, and 272–248 Ma from the younger plutons) and volcanic units (289 and 247 Ma) (Sato and Kawashita, 1988; Sato and Llambías, 1993; Llambías and Sato, 1995). The initial $^{87}Sr/^{86}Sr$ ratios in the range of 0.706–0.708 suggest certain degree of crustal component in the magma, and are similar to those reported from the Chilean side of the Frontal Cordillera (Parada, 1990; Mpodozis and Kay, 1992). In other regions of the Frontal Cordillera, reported U–Pb ages from granitoids are Permian (Orme and Atherton, 1999), while K–Ar ages generally cover the Triassic period (Dessanti and Caminos, 1967; Rocha-Campos et al., 1971; Caminos, 1972).

### 4.2. LA- ICPMS method

Zircon crystals were separated from six selected samples by hand picking after standard gravimetric and magnetic techniques. Mounting of zircon grains into epoxy resin discs, cathodoluminescence (CL) imaging and U–Pb age determinations were carried out in the Instituto de Geociências, Universidade de São Paulo. Thermo-Fisher Neptune laser-ablation multicollector inductively coupled plasma mass spectrometer equipped with a 193 Photon laser system was used, with the operating conditions and instrument settings and laser ablation system described in Sato et al. (2010). The data are represented in Tera- Wasserburg diagrams and weighted means of overlapping and coherent $^{206}Pb/^{238}U$ ages generated with the programme Isoplot/Ex (Ludwig, 2001).

### 4.3. Analysed samples

Five samples from plutonic units and one from a volcanic unit were selected in order to perform the U–Pb analyses.

Sample LS-4 (Los Leones Pluton): This is a tonalitic pluton belonging to Las Piedritas Granodiorite, and intruded by the Bauchazeta granitic pluton of Agua Blanca Granite (Fig. 4). Within the unit, this is the pluton with the most primitive composition, with the lowest $SiO_2$ content and the highest pyroxene content. The sample is a dark grey tonalite with medium to fine grained texture.

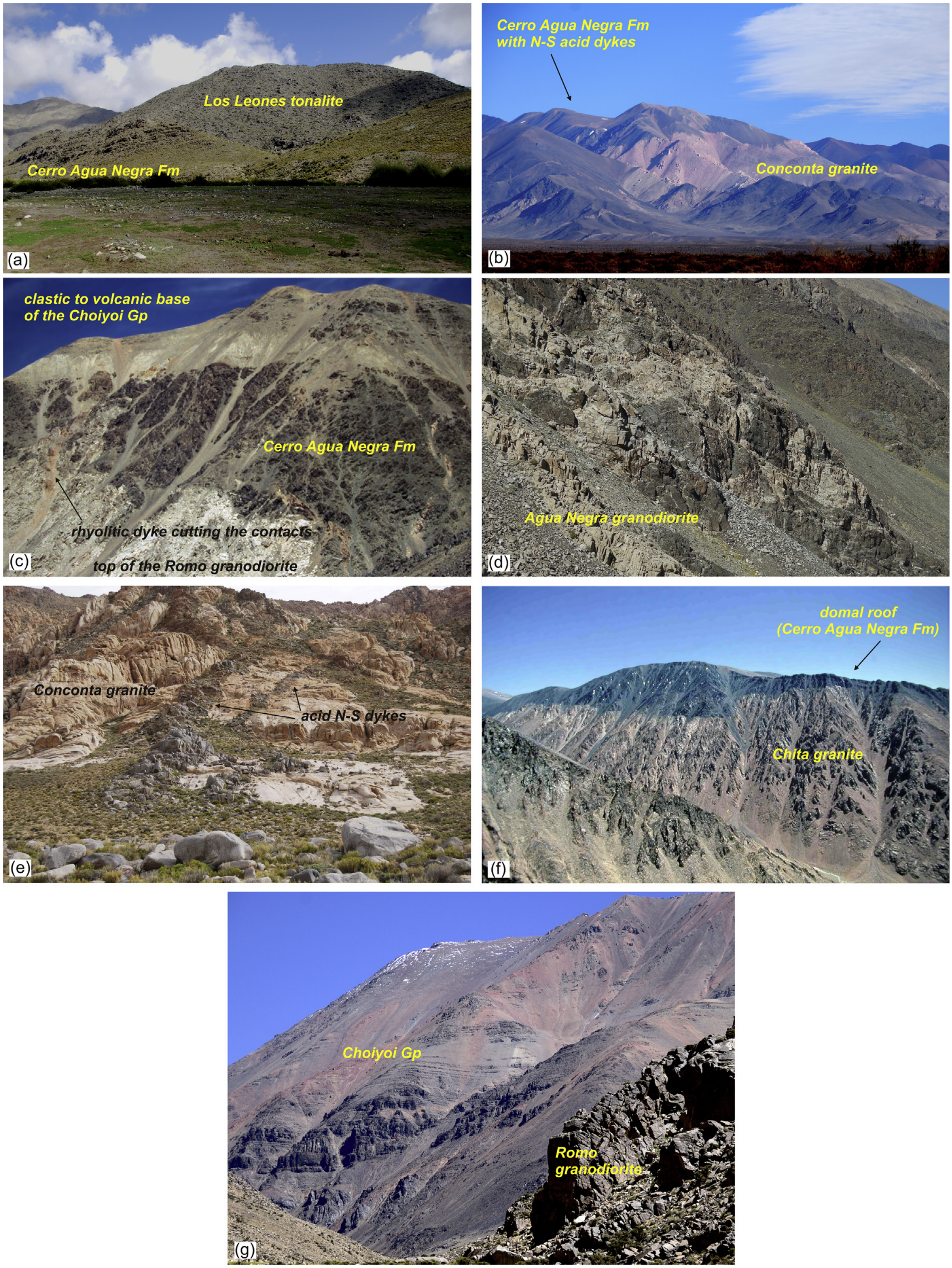


**Fig. 5.** Field photographs from the Colangüil area. (**a**) Los Leones tonalitic pluton and the folded host rock. (**b**) Southern end of the Conconta pluton (Los Puentes Granite), with the N–S dykes emplaced in the host rock. (**c**) Top of the Romo granodioritic pluton with a thin roof, almost reaching the clastic base of the Choiyoi volcanics. Rhyolitic dykes cut the contacts. (**d**) Border of the Agua Negra granodioritic pluton, with stoping of the host rock. (**e**) Detail of the Conconta granitic pluton, with N–S rhyolitic dykes (**f**) Domal roof of the Chita granitic pluton, which has a continuous vertical exposure of about 1.5 km. (**g**) Thick volcanic pile of the lower section of the Choiyoi volcanics, above the roof of the Romo granodioritic pluton.

Euhedral to subhedral plagioclase shows weak alteration to sericite, amphibole dominates over biotite and pyroxene, and quartz and minor K-felspar are interstitial (Fig. 6a). Accessory minerals are opaque minerals, apatite, zircon, and coarse titanite. Mafic minerals and plagioclase show variable degree of alteration to calcite, chlorite and scarce epidote.

Sample LS-265 (Agua Negra Pluton): This small pluton also belongs to Las Piedritas Granodiorite and crops out upstreams of Agua Negra creek (Fig. 4). It is a medium to coarse grained, pinkish grey granodiorite. Markedly zoned plagioclase contains inclusions of granular opaque, pyroxene and plagioclase. Green amphibole is associated with biotite, and quartz and K-felspar are interstitial (Fig. 6c). Accessory minerals are pyroxene, opaque minerals, titanite, apatite and zircon.

Sample LS-2 (Romo Pluton): This is another small pluton of the Las Piedritas Granodiorite, located between the Conconta Pluton and the Choiyoi volcanic outcrops. Only tens of meters of the sedimentary roof separate the top of the Romo Pluton from the clastic base of the andesitic Choiyoi volcanics (Figs. 4c and 5c). This pluton is intruded by the Conconta Pluton of Los Puentes Granite in its eastern side. The granodiorite is light-grey and has medium to coarse grain size, with general characteristics similar to the Agua Negra Pluton (Fig. 6d).

Sample LS-6 (Lower andesitic section): The sample is located along the Agua Negra creek, about 10 km to the west of sample LS-265, within the basal section of the volcanic pile. The sample is a purple coloured ignimbrite with eutaxitic texture (Fig. 6b). Abundant subparallel cm-scale fiammes are recognized containing plagioclase crystals up to few mm. Fiammes, volcanic clasts and matrix are devitrified, with spherulitic aggregates in the fiammes. All the components including plagioclase and mafic minerals are partially altered to chlorite, calcite and clay minerals.

Sample LS-3 (Conconta Pluton): This pluton belongs to the Los Puentes Granite and is intrusive into the Romo Pluton. The sample is taken around 4 km to the east of sample LS-2. The rocks are pinkish-grey, with coarse to medium grain size. Large perthite crystals contain small plagioclase inclusions, and albite rims develop along the contacts between feldspars (Fig. 6e). It also contains biotite, opaque minerals, apatite, zircon and very small quantity of fluorite.

Sample CH-120 (Chita Pluton): It belongs to the Agua Blanca Granite, and although small, it shows a continuous vertical exposure of about 1.5 km from its domed roof (Yoshinobu et al., 2003). Fluid inclusion study in the greisenised cuppola suggests a shallow emplacement of about 1.3 km (Sato, 1987). The sample is a reddish, medium grained leucogranite, with biotite, opaque minerals, fluorite, zircon and scarce apatite needles. Subsolidus activity is noticeable through albite rims in feldspars (Fig. 6f), swapped albite rims and irregularly replaced perthites.

### *4.4. Results*

The analytical data are presented as a table in a Supplementary material. Fig. 7 shows Tera-Wasserburg diagrams and weighted mean plots of $^{206}Pb/^{238}U$ ages, as well as zircon CL images for each sample.

Tonalite sample LS-4: Zircon crystals are long biterminated prisms and fragments, with axial ratios between 2:1 and 6:1. CL images show generally bright luminescence and parallel sector zoning. 26 spots (26 crystals) were analysed. U content is mostly between 111 and 323 ppm, and Th/U ratios between 0.6 and 1.4, a characteristic consistent with their magmatic origin (Hoskin and Schaltegger, 2003). As depicted in Tera Wasserburg diagram of Fig. 7 a, the ages show low degree of concordance. Therefore, the best age is calculated as a weighted $^{206}Pb/^{238}U$ mean age of 23 spots, with 278.8 ± 3.9 Ma, excluding 3 inherited and highly discordant ages.

Granodiorite sample LS-265: Zircon crystals are short to long prisms up to 4:1 axial ratio, with oscillatory growth zoning and parallel sector zoning. U content is mostly between 420 and 875 ppm, with Th/U ratios mainly between 0.4 and 0.8. Among the 26 spots (26 crystals) measured, the most coherent and concordant 14 spots yield a weighted mean age of 271.9 ± 2.4 Ma (Fig. 7 c).

Granodiorite sample LS-2: 26 short to long prisms with axial ratio up to 5:1 were measured. They generally show oscillatory

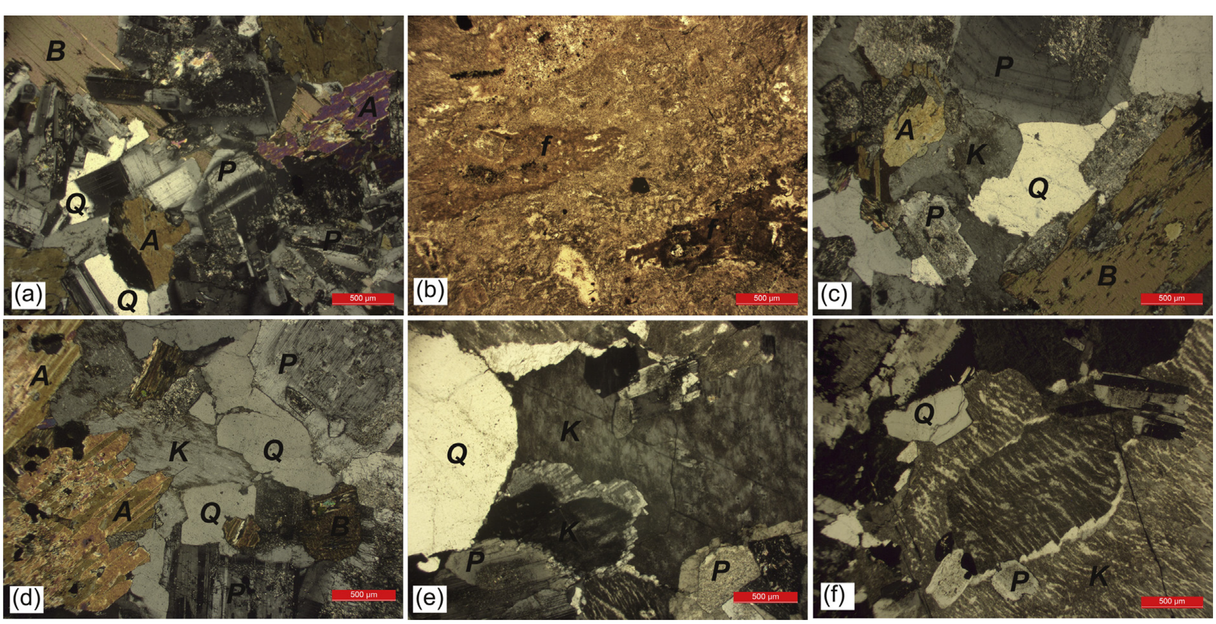


**Fig. 6.** Photomicrographs showing textures and mineralogy of the dated samples. (**a**) Sample LS4 (Los Leones Tonalite): medium to fine grained texture, with plagioclase, amphibole, biotite and scarce interstitial quartz. (**b**) Sample LS6 (Choiyoi Andesite): ignimbrite with eutaxitic texture. Fiammes and matrix are devitrified and altered to chlorite, calcite and clay minerals. (**c**) Sample LS265 (Agua Negra Granodiorite): medium to coarse grained texture, with zoned plagioclase, K-felspar, amphibole, biotite and interstitial quartz. (**d**) Sample LS2 (Romo Granodiorite): medium grained texture, with zoned plagioclase, amphibole, biotite, K-felspar and quartz. (**e**) Sample LS3 (Conconta Granite): medium to coarse grained texture, with perthitic K-felspar, plagioclase and quartz. Albite rims develop between felspars. (**f**) Sample CH-120 (Chita Granite): medium to coarse grained texture, with large perthite crystals with albite rims. Crossed nicols, with the exception of (**b**). Scale bar = 500 μm. A: amphibole, B: biotite, f: fiamme, K: K-felspar, P: plagioclase, Q: quartz.

zoning, with U content mostly between 400 and 815 ppm, and Th/U ratios between 0.5 and 0.8. The degree of age concordance is generally low (Fig. 7d), and 23 spots yield a weighted mean age of 259.1 ± 2.4 Ma.

Andesite sample LS-6: Among the 25 analysed crystals, short prisms and fragments with axial ratio up to 3:1 are dominant, while few are small and equant. They generally show oscillatory zoning. U content is mostly between 100 and 400 ppm, with Th/U ratios mostly 0.6 to 1.7. Part of the measured spots show concordant ages, while less than half of them discordance higher than 10%. 23 spots determine a weighted mean age of 272.8 ± 3.9 Ma (Fig. 7b).

Granite sample LS-3: 13 crystals (13 spots) were analysed, with dominant prisms and fragments with axial ratio up to 4:1, and minor crystals more equant. Oscillatory zoning is notable, with some crystals showing mainly bright luminescence and others darker. U content varies between 46 and 782 ppm, the more U-rich, the darker. Th/U ratios are generally lower than the granodioritc samples, including 3 spots with ratios lower than 0.3. The remaining spots are between 0.3 and 0.7. In the Tera-Wasserburg diagram (Fig. 7e) we exclude 3 spots with high error and older ages. The remaining spots are clustered into two groups, one with 262.2 ± 2.0 Ma, which can be considered as zircons inherited from an earlier magmatic pulse, since this pluton is emplaced into the Romo granodioritic pluton (259.1 ± 2.4 Ma for sample LS-2). The younger cluster of 5 spots defines a mean age of 252.5 ± 1.9 Ma, which is considered the crystallization age for this pluton.

Granite sample CH-120: 13 spots were analysed from 8 crystals, which are prisms and fragments with axial ratios up to 3:1. The crystals show oscillatory zoning, some of them with notable luminescence contrast, with brighter zones in the inner or outer zones. U content varies between 116 and 1550 ppm, and Th/U ratio between 0.3 and 1.0. In the Tera-Wasserburg diagram (Fig. 7f) it can be seen that the spots scatter with variable degree of discordance, with ages younger than 280 Ma. The three younger spots in the surroundings of 180 Ma are considered as resulting from hydrothermal activity, and correspond to outer zones of crystals. The four spots more consistent and close to the concordia curve define a poor age of 259.7 ± 4.7 Ma, which is the best date that can be derived.

Our U–Pb results agree with the previous Rb–Sr determinations in general terms, and constrain the Choiyoi magmatism in the area of Colangüil between 279 and 253 Ma (Table 1). Three plutons of Las Piedritas Granodiorite yielded ages of 278.8 ± 3.9 Ma (Los Leones Pluton), 271.9 ± 2.4 Ma (Agua Negra Pluton) and 259.1 ± 2.4 Ma (Romo Pluton). The age of 272.8 ± 3.9 Ma from the andesitic ignimbrite is within the time interval obtained from the granodiorites. For the Los Puentes Granite, the age of 252.5 ± 1.9 Ma (Conconta Pluton) is consistent with the igneous evolution of the batholith. However, the age of 259.7 ± 4.7 Ma from the Chita Pluton of the Agua Blanca Granite, does not agree with the igneous stratigraphy defined by Llambías and Sato (1990), our expectation having been an age younger than the Conconta Pluton. As this last age is based only on 4 spot points, we expect the age of this pluton might be improved in the future.

## 5. Late Paleozoic tectonomagmatic evolution of the southwestern Gondwana margin

Previous to the Late Paleozoic, orogenic events of the Early Paleozoic Famatinian cycle took place mainly along the Sierras Pampeanas region and culminated with the regional unconformity related to the Chañica phase. Two terranes (Cuyania and Chilenia) are considered to have accreted during the evolution of this orogenic cycle. After these events, the orogenic belt shifted to the west, mainly along the Chilean and Argentine Frontal Cordillera, its southern extension in the Principal Cordillera and northern extension in the Chilean Precordillera (see locations in Fig. 1b).

As the Argentine Frontal Cordillera is one of the key areas in order to understand the Late Paleozoic tectonomagmatic evolution, we have synthesized in Fig. 2 the sedimentary and igneous successions, their relationships with the tectonic events and age controls including the new ages obtained in this contribution, and contrasted them with those of the neighbouring San Rafael Block, Precordillera and Sierras Pampeanas between 28° and 35°S.

This figure shows the regional extent and importance of the San Rafael phase in concluding or interrupting the deposition in the Rio Blanco–Calingasta–Uspallata and San Rafael retroarc basins —which were active during Carboniferous to Cisuralian— and in deforming their sequences (Caminos, 1979; Criado-Roque and Ibáñez, 1979; Azcuy et al., 1999; Limarino et al., 1996; Azcuy and Caminos, 1987; Heredia et al., 2002; López Gamundí, 2006). Towards the foreland region in the east, its effects do not seem to be conspicuous in structural terms (Salfity and Gorustovich, 1983; Azcuy and Caminos, 1987; Limarino et al., 2006), even though the basin fill in the Paganzo basin might have ended in relation to this phase. On the basis of data depicted in Fig. 2, the San Rafael phase may be constrained within the Sakmarian–Artinskian interval in this region.

Another point to note in Fig. 2 is the postorogenic character (with respect to the San Rafael phase) of the prominent plutonic and volcanic event of the Choiyoi magmatism, which dominates the Frontal Cordillera, San Rafael Block and western Precordillera until early Triassic. The end of the Choiyoi magmatism is indicated by extensional tectonics assigned to the Huarpica phase which leads to diachronic and isolated initiation of rift depocenters, such as in the Cuyo basin (Precordillera), Ischigualasto basin (Sierras Pampeanas) and Neuquen basin (Principal Cordillera) (Stipanicic and Bonaparte, 1979; Gulisano, 1981; Kokogian et al., 1993; Ramos, 1993; Milana and Alcober, 1994).

Moreover, magmatic activity in the region considered in Fig. 2 appears to be scarcer, both previous to and after the Choiyoi stage. They mainly consist of scattered plutonic rocks, such as the Carboniferous Tabaquito Granodiorite in the north of the Colangüil Batholith, and pyroclastic flow and fall deposits interlayered in sedimentary sequences both predating and postdating the Choiyoi units.

In order to better constrain the age of the Choiyoi magmatism, we have compiled in Fig. 8 the available U–Pb data from the Argentine side of the Choiyoi province, from sites with known geologic control. On the basis of this compilation we suggest that the interval of around 40 m.y., between 286 and 247 Ma in Early Permian to Early Triassic time (Artinskian to Olenikian), corresponds to the activity of the Choiyoi magmatism. This figure also shows that in general terms, the younger rocks are of more acid compositions (granites and rhyolites) than the older ones (granodiorites and andesites), in accordance with the previous division of the magmatism into two compositional sections (Llambías et al., 1993; Sato and Llambías, 1993).

For the purpose of comparing the spatial distribution and evolution of the Late Paleozoic magmatism along the southwestern Gondwana margin, we have depicted in Fig. 9 the available U–Pb ages of Carboniferous to Triassic magmatism from the morphostructural provinces involved. We exclude from this analysis the ages of mainly Mississippian, postorogenic and A-type granitoids in Sierras Pampeanas (*e.g.* Grissom et al., 1988; Grosse et al., 2009; de los Hoyos et al., 2011; Dahlquist et al., 2013), which might be related to the very last events of the previous Famatinian cycle.

In contrast to the eastern side of the Gondwana continental margin (such as the region depicted in Fig. 2), the western side in Chile registers abundant age records from Mississippian to

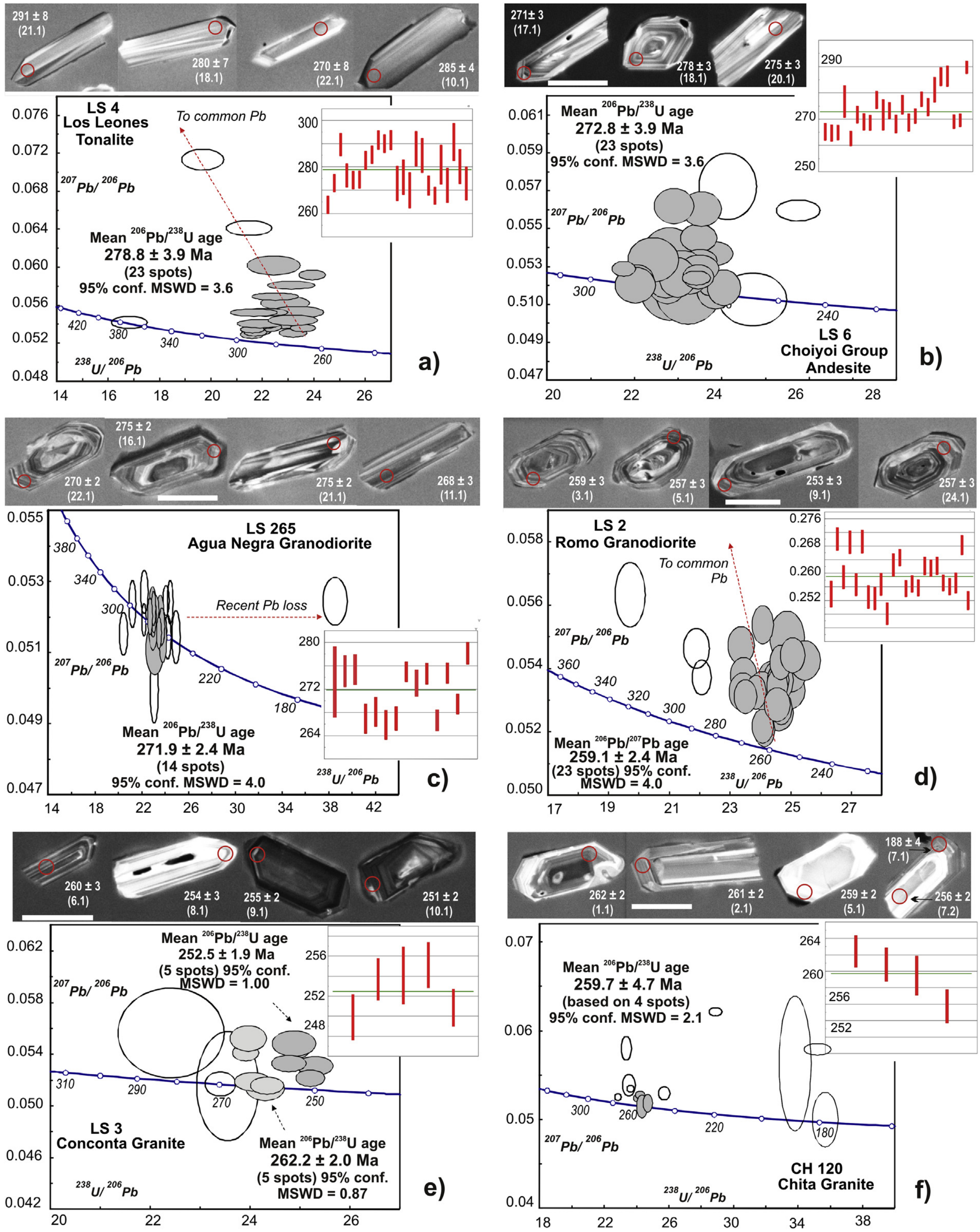


**Fig. 7.** Concordia diagrams of zircon data from plutons of the Las Piedritas Granodiorite (**a**, **c**, **d**), El Fierro Granite (**e**) and Agua Blanca Granite (**f**). Also from Choiyoi Group Lower section (**b**). Insets show $^{206}Pb/^{238}U$ ages of those spots used to derive the weighted mean age, and error bars show the standard deviation for each spot age. Cathodoluminescence images of typical zircon crystals are also shown for each sample. Scale bar: 100 μm.

Triassic. Having constrained the Choiyoi magmatism between 286 and 247 Ma, we assign to the pre-Choiyoi magmatism those units with older ages, and to the post-Choiyoi magmatism to those units with younger ages (Fig. 9). This division is based on considerably more numerous (U–Pb) ages than the division proposed by Mpodozis and Kay (1992), and covers wider regions. In the following sections we intend to delineate their distribution and significance.

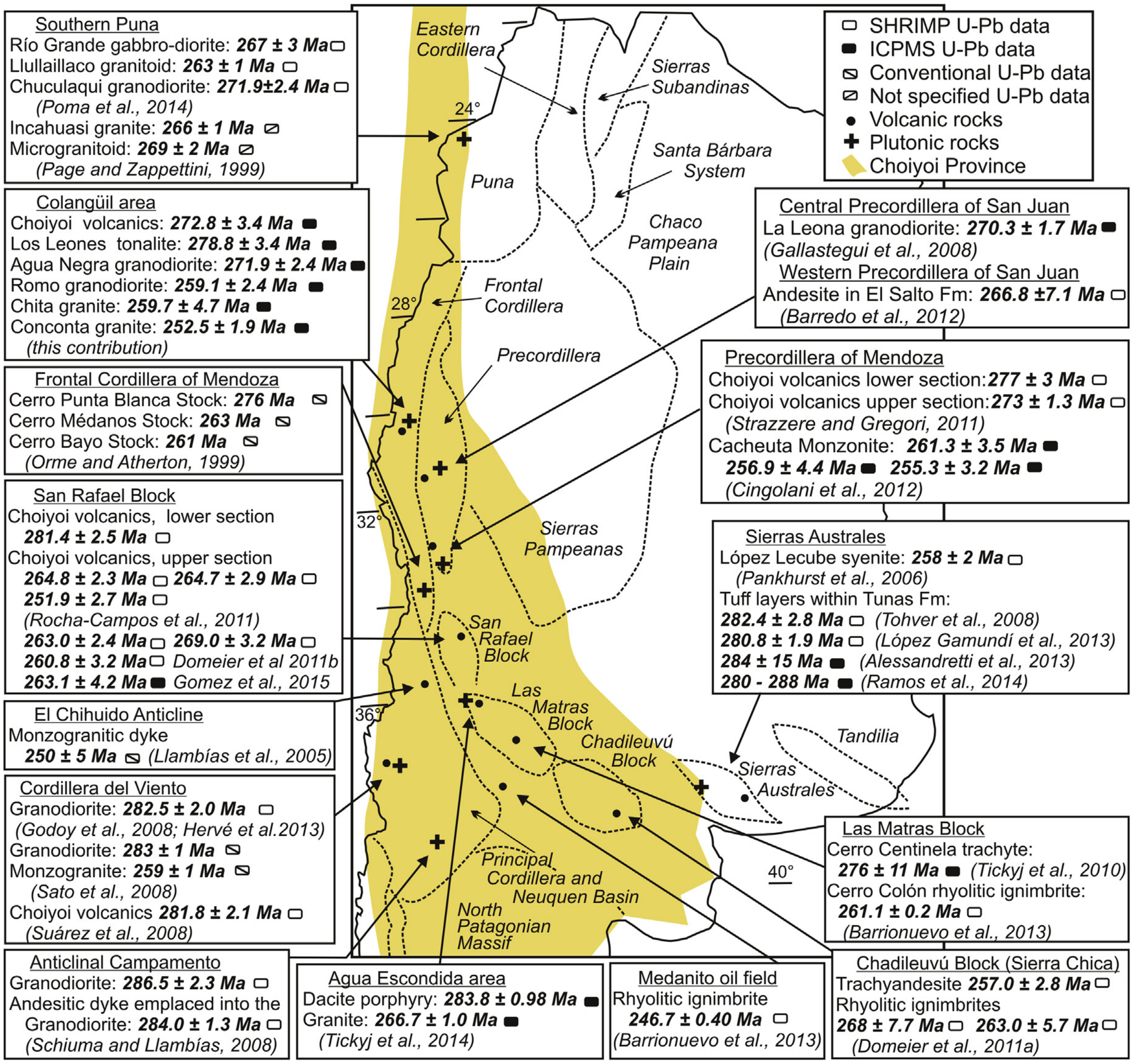


**Fig. 8.** U–Pb data compile with location and lithology, from rocks related to the Choiyoi magmatism, between 25° and 39°S in Argentina. The base and/or top geological constraint of the Choiyoi magmatism is clear in most of the region. Although equivalent outcrops do exist in Sierras Pampeanas, they lack U–Pb ages. According to the data, the Choiyoi magmatism in this region is mostly bracketed between **286 Ma and 247 Ma** (Cisuralian to Early Triassic). To the south of this region, in northern Patagonia, the ductile character and possible diachrony of the San Rafael phase make difficult to constrain geologically the base of the Choiyoi magmatism. Two of the ages reported by Domeier et al., 2011b are from zircon xenocrysts found in volcanic layers within the Triassic Puesto Viejo Group.

### 5.1. *Pre-Choiyoi magmatism (Late Mississippian to Artinskian)*

This late Mississippian to early Cisuralian magmatism is conspicuously registered along the Chilean Precordillera and its southern extension into the Chilean side of Frontal Cordillera (see locations in Fig. 1b), also with prominent outcrops along the Coastal Cordillera, and scattered ones in the Principal Cordillera and Patagonia region.

Along the westernmost Coastal Cordillera, the Coastal Batholith forms an almost continuous belt between 33° and 40°S (Figs. 1 and 9), of calcalkaline gabbros to granites intruding the Eastern Series of an accretionary metamorphic complex, whose ages are mainly 320–300 Ma (Willner et al., 2005; Deckart et al., 2014 and references therein). Their textures show minor ductile to fragile deformation, and their southern extreme shifts to the southeast, within the Principal Cordillera.

The Chilean Frontal Cordillera (27–31°S) records a more continuous exposure of dominantly plutonic rocks with 328 to 288 Ma (Fig. 9) (Hervé et al., 2014; Maksaev et al., 2014 and references therein), mostly along the western side of the Late Paleozoic outcrops (see Fig. 4 in Maksaev et al., 2014). The plutonic rocks are mainly early plutons of the Elqui-Limarí Batholith, considered to have emplaced before the San Rafael phase (Mpodozis and Kay, 1990). Along the Argentine side of the Frontal Cordillera, only two granitoid records of 301 Ma (Pérez and Musso, 2014) and 297 Ma (Maydagán, *pers. comm.*) are reported close to the border area with the Principal Cordillera at 31° 30′S, in addition to the Tabaquito Granodiorite with Rb–Sr 329–326 Ma, (29°S, Fig. 3) and a recently dated 320 Ma volcanic rock from the northern extreme of the Argentine Frontal Cordillera (27°S, Zappettini et al., 2015). A 336 Ma, orogenic andesite from northern Precordillera (Fig. 2; Remesal et al., 2004; Gulbranson et al., 2010) represents one of the oldest ages from this magmatic stage.

The Chilean Precordillera to the north of Frontal Cordillera is the region that provides the most abundant volcanic and intrusive ages in relation to this magmatic stage (*e.g.* Collahuasi Group), starting

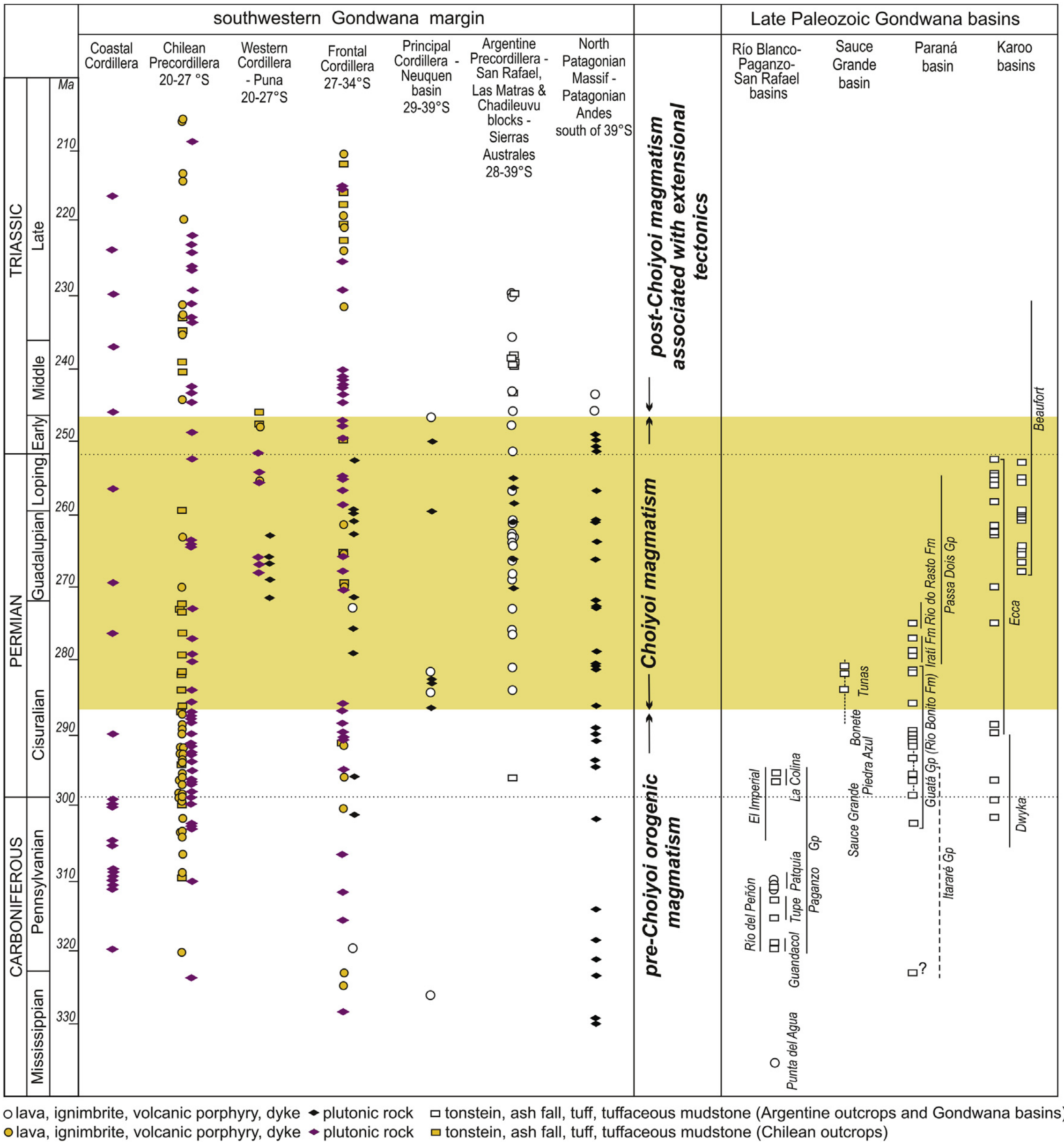


**Fig. 9.** U–Pb age constraints for the Upper Carboniferous to Triassic igneous outcrops and comparison with magmatic ages found in coeval sedimentary basins. Data source: **Coastal Cordillera**: Willner et al., 2005; Maksaev et al., 2014 and references therein; Deckart et al., 2014 and references therein. **Chilean Precordillera**: Munizaga et al., 2008; Maksaev et al., 2014 and references therein. **Chilean Frontal Cordillera**: Pankhurst et al., 1996; Martin et al., 1999; Hervé et al., 2014; Maksaev et al., 2014 and references therein. **Western Cordillera**: Niemeyer, 2013 and references therein; Maksaev et al., 2014 and references therein. **Puna**: Page and Zappettini, 1999; Poma et al., 2014. **Argentine Frontal Cordillera**: Orme and Atherton, 1999; Pérez and Musso, 2014; Maydagán, *pers. comm.*; Zappettini et al., 2015; this contribution. **Principal Cordillera and Neuquen basin**: Godoy et al., 2008; Hervé et al., 2013; Llambías et al., 2005; Sato et al., 2008; Suárez et al., 2008; Schiuma and Llambías, 2008; Barrionuevo et al., 2013. **Argentine Precordillera, San Rafael-Las Matras-Chadileuvú blocks, Sierras Australes**: Strazzere and Gregori, 2011; Gallastegui et al., 2008. Barredo et al., 2012; Spalletti et al., 2008. Avila et al., 2006; Cingolani et al., 2012. Mancuso et al., 2010. Rocha-Campos et al., 2011. Gómez et al., 2015. Domeier et al., 2011 a,b; Monti, *pers. comm.*, Ottone et al., 2014; Tickyj et al., 2010, 2014; Barrionuevo et al., 2013; Pankhurst et al., 2006. **Patagonian Andes–North Patagonian Massif**: Varela et al., 2005, 2008; Pankhurst et al., 2006, 2014; Chernicoff et al., 2013; Garcia et al., 2014; González et al., 2014. **Rio Blanco – Paganzo – San Rafael basins**: Gulbranson et al., 2010; Rocha-Campos et al., 2011). **Sauce Grande basin**: Tohver et al., 2008; Alessandretti et al., 2013; López Gamundí et al., 2013; Ramos et al., 2014. **Paraná basin**: Rocha-Campos et al., 2006; Sommer et al., 2008 a,b,c; Santos et al., 2006; Mori et al., 2012; Simas et al., 2012; Cagliari et al., 2014; Philipp et al., 2014. **Karoo basin**: Bangert et al., 1999; Coney et al., 2007; Fildani et al., 2007, 2009; Lanci et al., 2013; Rubidge et al., 2013). The magmatic outcrops in the orogenic region are divided into pre-Choiyoi orogenic magmatism, Choiyoi magmatism (**286–247 Ma**, derived from data in Fig. 8) and post-Choiyoi magmatism associated with extensional tectonics. See text for interpretations of data.

mainly around 310 Ma and continuing into the Choiyoi magmatic stage, with scarcer data in the Late Permian and Early Triassic (Fig. 9) (Munizaga et al., 2008; Maksaev et al., 2014 and references therein).

The basement of Principal Cordillera in the Cordillera del Viento of Argentine side (37°S) also registers a 326 Ma, pre-Choiyoi magmatism within the Andacollo Group (Godoy et al., 2008; Hervé et al., 2013), affected by the San Rafael phase (Llambías et al., 2007).

In the Patagonia region, igneous rocks coeval with this magmatic stage are found along the Patagonian Andes and in the western side of the North Patagonian Massif, as part of the Colohuincul Metamorphic Complex and other granitoids ductilely deformed by the San Rafael phase. The intervals 330–314 Ma and

295–290 Ma are representative (Fig. 9; Varela et al., 2005; Pankhurst et al., 2006).

The late Mississippian to early Permian, pre-Choiyoi magmatism is a calcalkaline, orogenic magmatism attributed to a period of fast subduction along the continental margin of Gondwana (Parada, 1990; Mpodozis and Kay, 1990, 1992; Llambías and Sato, 1995; Charrier et al., 2007). The Carboniferous I-type magmatism in the Patagonian Andes and western North Patagonian Massif are, according to Pankhurst et al., 2006, the southeasterly extension of the Coastal Batholith in Chile, and represents pre-collision and collision-related magmatism. Their ages, however, do not coincide entirely (Fig. 9).

### 5.2. Choiyoi magmatism (Artinskian to early Triassic, ~286–247 Ma)

Rocks with Choiyoi age are very scarce along the Coastal Cordillera south of 33°S in the region of the Coastal Batholith (Willner et al., 2005; reference in Deckart et al., 2014) and north of 26°S (Maksaev et al., 2014).

The main region affected by the Choiyoi magmatism is located along the Chilean Precordillera, the Frontal Cordillera, basement of the Principal Cordillera, and expands to the east and south along the Argentine Precordillera, San Rafael-Las Matras-Chadileuvú blocks, reaching the easternmost Sierras Australes and the Patagonia region (Fig. 9). In Sierras Pampeanas, subvolcanic andesitic to rhyolitic stocks and dykes emplaced in the Early Paleozoic crystalline basement of Marayes are the easternmost outcrop of this magmatism, albeit only with K–Ar and Ar–Ar constraints (Castro de Machuca et al., 2007 and references therein). All these regions define the Choiyoi magmatic province depicted in Fig. 1.

North of 27°S along the Chilean Precordillera, volcanic as well as plutonic rocks compose the Choyoi magmatism (Munizaga et al., 2008; Maksaev et al., 2014 and references therein). To the east of this belt around 23–25°S, Middle Permian to Early Triassic plutonic and volcanic units (*e.g.* Cass and Peine formations) are located in the Western Cordillera to Puna region (Niemeyer, 2013; Maksaev et al., 2014; Poma et al., 2014; and references therein) (Fig. 9).

Along the Chilean Frontal Cordillera, this stage includes the major components of the Elqui-Limarí, Chollay and Montosa-El Potro batholiths (Mpodozis and Kay, 1990) among others, and less extended volcanic units that are generally exposed to the east of the batholiths (Pankhurst et al., 1996; Martin et al., 1999; Hervé et al., 2014; Maksaev et al., 2014 and references therein). The unconformity related to the San Rafael orogenic phase is recorded between 29 and 31° along the base of volcanic sequences of the Pastos Blancos Formation (Nasi et al., 1986; Mpodozis and Cornejo, 1988).

Details of the Choiyoi magmatism in the Argentine side of the Frontal Cordillera and Principal Cordillera, Argentine Precordillera, San Rafael-Las Matras-Chadileuvú blocks and Sierras Australes have been given in the preceding sections and Figs. 1, 2, 4 and 9. In contrast to the Chilean Frontal Cordillera, where larger batholiths are exposed, the Argentine exposures north of Patagonia are comparatively more dominated by volcanic rocks, with the San Rafael phase-related basal unconformity clearly observable in the Frontal Cordillera, Precordillera, San Rafael Block and Principal Cordillera (*e.g.* Sato and Llambías, 1993; Llambías et al., 1993, 2005; Azcuy et al., 1999). In the Las Matras and Chadileuvú Blocks, although the compressive ductile shear deformation in Cerro Los Viejos is attributed to this phase (Tickyj et al., 1997), the sedimentary to volcanic transition is less clear (Llambías et al., 2003).

In the Sierras Australes, the fold and thrust deformation affecting all the area is assigned to the San Rafael phase (*e.g.* Dimieri et al., 2005 and references therein). Although the action of the San Rafael phase may be constrained to Sakmarian–Artinskian interval on the basis of data depicted in Fig. 2 in the vicinity of Frontal and Principal Cordillera, this timing may vary regionally within the Early to Middle Permian interval. In the case of Sierras Australes, an upper limit for this timing is generally considered to be given by the emplacement of the mostly undeformed López Lecube syenite, at 258 ± 2 Ma (Pankhurst et al., 2006). In coincidence with this timing, 265–260 Ma Ar–Ar dates from basement micas are reported (Tohver et al., 2008). Similar Rb–Sr dates of 260–265 Ma from moscovites in the Cerro Los Viejos mylonite zone (Chadileuvú Block) are obtained by Tickyj et al. (1997). Moreover, these ages are more similar to the Ar–Ar constraint of *c.* 275–260 Ma reported for the Cape Orogeny from the Cape Fold and Thrust Belt (Hansma et al., 2015), than to the pre–286 Ma (Sakmarian to Artinskian) constraint of the San Rafael phase along the Frontal Cordillera to San Rafael Block region. These differences are probably due to the diachronic effects of the Gondwanide deformation along the orogen.

The Choiyoi event corresponds to a postorogenic magmatism, as it postdates the San Rafael orogenic phase. This compressive phase has been related to a collisional event by Mpodozis and Kay (1992). In the Colangüil area, the magmatism evolves from calcalkaline tonalites to granodiorites (and coeval andesites to dacites), to peraluminous and A-type granites (and coeval rhyolites), and the extensional regime is attributed to the relaxation collapse of a thickened orogen (Sato and Llambías, 1993; Llambías and Sato, 1995), in a period when subduction seemed to be slow (Mpodozis and Kay, 1992; Charrier et al., 2007). In the region of Las Matras and Chadileuvú Blocks (Fig. 8) the rocks belong to shoshonitic and trachydacitic–rhyolitc series with subalkaline to alkaline signatures (Llambías et al., 2003), and on this basis they were characterized as intracratonic (Fig. 1; Llambías and Sato, 2011), toghether with the anorogenic López Lecube syenite (Gregori et al., 2003; Pankhurst et al., 2006).

The Choiyoi magmatism in the North Patagonian Massif is distinct because of its entirely plutonic character. The effects of the San Rafael phase are observable in a wide area, affecting ductile to fragilely Early Paleozoic basement units, as well as Early to Late Paleozoic sedimentary and igneous units (von Gosen, 2002, 2003, 2009; Giacosa, 1997; García-Sansegundo et al., 2009; Greco et al., 2015). This situation makes difficult the definition of the Choiyoi magmatism on structural basis, because although all the Choiyoi interval is represented in northern Patagonia (Fig. 9), they include both deformed and undeformed granitoids, even with an orthogneiss and a foliated tonalite form the Yaminué Complex providing ages as young as 261 and 251 Ma (Varela et al., 2005, 2008; Pankhurst et al., 2006, 2014; Chernicoff et al., 2013; García et al., 2014).

### 5.3. Post-Choiyoi magmatism (Middle to Late Triassic)

In this stage, igneous rocks are again scarce along the Coastal Cordillera but abundant along the Chilean Precordillera and Frontal Cordillera, and less abundant in the Argentine Precordillera, San Rafael Block and Sierras Pampeanas, interlayered with rift deposits overlying the Choiyoi units (Figs. 2 and 9).

In the Chilean side of the Frontal Cordillera, Triassic bimodal volcanic rocks (basalts and rhyolites) of the Totora Formation unconformably overlie granitoids of the Choiyoi stage in Vallenar area (Maksaev et al., 2014 and references therein) and are considered the northwesterly extension of the Cuyo basin (Charrier et al., 2007) of Argentine Precordillera (Fig. 2). Similarly, acid volcanic units of the Los Tilos sequence covering unconformably the Guanaco Sonso sequence comparable to the Choiyoi volcanics, are constrained within the Middle to LateTriassic (Martin et al., 1999; Maksaev et al., 2014). The younger epizonal intrusions of the

Elqui-Limarí and Chollay batholiths also have comparable Triassic ages (Martin et al., 1999; Hervé et al., 2014; Maksaev et al., 2014).

Coeval volcanic and plutonic rocks are extensively exposed along the Chilean Precordillera, north of 27°S (Fig. 9; Munizaga et al., 2008; Maksaev et al., 2014 and references therein).

The Middle to Late Triassic post-Choiyoi magmatism is associated with normal faults and rift-related deposits that led to the break-up of Gondwana (Charrier et al., 2007; Ramos, 2009). Thick volcanic piles, often with bimodal compositions and primitive magma are reported from Chilean exposures (Munizaga et al., 2008; Maksaev et al., 2014).

### 5.4. Synthesis of the three stages of magmatism

According to the descriptions in Sections 5.1–5.3, the deeper plutonic levels of the pre-Choiyoi magmatism seem to be exposed along the Coastal Cordillera and northern Patagonia, with ductile to fragile deformation. In the Chilean Frontal Cordillera, the plutonic rocks from this stage crop out along a western belt, while along the Chilean Precordillera the exposed levels are shallower and represented by plutonic and volcanic units.

During the Choiyoi stage, the magmatic axis records a shift to the east (Maksaev et al., 2014), and an expansion to the southeast, covering the extended region depicted in Fig. 1. The deeper plutonic levels are again exposed along the Chilean Frontal Cordillera with volcanic levels mainly to the east. Shallower, plutonic to volcanic transitional levels are observed along the Argentine Frontal Cordillera, while farther east, the outcrops are maily of volcanic character. For this reason, the angular unconformity that defines the base of the Choiyoi units is better observed in the Argentine outcrops. The extensional collapse of the previously thickened orogen —resulted from the San Rafael phase— controlled the emplacement of plutonic and volcanic units along the Frontal Cordillera (Llambias and Sato, 1995). In the Northern Patagonia, deformed and non-deformed granitoids cover the entire interval of the Choiyoi magmatism.

The generalized Triassic extensional regime facilitates the exhumation of the cupola of Permian plutons through the action of the diachronic Huarpica phase, and enables the development of half grabens that precede more widespread subsidence and marine transgression cycles (Uliana et al., 1989; Llambías et al., 2007; Leanza, 2009). In this post-Choiyoi stage, voluminous volcanism is recorded along the Chilean Frontal Cordillera, Chilean Precordillera, and Principal Cordillera. In this last region, isotopic constraints from the Precuyano deposits are still scarce (*e.g.* Schiuma and Llambías, 2008; Spalleti et al., 2010; Suárez et al., 2008), in spite of their being well represented as detrital zircon ages in the subsequent basin fill deposits (*e.g.* Naipauer et al., 2014). To the east, the mesosilicic and acid volcanic lava and pyroclastic flow deposits interlayered in the Cuyo basin (Precordillera and San Rafael Block) are thinner. In northern Patagonia, this widespread extension is evidenced by the emplacement of a regional scale, trachyiandesitic dyke swarm dated at 244 ± 2 Ma (González et al., 2014).

## 6. Late Paleozoic magmatism as possible volcanic source for the coeval Gondwana basins

South America and Africa in Gondwana time register the evolution of several sedimentary basins, in response to tectonic, climatic and sea level fluctuations (Fig. 10). Marine and continental deposits document the distinct episodes of the Late Paleozoic glacial event (*e.g.* Isbell et al., 2008; López Gamundí, 2010; Limarino et al., 2014), the transitions from icehouse to greenhouse conditions and associated biodiversity of fossil flora and fauna. The basin fill also records coeval explosive eruptive activity in the form of ash fall deposits, tuffs, tuffaceous mudstones and tonsteins, generally considered to have derived from orogenic regions in Chile and Argentina.

Having identified in the previous section the ages of the possible explosive volcanic sources for the volcanogenic layers found in different Late Paleozoic Gondwana basins and grouped them into the pre-Choiyoi, Choiyoi and post-Choiyoi activities, we now proceed to compare them with ages compiled from those basins (right side in Fig. 9).

### 6.1. Rio Blanco, Calingasta–Uspallata, Paganzo and San Rafael basins

The retroarc Rio Blanco–Calingasta–Uspallata basin (primarily around 28° to 34°S; Azcuy et al., 1999; Limarino and Spalletti, 2006; Limarino et al., 2006) includes the mainly marine Carboniferous to Permian beds located along the eastern side of the Argentine Frontal Cordillera and western side of Argentine Precordillera. To the east, the Paganzo basin (Salfity and Gorustovich, 1983; Limarino and Spalletti, 2006; Azcuy et al., 2007) includes a number of Upper Carboniferous to lower Permian units of mostly continental origin, deposited along the eastern side of Precordillera and in Sierras Pampeanas. These units are gathered in the Paganzo Group. The San Rafael basin is composed of coeval marine to continental units in the San Rafael Block and continental beds in Las Matras to Chadileuvu Blocks (see Figs. 1, 2 and 10).

With regard to the Paganzo basin and the related Rio Blanco basin, the high precision ID TIMS data by Gulbranson et al. (2010) not only allowed a chronostratigraphic redefinition of the Paganzo Group and a time constraint of the Carboniferous glaciation (*e.g.* Césari et al., 2011; Isbell et al., 2012; Gulbranson et al., 2014; Limarino et al., 2014), but also confirmed important proximal and distal volcanic activities in the Pennsylvanian time (mainly 320 to 310 Ma, Rio del Peñón, Guandacol, Tupe and Patquía formations), with additional ages at middle Mississippian (335.99 ± 0.06 Ma, orogenic andesitic lava from Punta del Agua Formation, Remesal et al., 2004), and earliest Cisuralian (296.09 ± 0.08 Ma, La Colina Formation) (Figs. 2 and 9). This 320–310 Ma interval is not very well represented along the Coastal Cordillera and Frontal Cordillera, and might represent an independent proximal source from a moment when the magmatic axis in Sierras Pampeanas (last events of the Famatinian cycle) migrated to the west (onset of the Gondwana active margin).

The youngest and isolated age of 296 Ma from a tuff level in the La Colina Formation (Gulbranson et al., 2010; upper section of the Paganzo Group) is similar to the 297 Ma single zircon age obtained from a thin silty level in the top of the pre-Choiyoi El Imperial Formation in the San Rafael basin (Figs. 2 and 9; Rocha-Campos et al., 2011). They are within the interval registered in the Frontal Cordillera as a whole.

The above ages suggest that in the pre-Choiyoi magmatism identified in the Paganzo basin, at least part of the proximal ignimbrites may relate to a local volcanic source, and part to the Frontal Cordillera (Figs. 9 and 10). The youngest age of 296 Ma in the upper level of the Paganzo basin allows us to consider the possibility that the deposition in the Paganzo basin ended with the compression of the San Rafael phase, as did in the Rio Blanco–Uspallata–Calingasta and San Rafael basins (Fig. 2).

### 6.2. Chaco-Paraná basin

In the underground units of the intracratonic Chaco-Paraná basin (Figs. 1 and 10) the diamictite-bearing Ordóñez Formation is constrained in the Late Carboniferous – Early Permian interval on

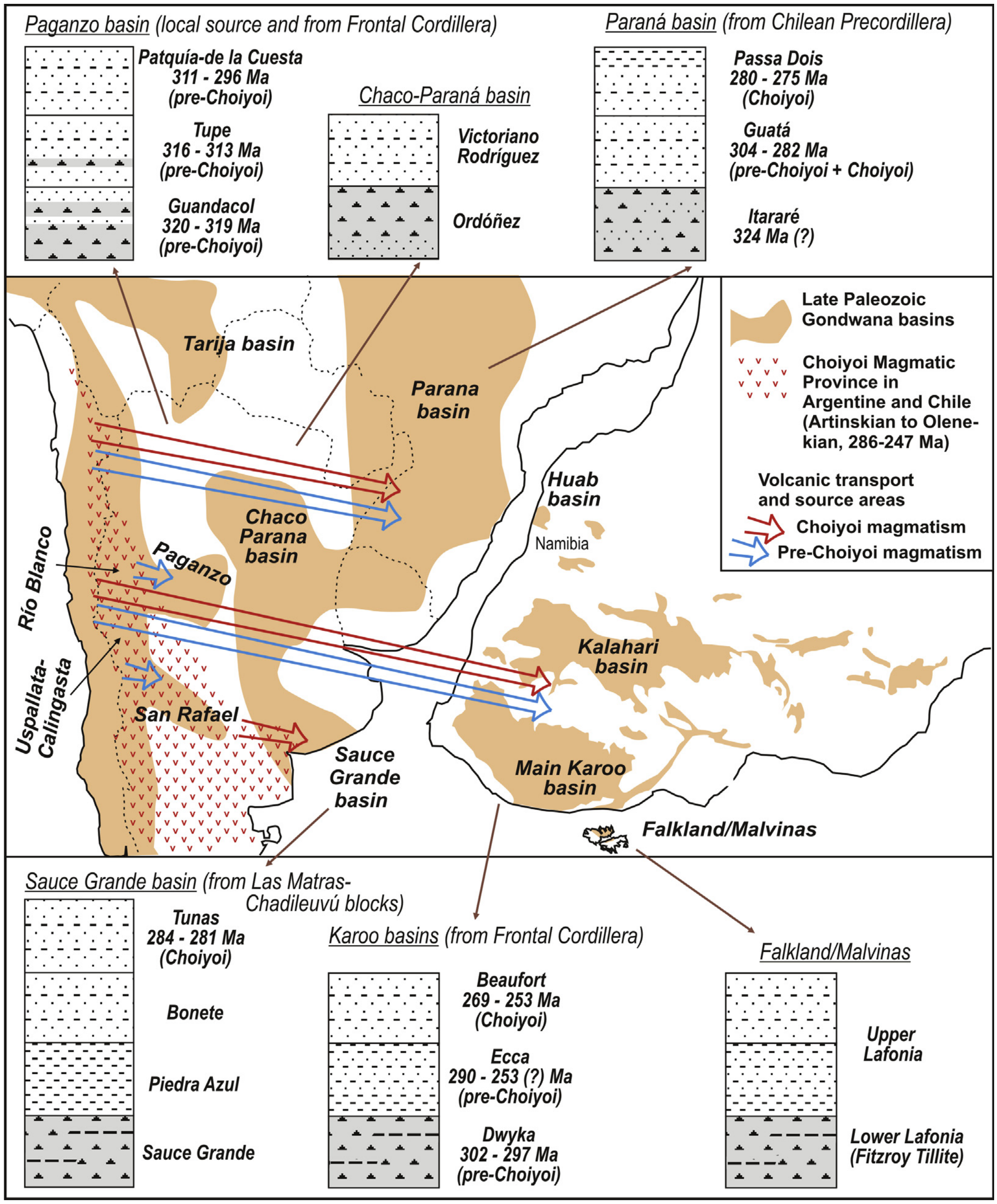


**Fig. 10.** Spacial relationships between the Late Paleozoic sedimentary basins of southwestern Gondwana and the Choiyoi Magmatic Province in Argentina and Chile. For each basin their general stratigraphy and age intervals from volcanogenic levels are indicated, with their belonging to the pre-Choiyoi magmatism or Choiyoi magmatism. Post-Choiyoi magmatism is not represented in the units considered. As the result of our analysis (see text and compare with Fig. 9), we propose the following: The pre-Choiyoi volcanism found in the Paganzo basin (320–296 Ma) derives from a local source and probably the region of Frontal Cordillera. The pre-Choiyoi and Choiyoi volcanic activities identified in the Paraná basin (304–275 Ma) are likely to have their source in the Chilean Precordillera region. The early Choiyoi activity dated in the Sauce Grande basin (284–281 Ma) may have come from the neighbouring Las Matras to Chadileuvú blocks. In the pre-Choiyoi and Choiyoi volcanic activities found in the Karoo basins (302–253 Ma) the longest Choiyoi interval is registered, and as a whole they bear the best resemblance to the age records along the Chilean and Argentine Frontal Cordillera. These possible sources and wind directions are also indicated.

the basis of palinological remains from coaly layers (Fernández Garrasino, 1996; Archangelsky and Vergel, 1996; Winn and Steinmetz, 1998; Azcuy et al., 2007). This unit is followed by the Permian Victoriano Rodríguez Formation. Previous suggestions about the existence of a silty layer with volcanic origin are denied by Winn and Steinmetz (1998), who reinterpreted it as a pebbly mudshale of diamictitic origin.

Consequently, no bed with undoubtedly volcanogenic origin has been reported from this basin. However, being located to the east of the Paganzo basin, and with which a connection through the Salinianas pass is suggested (Salfity and Gorustovich, 1983), these two basins may have shared a considerable part of their time of deposition.

### 6.3. Sauce Grande basin

As a possible southern extension of the Chaco-Paraná basin, the Sauce Grande basin crops out in Sierras Australes. Its offshore extension and link to the Karoo basins are pointed out by Pángaro et al. (2015). The glaciomarine diamictite-bearing Sauce Grande

Formation is constrained to the Pennsylvanian to Cisuralian time on the basis of NBG flora (Morel and Gutiérrez, 2000) and palinomorphs (Di Pasquo et al., 2008). The succeeding formations contain *Eurydesma* fauna and *Glossopteris* flora of Early Permian (see synthesis in Azcuy et al., 2007). The uppermost Tunas Formation, considered a syntectonic, foreland basin fill (López-Gamundi et al., 1995) contains tuff levels (Iñíguez et al., 1988) that have provided U–Pb ages in recent years, particularly the outcrop at Abra del Despañadero. SHRIMP U–Pb ages are obtained by Tohver et al., 2008 (282.4 ± 2.8 Ma) and López Gamundí et al., 2013 (280.8 ± 1.9 Ma), while LA-ICP-MS ages are published by Alessandretti et al. (2013) and Ramos et al. (2014). Alessandretti et al. (2013) reports a mean $^{206}Pb/^{238}U$ age of 284 ± 15 Ma on the basis of 3 younger spots out of 9, while Ramos et al. (2014) consider an interval between 280 and 288 Ma as representative of the crystallization age, on the basis of 3 tuff layers.

As pointed by López Gamundí et al. (2013), the SHRIMP U–Pb ages are contemporaneous to the beginning of the Choiyoi magmatism in the Andean region of Chile and Argentina and inboard region in Argentina. Particularly, some of the chemical features given by Alessandretti et al. (2013) for the three tuff layer samples dated by Ramos et al. (2014), are similar to those from the volcanic outcrops along the Las Matras and Chadileuvú blocks (Llambías et al., 2003) and the López Lecube syenite (Gregori et al., 2003; Pankhurst et al., 2006), which have characteristics of intracratonic magmatism (see limit between the orogenic and intracratonic Choiyoi province in Figs. 1 and 8). Therefore, the explosive volcanism source for the tuff layers may be found as close as the Las Matras to Chadileuvú areas (Figs. 9 and 10). Detrital zircon ages in Tunas Formation from two samples record youngest and most important peaks of 291 and 281 Ma (Ramos et al., 2014) respectively. These data, added to the 304 Ma-youngest peak from the three tuff levels taken together by the same authors may suggest that the last part of the pre-Choiyoi volcanism like those cropping out along the Andean region –such as the former orogenic areas currently in the underground of the Principal Cordillera and Nequen basin– is also involved in the basin fill of the Tunas Formation (Fig. 9).

### 6.4. Paraná basin

The eastern extension of the intracratonic Chaco-Paraná basin corresponds to the Paraná basin covering Brazil, Uruguay, and partly Paraguay and Argentina, also connecting with the Huab basin in Namibia, as part of the Karoo basins in the south of Africa. During the Late Paleozoic, its evolution was linked in some way to distal orogenic events along the southwestern margin of Gondwana (Milani and Ramos, 1988; Milani and de Witt, 2008). The basal and glaciomarine Itararé Group is Late Carboniferous to early Permian, according to invertebrates, paleoflora and palinoflora (synthesis in Holtz et al., 2010; Azcuy et al., 2007). In the upper part of this group is found the Early Permian *Eurydesma* fauna. Within the following Guatá Group, the Rio Bonito Formation is the coal-bearing unit, characterized by Early Permian *Glossopteris* flora in association with bivalves. It is followed by shallow marine Palermo Formation, still in the Early Permian, according to paleo- and palinoflora and bivalves. The subsequent Passa Dois Group consists of Irati (late Artinskian), Serra Alta, Teresina and Rio do Rasto (Guadalupian to Lopingian) formations (Holtz et al., 2010).

The age of 323.6 ± 15 Ma within the Itararé Group is considered older than the age of the sedimentary layers containing the ash fall deposit (Rocha-Campos et al., 2006). The abundant ash fall beds and tonsteins interlayered with coal levels in Rio Bonito Formation record a considerable number of U–Pb ages, in the interval 298.5 ± 2.6 to 281.7 ± 3.2 Ma (Asselian to Kungurian, Rocha-Campos et al., 2006; Sommer et al., 2008a,b,c; Mori et al., 2012; Simas et al., 2012; Cagliari et al., 2014) (Fig. 9). In addition, an oldest age of 303.6 ± 0.66 Ma (Gzelien), and ages between 299 and 290 Ma from two ash fall layers are obtained by Philipp et al., 2014 for the same formation. Moreover, Canile et al. (2014) note the importance of the 285 ± 2 Ma peak among detrital zircons, as close to the depositional age. The Passa Dois Group is characterized by U–Pb ages between 279.4 ± 4.8 Ma and 275.1 ± 5.4 Ma (Iratí and Rio do Rasto formations, Rocha-Campos et al., 2006; Santos et al., 2006).

In this way, the Río Bonito Formation (303.6 Ma–281.7 Ma, Gzhelian to Kungurian) has proved to record the transition between the last part of the pre-Choiyoi magmatism and the beginning of the Choiyoi magmatism, in a similar way to the Tunas Formation in the Sauce Grande basin. However, we consider that their source region might be the Chilean Precordillera region north of 27°S, where the pre-Choiyoi and Choiyoi stages are more continuously exposed. (Figs. 9 and 10). The Choiyoi magmatism is also represented in the Iratí and Rio do Rasto formations (Passa Dois Group), where the youngest age of 275.1 Ma is still within the Kungurian (Early Permian), although the Passa Dois Group covers the Early to Late Permian time, according to their fossil record (late Artinskian to Wuchiapingian, Holtz et al., 2010). Guadalupian and Lopingian volcanic ages are not recorded up to now in the Paraná basin, and this might be related to the fact that magmatism declines along the Chilean Precordillera region (Fig. 9).

### 6.5. Karoo basins

In the south of Africa, the main Karoo foreland basin developed in response to Late Paleozoic orogenic processes, while to the north, coeval basins evolved under extensional to transtensional regime (Catuaneanu et al., 2005). The correlation and parallel evolution of these basins and the Paraná basin is discussed by Milani and de Witt (2008), and the Permian correlation with the Malvinas/Falkland Islands is suggested by Trewin et al. (2002). Ar–Ar age constraints for the Cape Orogeny in the Cape Fold Belt are given by Hansma et al. (2015).

The fossil records are mainly based on palinoflora, paleoflora and vertebrates (*e.g.* Rubidge et al., 2013; Barbolini and Bamford, 2014; Ruckwied et al., 2014 and references therein). The glaciogenic Dwyka Group (Upper Carboniferous to Lower Permian) consists of several deglaciation cycles (Visser, 1996; Bangert et al., 1999; Isbell et al., 2008; Stollhofen et al., 2008) and contains *Eurydesma* fauna in the upper part. The following Ecca Group documents the transition from icehouse to greenhouse conditions and includes the major part of coal deposits (Scheffler et al., 2006; Caincross, 2001; Ruckwied et al., 2014). The succeeding Beaufort Group (Middle Permian to Triassic), which diachronically covers the Ecca Group, represents mostly subaerial deposition and documents a great biodiversity of tetrapods (Hancox and Rubidge, 2001; Jirah and Rubidge, 2014). Permian and Permo-Triassic mass extinction events are under debate within these units (Retallack et al., 2006; Lucas, 2009; Rubidge et al., 2013).

The Dwyka Group is dated by 3 SHRIMP U–Pb ages, covering the 302.0 ± 3.0 Ma to 297.0 ± 1.8 Ma interval (Bangert et al., 1999) (Fig. 9). Basal sections of the Ecca Group are dated by two SHRIMP U–Pb ages of 289.6 and 288.0 Ma in the main Karoo basin (Bangert et al., 1999). On the basis of 11 ages from 16 ash beds documenting a time interval between 274.8 ± 1.5 Ma and 252.7 ± 2 Ma in Ecca Group (Fildani et al., 2007, 2009), the authors claim that the Permo-Triassic boundary can be placed within the marine Ecca Group. Available U–Pb ages from the Beaufort Group are those reported by Coney et al. (2007) at 252.5 ± 0.8 Ma (single crystal, CA-TIMS), Lanci et al. (2013) in the interval 268.5 + 3.8/−1.7 Ma and 264.6 + 1.9/

−4.3 Ma (5 SHRIMP ages), and Rubidge et al. (2013) in the interval 261.241 ± 0.088 Ma and *c.* 255.2 Ma (7 ages, CA-TIMS). These ages from the Beaufort Group covers an overall interval between 268.5 and 252.5 Ma, overlapping the major part of the ages obtained by Fildani et al. (2007, 2009) for the Ecca Group. According to Lanci et al. (2013), this discrepancy might result from the different criteria used when interpreting the U–Pb analytical data.

Despite the unsolved final age interpretations for the Ecca and Beaufort groups, the cumulative probability plots and histograms of $^{206}Pb/^{238}U$ ages younger than 300 Ma shown by Fildani et al. (2009) for the Ecca Group and Lanci et al. (2013) for the Beaufort Group present remarkable similarities. 205 concordant ages from Ecca Group cover an interval given by the oldest and youngest small peaks of 290.2 to 247.9 Ma, with the prevalence of 280–265 Ma time (Fig. 3 in Fildani et al., 2009), while 119 ages from Beaufort Group cover an interval between 310 and 245 Ma, with the prevalence of 280–260 Ma (Fig. 8 in Lanci et al., 2013). These data, added to the 265.52 to 255.22 Ma interval obtained by 50 spots out of 53 by Rubidge et al. (2013), clearly reflect the total interval of the Choiyoi magmatism in Argentina and Chile (286–247 Ma), documenting additionally few ages from the last part of the pre-Choiyoi magmatism (Figs. 9 and 10). This situation is more in accordance to their source being the Chilean and Argentine Frontal Cordillera region (see Fig. 9), where age records are comparable.

### 6.6. Summary of the interpretations

From the analysis of the volcanogenic bed ages among the Gondwana basins, we have summarised in Fig. 10 the geological units, their basic lithology, the volcanogenic age constraints in the Paganzo, Chaco-Paraná, Paraná, Sauce Grande, Karoo and Falkland/Malvinas basins. We have also added in this figure the main source areas proposed in this contribution. Among the considered basins, volcanogenic beds have not been recorded from the Chaco-Paraná basin. In the Falkland/Malvinas basin, even though they are recorded (Scasso and Mendía, 1985), still lack geochronologic constraints. The above detailed interpretations of the source areas of the volcanogenic events are also depicted in Fig. 10. It is noticeable in this figure that only the pre-Choiyoi orogenic magmatism and the Choiyoi magmatism are represented in the basin records. This is in accordance with hydrous magmas generated by subduction along continental margins, with the capacity for causing explosive volcanism with high eruptive columns spreading long distances following wind directions. The source area interpretations are consistent with a uniform wind scheme from the orogenic region for the time involved.

The post-Choiyoi magmatism related to rift deposits is only recognized within these isolated rift basins, and not within Middle to Late Triassic deposits like in the distal Karoo basin. This situation might be related to different, less explosive eruptive styles of the volcanism, or otherwise the wind-carried ash fall deposits would have failed to survive the continental deposition conditions.

## 7. Conclusions

(a) Within the Colangüil area, we have obtained five LA-ICPMS ages from tonalitic to granitic rocks of the Colangüil Batholith and one from an andesite of the Choiyoi Group, belonging to the Choiyoi magmatism. The ages are between 279 and 253 Ma.

(b) With the addition of the new ages in the data compile of the Late Paleozoic to Triassic magmatic rocks, and the analysis of geologic relationships, we could identify three magmatic stages. (1) Late Mississippian to early Cisuralian, Pre-Choiyoi orogenic magmatism, with plutonic rocks exposed along the Coastal Cordillera, mainly western side of the Frontal Cordillera and the northwestern Patagonia, while shallower volcano-plutonic levels are exposed along the Chilean Precordillera. (2) Choiyoi magmatism (286–247 Ma), with magmatic axis shifting to the east and expanding to the southeast during an interval of nearly 40 m.y., covering an extended region that characterizes the Choiyoi province. (3) Triassic post-Choiyoi magmatism, associated with diachronic initiation of rift tectonics, with voluminous volcanism primarily along the Frontal Cordillera, Chilean Precordillera and Principal Cordillera.

(c) From the analysis of the ages and possible source areas of the volcanogenic levels identified in the Gondwana basins, we have found that only the pre-Choiyoi and Choiyoi magmatic events are represented there.

(d) The proximal to distal pre-Choiyoi volcanogenic events dated in the Paganzo basin (320–296 Ma) are likely to have derived from local sources as well as from the Frontal Cordillera region.

(e) The early Choiyoi event found in Las Tunas Formation (284–281 Ma) of the Sauce Grande basin may have its source in the adjacent Las Matras and Chadileuvú blocks.

(f) The mainly 304–275 Ma, pre-Choiyoi and Choiyoi events recognized from the Paraná basin are most likely to have derived from the Chilean Precordillera, where a conspicuous and continuous volcanic and plutonic magmatism is described covering this interval.

(g) The principally 302–253 Ma, pre-Choiyoi to Choiyoi ages found in the Karoo basins have strong similarities with the records along the Chilean and Argentine Frontal Cordillera. All these interpretations are consistent with a uniform easterly wind scheme.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsames.2015.07.005.

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