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The Sierra de Macon, Plutonic expression of the Ordovician magmatic arc, Salta Province Argentina

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Abstract

The Macon granitoids are part of a tonalite/diorite granodiorite suit. Their trace elements place these rocks in the volcanic arc field. They have distribution patterns similar to those observed for rocks from Choschas, Taca Taca, Chuculaqui, and Quebrada de Batin. Macon rocks show strong enrichment of elements such as K, Rb, Th, and light REEs, which suggests crustal participation associated with the arc source. $^{87}Sr/^{86}Sr_i$ and $(^{143}Nd/^{144}Nd)_i$ isotopic ratios of two samples are compatible with arc-related rocks. Their calculated age of 482.7 Ma is consistent with other ages determined for the Ordovician western Puna eruptive belt (Faja Eruptiva de la Puna Occidental). This belt is made up of a set of granitoids, characteristic of the northern part of the Puna of Catamarca that, together with similar exposures of Salta and the Chilean region near the border with Argentina, suggests a meridian strike. The Ordovician ages and arc characteristics of the Sierra de Macon rocks, at the eastern extreme of the belt, incorporate them into this igneous province. This significantly increases the width of the Sierra de Macon igneous province to as much as 150 km at this latitude.
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Keywords: Andes; Granitoids; Magmatic arc; Ordovician; Puna

Résumé

Las rocas graníticas de la sierra de Macón forman parte de una asociación integrada por granodioritas con tonalitas y dioritas subordinadas. Los elementos traza ubican a estas rocas en el campo de las rocas de arco, las que muestran un patrón de distribución similar a la reconocida en otros granitoides como Choschas, Taca Taca, Chuculaqui y las rocas aflorantes en la quebrada de Batín. Se caracterizan por el enriquecimiento en elementos incompatibles como K, Rb, Th, y elementos de las Tierras Raras livianas sugiriendo que en su formación participaron componentes corticales asociados a una fuente de arco. Las relaciones isotópicas $^{87}Sr/^{86}Sr_i$ y $^{143}Nd/^{144}Nd$ son comparables con las reconocidas en las rocas de arco. La edad determinada en 482.7 Ma es consistente con edades determinadas para otras rocas de la Faja Eruptiva de la Puna Occidental. Este cinturón ígneo está conformado por un grupo de granitoides característicos en la Puna catamarqueña, los que junto con otras exposiciones en Salta y la región chilena próxima al límite con Argentina, constituyen un cinturón de rumbo meridiano. La edad ordovícica y las características de arco de las rocas del Macón, en el extremo este de la faja permite incorporarlas a esta provincia ígnea e incrementar significativamente sus dimensiones las que alcanzan los 150 km de ancho a esta latitud.
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1. Introduction

The Puna is one of the largest and highest plateaus on Earth, an elevated zone with a local base level at 3700 m above sea level, and has been uplifted since the lower Miocene. Its present configuration is the consequence of tertiary/quaternary intense volcanism along the arc with synchronic crustal thickening and periods of crustal extension. Large centripetal basins developed in relation to this extensional setting. Due to extreme climatic conditions, the basins evolved into characteristic Puna salt deposits (salars). West of Puna (Salta) and north of Catamarca, a series of granitoids, whose age has been attributed to either

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the Precambrian or the Lower Paleozoic, are exposed. Recently, a set of absolute ages was obtained that confirms an Ordovician age for most of these rocks (Palma et al., 1986; Llambías and Caminos, 1986; Blasco and Zappettini, 1996; Koukharsky et al., 2002). This confirmation for the Macon granites (Koukharsky et al., 2002) enables us to outline the paleogeography of the magmatic series and reinforces the concept of a western Puna eruptive belt (Faja Eruptiva de la Puna Occidental; Mpodozis et al., 1983; Palma et al., 1986; Damm et al., 1986, 1990, 1991; Page et al., 1999; Rapela et al., 1999; Koukharsky et al., 2002). The igneous belt consists of a series of granitic bodies between 24° and 26°30′S; among those, the Cordon de Lila complex and Sierra de Almeida in Chile and the Sierra de Taca Taca and Sierra de Macon in Argentina are the most important.

The survey of these genetically related magmatic units, which appear as either small and isolated outcrops or huge bodies, and the understanding of their genesis and tectonic setting are essential to establish the geologic evolution of this portion of the Central Andes during the early Paleozoic. In this article, we present the petrography, chemistry, and isotopic relations of the units found in the Sierra de Macon and discuss its nature in the context of their extreme eastern location in the Ordovician western magmatic arc.

2. Background

Ordovician magmatism in northwestern Argentina constitutes two NE-trending subparallel belts known as the eastern (Faja Eruptiva de la Puna Oriental; Méndez et al., 1973) and western (Faja Eruptiva de la Puna Occidental; Palma et al., 1986) Puna eruptive belts. The first is associated with epizonal bodies and volcanic rocks, initially considered of Silurian age, that have been interpreted as (1) a product of an extensional crustal environment (Davidson and Mpodozis in Coira et al. (1982) and Aceñolaza and Toselli (1984)); (2) the expression of early stages of a calc-alkaline arc related to subduction (Coira et al., 1982); or (3) related to a transpressive geodynamic regime that controlled their origin and emplacement (Coira et al., 1999a,b). In contrast, the western Puna belt is made up of a set of granitoids that crop out from northeastern Chile to western Salta and Catamarca, though there also have been different tectonic interpretations for this belt. Palma et al. (1986) believed it a Cambro-Ordovician magmatic arc unrelated to the eastern belt. Similarly, Bahlburg (1990, 1993) restricted the arc concept to the western magmatic belt. Coira et al. (1999a,b) proposed a generalized, three-stage tectonic model with an early arc stage, with arc, behind the arc, and backarc volcanism. According to these authors, the Cordon de Lila volcanic units in the arc represent such a model, and the basal mafic volcanic units of Huaitiquina, Calalaste, and Pocitos erupted in an arc/backarc setting.

3. Geology

In this part of the Puna, the local basement is composed of Cambrian quartz sandstones and quartzitic sequences known as the Tolar Chico Formation (Zappettini et al., 1994). They outline a thin belt of outcrops located at the southeastern border of the Salar de Pocitos. The Ordovician sequence starts with marine dark shales that contain lower Tremadocian fossils and subordinate amounts of sandstones, limestones, tuffs, and volcanic rocks of acidic composition. The sequence is known as Las Vicuñas Formation (Moya et al., 1993) and outcrops at Quebrada El Medano, southwest of the Salar del Rincon. Marine sedimentation continues with wackes and subordinated sandstones (Tolillar Formation; Zappettini et al., 1994), which cover a wide sector of the Puna and concordantly overlie the Cambrian quartzitic sandstones. In the eastern sector of the Salar de Pocitos, the outcrops draw a narrow belt (Fig. 1), and layered basic and ultrabasic sills are interbedded in the Tolillar Formation. However, these contacts may also be tectonic (Zimmermann et al., 1999). Basic igneous rocks are shallow intrusions known as the Ojo de Colorados mafic–ultramafic complex (Zappettini et al., 1994). Mafic and ultramafic magmatic sequences outcrop from south of the Salar de Arizaro to Sierra de Calalaste. They occur interlayered in metamorphosed turbiditic sediments (Blasco et al., 1996; Bahlburg et al., 1997), as small bodies that intrude sediments, or as fragments of basic rocks that are tectonically emplaced (Zimmerman et al., 1999; Seggiaro and Hongn, 2003). In the tectonic contact overlying previous sedimentary and volcaniclastic sequences, there are sandstones and fossiliferous shales (Coquena Formation, Schwab, 1971) interbedded with contemporaneous volcanic and volcaniclastic rocks. The volcaniclastic fraction increases upward; is dominant at the uppermost levels; and outcrops south of Quebrada La Petaquilla, north of the Lari Grande granite, and north of Sierra de Macon (Fig. 1). The same sedimentary rocks are preserved as a roof pendant in the northern part of the Macon granite. They border the eastern end of the Salar de Pocitos, and other exposures continue to outcrop to the south to Sierra de Calalaste in an isolated fashion.

The Ordovician granitoids clearly intrude the sedimentary sequence. From south of the Quebrada Lari to Salar de Antofalla (Catamarca Province), the outcrops of these rocks build a long north–south belt. The magmatic intrusions produce a thermal effect on the adjacent sedimentary country rock, hornfels, which are derived from the hot magma that intrudes the cooler sedimentary rocks. In some places, outcrops are partially covered by Tertiary volcanic rocks and salt deposits.

During Permotriassic times, intrusive felsic bodies of granitoid rocks characterized another eruptive cycle. These granites share some petrographic characteristics with the Ordovician ones and are commonly confused with them. In recent years, after the absolute dating of many rocks, the granites have been differentiated. Commonly, the younger granitoids are located west of the Ordovician

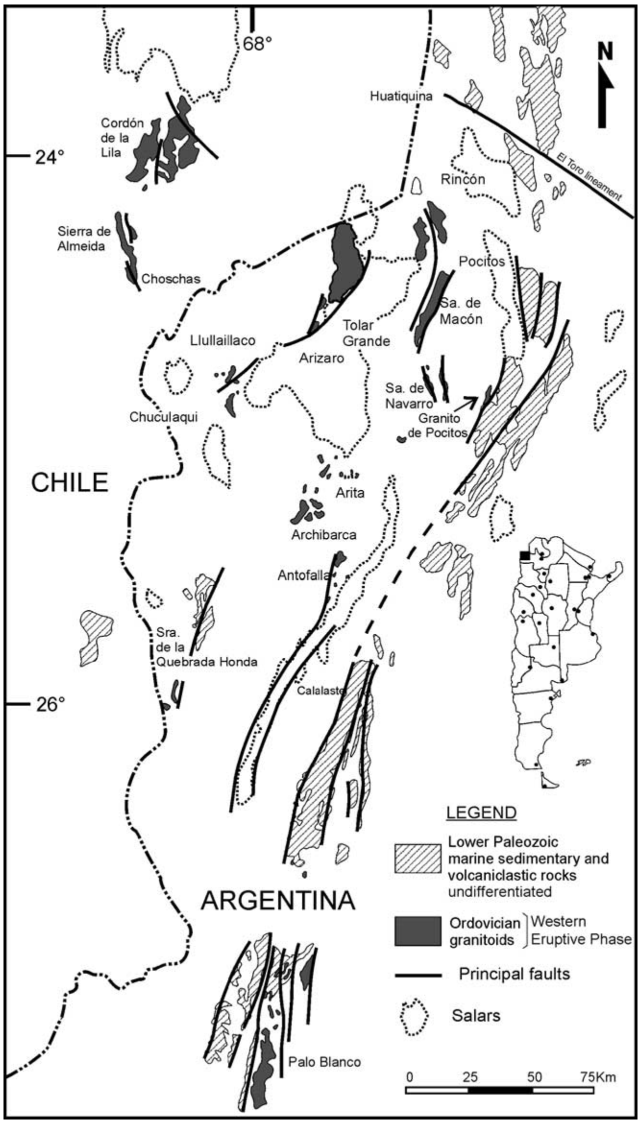

Fig. 1. Generalized sketch map of northwestern Argentina and Chile showing the distribution of lower Paleozoic marine sedimentary and eruptive rocks. Labeled localities are indicated in the text. Figure is modified from Mpodozis et al. (1983), Palma et al. (1986), Martínez et al. (1995), Salfity et al. (1998) and Zappettini and Blasco (1996, 1998).

rocks along a north–south belt. The main bodies—in Taca Taca, Samenta, Salar de Llullaillaco, and Arita—have been grouped into the Llullaillaco plutonic complex and the Laguna de Aracar Formation (Zappettini and Blasco, 1998). The Permotriassic series includes not only intrusive bodies, but also lavas and ignimbrites interbedded with sediments. Locally, they produce thermal and hydrothermal effects on the country rock. Tertiary and quaternary sedimentary and volcanic rocks partially cover the granitoid units.

4. Distribution and age of the granitoids

As mentioned previously, Ordovician granitoid outcrops are located along the western border of Salar de Arizaro, where they are known as the Taca Taca Granite. Rb/Sr isochrone determined a 469 ± 4 Ma age (Llambías and Caminos, 1986), whereas U/Pb zircons indicate a 476 ± 7 Ma age (Makepeace et al., 2002). Granitoids also occur in the Chuculaqui area and farther south, near the La Casualidad mine, where the road cuts granite outcrops associated with other mesosilicic/basic bodies (Río Grande diorite; Zappettini and Blasco, 1998). Most of these rocks are part of dikes or small bodies found at the northern extreme of the Salar de Rio Grande. The salt deposits drown the granitic rocks that border the Salar de Arizaro, such as the Taca Taca Granite, where they are found at the south of the Quebrada de Lari, Cerro Rincón, and south of the Quebrada La Petaquilla. These outcrops were grouped by Koukharsky (1988a,b) as the Chachas eruptive complex. The granitoids are also observed in the Sierra de Macon, where a fault parallel to the eastern border uplifts a longitudinal sliver of magmatic rocks from the local basement. The established hornblende Ar/Ar age (Koukharsky et al., 2002) is Ordovician (482.7 ± 7.8 Ma). To the south, at Cerro Navarro and Cerro Lari Grande, they are known as the Navarro Formation (Blasco and Zappettini, 1996). To the southwest, where they are associated with basic bodies, the whole set is known as the Pocitos eruptive complex (Blasco and Zappettini, 1996), dated at 494 ± 20 and 470 ± 17 Ma with hornblende K/Ar ages. Basic or dioritic rocks, associated marginally with granitoids, are common, as are mixing processes, generally mingling, in the felsic acid rocks. Moreover, there are scattered granitoid outcrops of this type that occur as a belt along Arita (south of the Salar de Arizaro), Archibarca, and surrounding the Salar de Antofalla. At the beginning of the Quebrada de Caballo Muerto, east of the Archibarca spring, a sample has been dated at 485 ± 15 Ma (K/Ar from biotite; Palma et al., 1986). Similarly aged granitoids are known to crop out as far south as Palo Blanco (27°S) and even farther (Martínez et al., 1995).

5. The Sierra de Macon

The Sierra de Macon is an elongated elevation of approximately 30 km longitude with a NNE trend. It borders the northeastern extreme of the Arizaro Salar in Salta (Fig. 2). The eastern edge is sharp due to regional fractures that uplift this side and expose Ordovician granitoids. The western border shows a strong slope to the salar. The Tertiary sequence, the Pastos Grandes Formation, overlies the granitoid. The granites are crossed by small bodies of volcanic acidic rocks and carry megaxenoliths of arc volcanic rocks (Koukharsky et al., 2002). The preferred direction of the structures is NNE and its conjugate (Fig. 2).

Granitoid rock exposures are limited to the areas where recent detritic cover is less significant, near the creeks and at the top of the range. In these places, the initial stages of unroofing may show a small outcrop area with

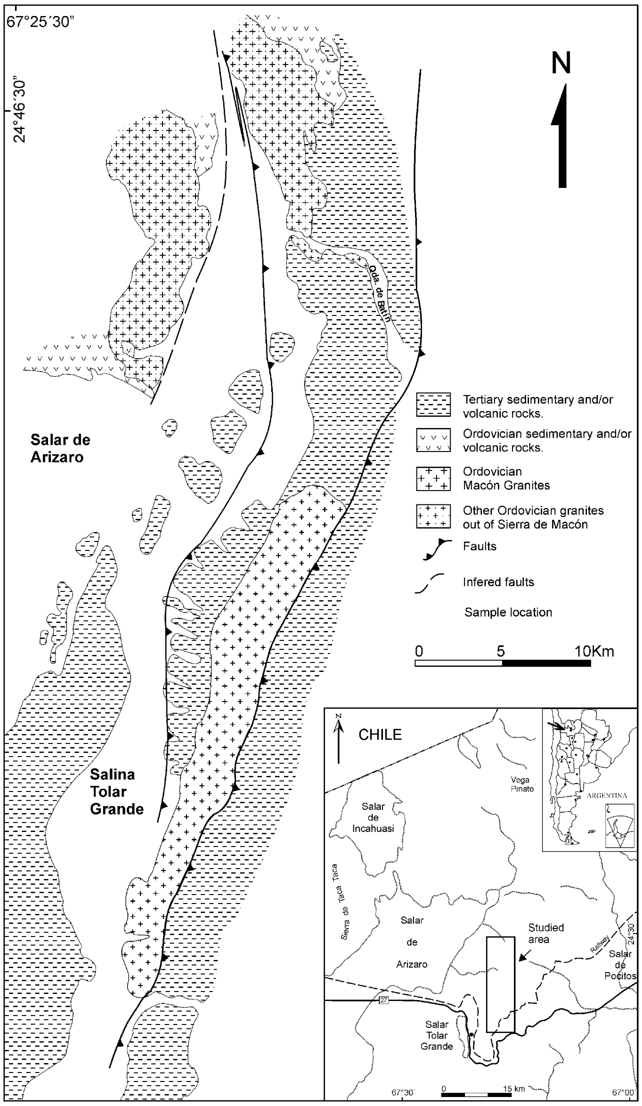

Fig. 2. Map of Sierra de Macon showing Ordovician granitic rocks and spatially related rocks.

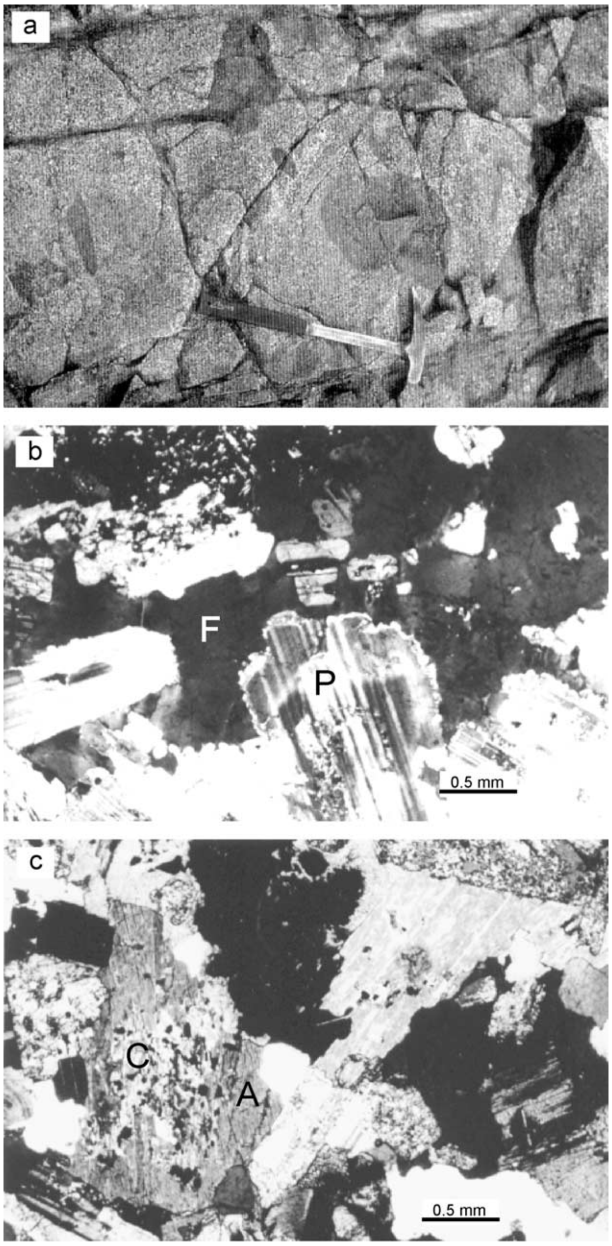

Fig. 3. (a) Outcrops of Macon granitoids showing fine-grained dioritic enclaves. Hammer at the lower border for scale. (b) Texture of poikilitic anhedral alkali feldspar (F) enclosing subhedral zoned plagioclase (P). (c) Texture of pyroxene (C) with partial replacement by green amphibole (A). Scale as indicated.

homogeneous textures; particularly, the top of the range outcrops are dominated by two-dimensional shapes that roughly define tabular bodies. Light grayish colors prevail, though there are variant shades due to secondary processes.

The contacts between the country and intrusive rocks at the southwestern side of the granitoids are covered. At the northeast side of the sierra, the low-grade metamorphic rock basement is exposed. The exposure is discontinuous, thin, and small, and always next to the border of the granitoid rock. They are fine-grained biotitic hornfelized schists. Some xenoliths of these rocks are found within the granites near the contact. Most are small and fine grained with sharp contacts against the granite.

In some cases, the granitoids contain dark enclaves (Fig. 3a) that are heterogeneously distributed and concentrated in the periphery of the outcrop. Most enclaves are metadiorites with variable amounts of quartz. The southwestern margin displays a higher density of dark, fine- to medium-grained enclaves that locally constitute more than 70% of the rock by volume. The enclaves are lensoidal, ellipsoidal, pillow, or blocky. Some lenses display progressive mechanical disruption in the host granitoid. The continuous shearing that modified the enclaves into mafic schlieren gives a darker shade to the outcrops. Field evidence suggests that neither the diorite nor the granitic rocks were completely solidified when they were intruded. Enclaves represent fragments of a more mafic phase related to the pluton and may be the result of the mingling of two effectively immiscible melts of different compositions that were spatially related during the intrusion.

6. Petrography

The granitoids are inequigranular, medium-grained rocks. Granodiorites are the prevailing phase, but granites and tonalites are also present. They are coarse to medium grained, and the most common textures are hipidiomorphic to alotriomorphic, though it is not uncommon to find monzonitic textures (Fig. 3b) with anhedral crystals of alkaline feldspar and quartz that include other minerals. The granites have plagioclase, quartz, and alkali feldspar as predominant phases, though biotite and amphibole are also present. As accessory phases, apatite, opaque minerals (magnetite), zircon, allanite, and tourmaline appear. Sphene also is present, but the lack of idiomorphism and its disposition between biotite's cleavage planes defines it as a secondary mineral.

Plagioclase tends to be an early, dominant phase. It appears as tabular crystals with compositional zonal patterns (oscillatory zoning). In general, the central zones are euhedral with patchy, inhomogeneous replacements overgrown. A wide euhedral growth, at the clean and more sodic border, coats many crystals. Individual rocks are partially replaced by secondary minerals such as sericite, clay minerals, and, in lesser amounts, epidote. In some rocks, a reaction phenomena is evinced, such as eroded crystals of plagioclase with rounded shapes coated by alkaline feldspar. In these cases, bulbous, abundant myrmekites seem to have grown at the boundary of large K-feldspar crystals invading and replacing in that direction. Alkaline feldspars form slightly argillized anhedral crystals that are homogeneous or with some fine pertitic intergrowth. Quartz is present in variable proportions. Both minerals are commonly late interstitial phases, even when the feldspar occurs as large subhedral crystals.

Common mafic minerals are green hornblende and biotite. Amphibole is recognized in euhedral to anhedral prisms of variable size and commonly displays simple twinning (Fig. 3c). Biotite is subordinate, fresh, or scarcely altered to chlorite with epidote and/or sphene. Mafic minerals are associated with opaque minerals, and biotite and hornblende often have small inclusions of euhedral plagioclase, generally near the crystal border, to resemble subophitic textures.

As described previously, several observed textural relations—such as igneous or metaigneous xenoliths, schlieren, complex oscillatory zoning in plagioclase, and so forth—are compatible with magma mixing, but until now, no irrefutable evidence has been presented. In the plutonic rocks, the record of magma mixing is more likely to have been erased over time, so evidence of that process may not be completely preserved.

The interaction between magma and country rocks (assimilation) is also present but not easily demonstrated, except for the presence of some xenoliths of metasedimentary rocks. Although there could have been assimilation, there was little chance for chemical interaction. These are mostly unmodified rocks that show only scarce hornfels structure.

The important textural variations described for the granitoids at the outcrop scale reflect slow cooling and the presence of a volatile, which facilitates mineral growth. In the same way, biotite and amphibole indicate the availability of water and elevated pressure during crystallization. However, it is possible that not all crystals of amphibole are products of magmatic crystallization. In some crystals, commonly preserved relic patches of clinopyroxene (Fig. 3c) indicate late magmatic or postmagmatic crystallization replacement. Reactions involving water-rich fluids also include late magmatic overgrowth processes responsible for the replacement of pyroxene by green hornblende. Previous studies in the north (Koukharsky et al., 2002) show that fractional crystallization of plagioclase feldspar and amphibole has been an important mechanism for differentiation.

7. Chemical characteristic of granitoids

7.1. Major and trace elements

New chemical analysis from the Sierra de Macon are presented (Table 1), along with previous data from that area (M98-4, M98-5, M98-10) (Koukharsky et al., 2002), one sample from north of Quebrada de Batin (M98-21), two samples from Taca Taca (688, 683) (Page and Zappettini, 1998), and four samples from Choschas (SO814, SO1121, SO1123, SO631) (Table 1 in Coira et al. (1999a)). Unaltered and homogeneous samples were collected and selected for the chemical analysis that was performed at Activation Laboratories Ltd of Canada. Sample preparation and analytical techniques are described in Appendix.

According to their major elements, the rocks are 60–71% SiO_2 and 13.6–16% Al_2O_3. The alkali/silica diagram (Fig. 4a) places them in the tonalite–diorite–granodiorite fields; however, granodiorites prevail, consistent with the observed mode. The Macon, Quebrada de Batin, and Taca Taca granitoids have typical calc-alkaline characteristics and are metaluminous with molar $(Al_2O_3/(K_2O + Na_2O + CaO) \leq 1$ (Fig. 4b).

In the case of the Macon, Batin, and Taca Taca samples, the La/Ce ratio (Fig. 5a) shows a coherent line, reflecting a common magma source for these rocks. Choschas plutonic samples were plotted in the same diagram to show their common signature. According to the tectonic discrimination diagram (Fig. 5b; Pearce et al., 1984), their relative low amounts of Nb + Y place these samples in the volcanic arc field. Something similar occurs with other trace elements, such as Hf, Nb, and Th. Moreover, the petrographic

Table 1
Chemical analysis of Sierra de Macon, Quebrada de Batin, and Taca Taca. Trace element detection limits are indicated in brackets

	South of Sierra de Macón				Enclave M055	Batín M98/21	Taca Taca		N Sierra de Macón		
	M052	M058	M056	M054			M683	M688	M98/4	M98/5	M98/10
SiO_2	66.28	61.22	60.9	62.45	56.67	72.3	66.14	67.96	69.32	70.8	65.17
Al_2O_3	14.07	15.97	16.24	15.66	14.03	13.8	15.49	15.64	14.15	13.63	15.71
TiO_2	0.4	0.655	0.637	0.522	0.666	0.22	0.63	0.36	0.28	0.36	0.36
Fe_2O_3	4.07	6.82	6.52	5.90	9.39	2.95	5.23	3.75	3.61	4.44	5.30
MnO	0.128	0.128	0.119	0.12	0.277	0.06	0.14	0.06	0.07	0.09	0.11
MgO	1.2	2.84	2.72	2.57	5.95	0.76	1.57	1.42	0.95	1.33	1.92
CaO	2.75	5.15	5.67	4.42	7.29	2.93	3.28	3.83	3.36	3.21	4.39
Na_2O	4.10	2.89	2.81	2.87	2.50	3.16	3.33	4.38	3.10	3	2.89
K_2O	3.18	2.58	2.67	3.32	1.54	2.98	3.57	1.94	3.09	2.76	2.45
P_2O_5	0.12	0.14	0.14	0.08	0.13	0.09	0.17	0.14	0.09	0.10	0.11
LOI	2.76	1.4	0.75	1.78	1.27	0.69	0.92	0.88	1.40	0.67	1.16
Sc (1)	14	22	21	19	63	7	13	7	10	15	16
Rb (1)	101	88	86	98	57	115	164	57	125	117	93
Sr (2)	128	202	206	245	141	123	172	327	113	100	164
Y (0.5)	19.8	26.4	24.6	14	63.3	13	30	11	18.7	27.3	12.9
Zr (1)	167	152	164	128	66	110	164	82	123	136	100
Nb (0.2)	5.8	6.3	6.2	5.7	9.1	7.1	12.1	5.2	7.3	9.90	6.7
Cs (0.1)	11.7	3.6	3	1.8	7.6	2.5	8.54	1.31	16	9.80	5.2
Ba (3)	536	475	489	607	165	456	494	376	420	370	354
Hf (0.1)	4.2	4.3	4.5	3.5	2.4	3.1	5.32	2.71	3.4	4.1	2.9
Ta (0.01)	0.74	0.75	0.7	0.76	0.69	0.7	0.97	0.42	0.61	0.99	0.61
Th (0.05)	9.44	8.63	10.8	12.9	3.32	10.8	14.26	5.74	9.37	15.5	7.85
U (0.01)	2.91	1.62	1.98	2.16	0.82	1.99	3.74	1.42	1.73	1.98	1.48
La (0.1)	31.9	25.6	27.1	28.8	20.7	16.3	36.87	16.18	25.0	31.0	17.1
Ce (0.05)	61.1	54.4	56.2	54.1	61.6	31	77.75	36.79	40.62	61.72	33.00
Pr (0.01)	5.95	6.22	6.12	5.35	8.95	3.14	8.43	3.6	4.56	6.75	3.63
Nd (0.05)	22.7	25.5	24.8	19.8	42.8	11.3	32.04	13.67	16.20	23.77	12.76
Sm (0.01)	3.97	5.07	4.88	3.49	10.8	2.34	6.17	2.73	3.09	4.79	2.69
Eu (0.005)	0.951	1.13	1.13	0.849	1.63	0.604	1.22	0.73	0.738	0.788	0.698
Gd (0.01)	4.03	5.07	4.84	3.32	10.7	2.02	5.16	2.2	2.92	4.24	2.28
Tb (0.01)	0.56	0.74	0.71	0.43	1.86	0.38	0.84	0.37	0.51	0.73	0.39
Dy (0.01)	3.2	4.56	4.12	2.46	11.5	2.08	4.9	1.99	2.83	4.22	2.24
Ho (0.01)	0.68	0.93	0.86	0.48	2.35	0.43	1.02	0.39	0.62	0.92	0.45
Er (0.01)	2.09	2.79	2.64	1.41	7.11	1.31	2.98	1.13	1.81	2.71	1.33
Tm (0.005)	0.325	0.411	0.379	0.208	1.04	0.231	0.48	0.17	0.312	0.461	0.206
Yb (0.01)	2.18	2.76	2.58	1.44	6.67	1.57	3.17	1.13	1.98	2.92	1.39
Lu (0.002)	0.328	0.415	0.373	0.214	0.97	0.262	0.48	0.17	0.321	0.474	0.226
Ratios											
La/Sm	8.03	5.05	5.55	8.25	1.9	6.96	5.97	5.93	8.09	6.47	6.35
Sm/Yb	1.82	1.84	1.89	2.42	1.62	1.49	1.95	2.41	1.56	1.64	1.93
La/Yb	14.6	9.30	10.5	20.0	3.10	10.40	11.60	14.30	12.60	10.60	12.30

distinctions observed in different granitoid rocks from Macon, Batin, and Taca Taca cannot be traced by their chemistry; chemically, they define a coherent, homogeneous group.

On the ORG normalized trace elements diagram (Fig. 6(a) and (b)), a signature typical of magmatic arc granites is observed. Macon, Batin, Taca Taca, and several samples of Choschas rocks reflect a strong enrichment of K, Rb, Th, and light REEs, which suggests that they had crustal participation associated with the arc source. The depletion in HFS elements, such as Ta, Nb, and Hf, also suggests an affinity with I-type granites (Pearce et al., 1984).

La/Ta and Ba/Ta ratios indicate assimilation to either the subduction zone or crustal components anywhere that magma is stored in the crust. These ratios show a positive linear trend, coherent with an increase of crustal components from west to east, or from Choschas to Sierra de Macon.

The La/Sm, Sm/Yb, and La/Yb ratios (Table 1) imply magma generation conditions at source regions. The Sm/Yb ratio shows a narrow range of values for all samples (1.49–2.42), whereas the La/Sm ratio varies between 5.05 and 8.09. The lowest ratio values belong to Choschas (Table 1 in Coira et al. (1999a)), followed by Taca Taca and Sierra de Macon. The ratios show a regional tendency to increase westward, suggesting a major LREE contribution from the continental crust. The enclave La/Yb ratio (3.1) indicates a relatively flat sloping of the REE pattern with Eu

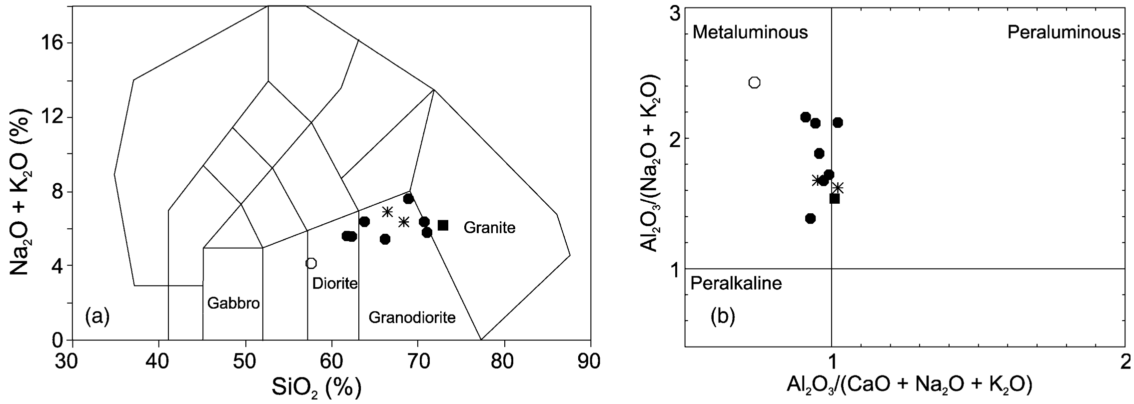

Fig. 4. (a) Plots of ($Na_2O + K_2O$) versus SiO_2 (all in wt %) for Ordovician granitoids (Middlemost, 1994). (b) Plots of $Al_2O_3/(Na_2O + K_2O)$ versus $Al_2O_3/(CaO + Na_2O + K_2O)$. Symbols: ●, Macón granitoids, ○, dioritic enclave, ■, Quebrada de Batín granitoids, ∗, Taca Taca granitoids. Analyses are recalculated to 100% on a volatile-free basis.

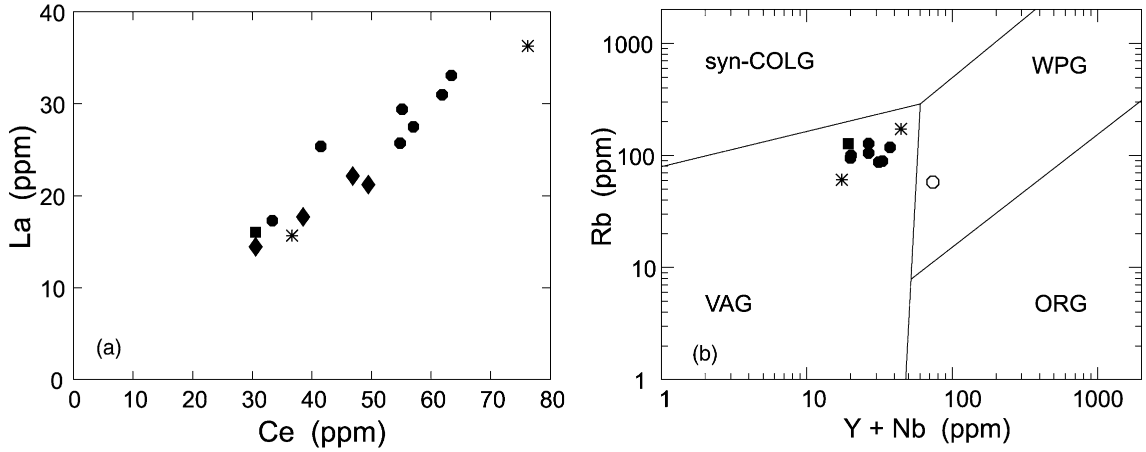

Fig. 5. (a) Plots of La (ppm) versus Ce (ppm) for Macón, Quebrada de Batín, and Taca Taca samples. (b) Rb (ppm) versus Y + Nb (ppm) discrimination diagram for granite (Pearce et al., 1984). Symbols as in Fig. 4, plus ◆ for Choschas (Coira et al., 1999a).

depletion (Fig. 7a). If this relationship is representative of those in the source, it indicates a mantle source with a flat REE pattern. The comparison of the granitoids, including those of Choschas (Fig. 7b), show that the relative abundance of these elements is very similar and therefore reflects a similar source.

7.2. Sr–Nd isotope data

Two rock samples were analyzed for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ at Activation Laboratories (Canada). Their initial isotopic ratios were determined by taking into account their Ar/Ar hornblende age of 482.7 Ma (M98/10

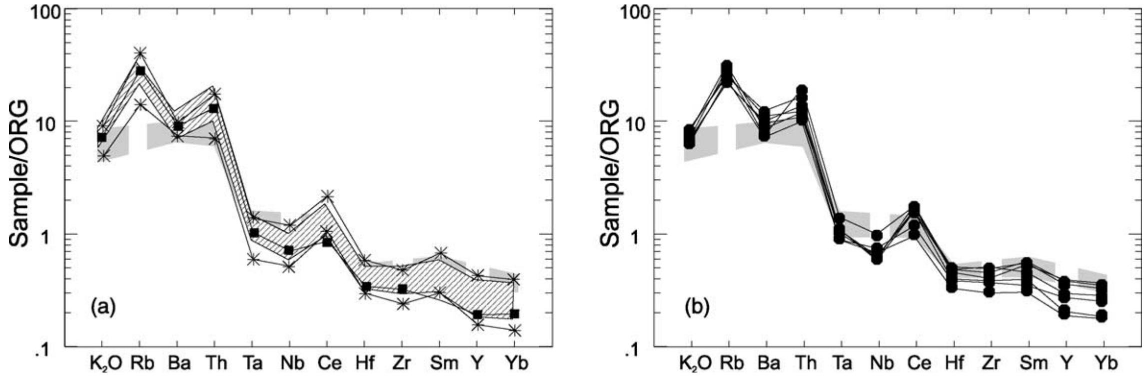

Fig. 6. (a) ORG normalized trace element variation diagram (Pearce et al., 1984). Macon samples appear as the streaked area and Choschas as the gray shadows. Symbols for Quebrada de Batín and Taca Taca samples as in Fig. 4. (b) ORG normalized trace element variation diagram for Macon and Choschas. Macon appears as black circles and Choschas as gray shadows.

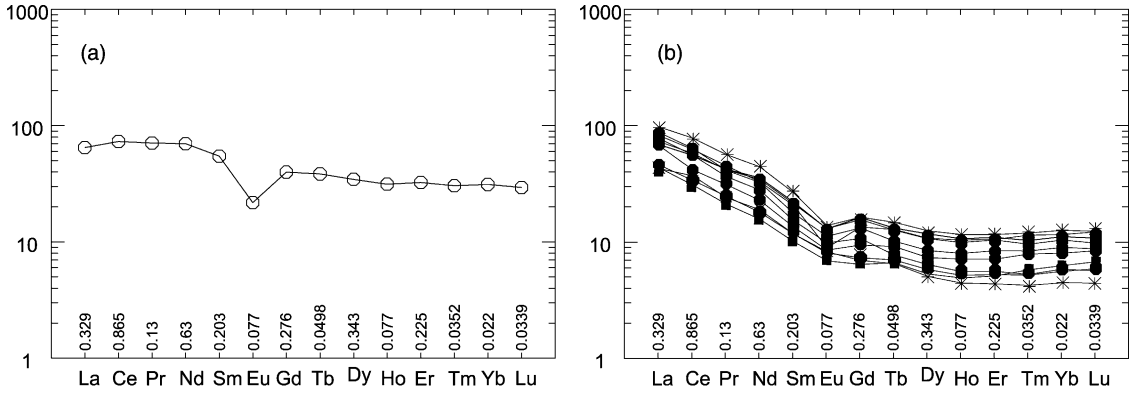

Fig. 7. Chondrite normalized REE variation diagram; the values of the normalizing constants are indicated at the bottom. (a) Enclave. (b) Macon, Taca Taca, and Quebrada de Batin samples. Symbols as in Fig. 4.

Table 2
Isotopic relations of Sierra de Macon granitoids

Sample	$^{87}Sr/^{86}Sr$*	$^{87}Rb/^{86}Sr$**	$(^{87}Sr/^{86}Sr)I$	εSr	$^{143}Nd/^{144}Nd$***	$^{147}Sm/^{144}Nd$[a]	$(^{143}Nd/^{144}Nd)i$	εNd
98–10	0.719569 ± 0.000009	1.6928	0.70793	+56.6	0.512178 ± 0.000004	0.1261	0.51181	−4.1
00–56	0.717883 ± 0.000006	1.5731	0.70706	+44.1	0.512247 ± 0.000004	0.1202	0.51187	−2.9

*Measured value of NBS 987 is 0.710247 ± 0.000014; absolute internal standard error measured during analysis; long-term reproducibility of Sr isotopic standards is ≤20 ppm (2-sigma s.d.). **Uncertainly is approximately ± 0.5%. ***Absolute standard error measured during analysis; long-term reproducibility of Nd isotopic standards is ≤20 ppm (2-sigma sd).
[a] Uncertainly is approximately ± 0.13%.

sample) using the λ ^{47}Sr constants (Steiger and Jager, 1977) and λ ^{147}Sm (Lugmair and Marti, 1978). For the calculation of εSr_{Ur}, the Faure reservoir values were considered, and for εNd_{Chur}, the values of Goldstein et al. (1984) and Peucat et al. (1988) were used.

As shown in Table 2, the isotopic composition of sample 00-56 (low silica tonalite) indicates a lesser degree of crustal contamination than granodiorite sample 98/10. The values obtained for both rocks certify a relatively low grade of heterogeneity in the originating magmas. The isotopic relations of the granitic rocks are similar to those of the volcanic arc rocks and the plutonic rocks related to subduction.

The εSr_{Ur} and εNd_{Chur} of Macon granitoids are similar to values previously reported from Cretaceous and Tertiary plutonic rocks of Sierra Nevada, in the southwestern United States, and from type I rocks of southeastern Australia (De Paolo, 1988) (Fig. 8). De Paolo (1988) interprets the origin of these similar rocks as a product of complex mixing between magmas derived from the mantle with rock assimilation of the crust. The data presented by Koukharsky et al. (2002) show that a fractioned crystallization process may occur in some samples, such as 98/10–98/34, crystallizing plagioclase (An_{10}), hornblende, orthopyroxene, and Ti-magnetite. The data in the previous section lead us to suggest that the Macon rocks are products of fractioned crystallization from a fluid blend derived from the mantle. The new isotopic data also indicate crustal contamination.

The participation of basic magmas is recognized through mafic microgranular xenolithes common in some rocks, whose isotopic data are not available. The metasomatic effects related to the crustal fluid assimilation is visible as pyroxene relics in hornblende and small grains of plagioclase feldspar in amphibole and biotite crystals, which often create textures that resemble ophitic intergrowth.

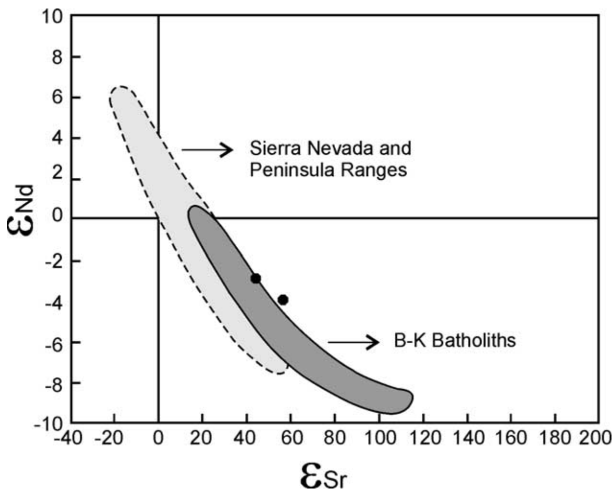

Fig. 8. Plots of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ correlation diagram showing the location of Macón granites compared to the isotopic composition of Sierra Nevada granites and (B-K) Batholiths Kosciuko, Australia (De Paolo, 1988).

Sm–Nd model ages (T_{DM}) yielded 1701 and 1485 Ga, thus suggesting different ages of the crustal sources. These values extend the 2.0–1.6 Ga range of Lucassen et al. (2000) for the metamorphic basement at 21°–27°S. The first model age (98/10) corresponds with two values of the Antofalla rocks.

8. Discussion

During the Early Ordovician, conspicuous magmatic sedimentary association occurred in the western Puna. The sediments are platform marine deposits that, in some localities, bear abundant lower Tremadocian fauna of trilobites (Moya et al., 1993; Moya, 1999). Related to these sediments are known contemporary volcanic sequences, including lavas and pyroclastic flows of acidic (rhyolitic–dacitic) to mesosilicic (andesitic) composition. Certain Ordovician sequences have been well described, including the Aguada de la Perdiz (Breitkreuz et al., 1989), Huaitiquina (Coira and Barber, 1989; Bahlburg, 1990), Salina de Jama (Coira and Nullo, 1989), and Guayaos (Coira et al., 1987; Koukharsky, 1988b; Koukharsky et al., 1996). Volcanic activity was coeval with sedimentation, as shown by the frequent interfingering. The petrography and chemistry of the volcanic rocks show clear volcanic arc affinities that relate them to an active arc during the Ordovician (Koukharsky, 1996). The middle part of the Sierra de Macon, near the local water catch (Koukharsky et al., 2001), evinces a close temporal relationship between this volcanic sequence and the granitic intrusions; thus, the granites intruded soon afterward. Sierra de Macon is the most eastern granitoid of the Ordovician western belt, as reflected by its chemical relationships. The La/Ce ratio (Fig. 5a) from Sierra de Macon rocks matches the trend defined by other Ordovician granitoids, such as Taca Taca, Choschas, and Batin (unpublished data; Coira et al., 1999b), pointing to a common source.

The stratified mafic rocks that crop out at Salar de Pocitos (Argañaraz et al., 1972; Blasco and Zappettini, 1996), the eastern border of Sierra de Quebrada Honda and Antofallita (Coira, 1974; Seggiaro and Becchio, 2002), and Sierra de Calalaste (Villar, 1975) have been interpreted as an ophiolite sequence due to an extensional tectonic event (Allmendinger et al., 1983; Damm et al., 1990; Forsythe et al., 1993; Zappettini et al., 1994; Blasco et al., 1996). These authors believe that the extension produced crustal thinning and the development of a rift, which led to the formation of a oceanic crust (Blasco et al., 1996). Therefore, Bahlburg and Herve (1997) propose an evolution from a backarc basin to a foreland basin in northern Puna and a pronounced backarc extension with ophiolites of inferred Ordovician age in southern Puna.

In this article, the stratified basic sequences interfingered with ultramafic and associated mesosilicic rocks are believed to have intruded in an extensional basin located behind the western Ordovician magmatic arc, in the sense of Bahlburg and Herve (1997). According to this interpretation, the basin had ensialic crust without any meaningful oceanic crust development. The basic suite is made up of stratified, homogeneous basic and ultrabasic rocks that represent mainly shallow intrusions with minor lava flows. The tectonic contacts seen in some localities are interpreted as consequences of later Ordovician deformation. Intrusive and stratigraphic relations place this suite as contemporaneous with the Ordovician granitic intrusion. The Rio Grande diorite (Ramallo, 1980; Zappettini and Blasco, 1998) is included in this setting. In this interpretation, in an extensional ensialic backarc setting, mafic rocks were intruded coeval with emplacement in the arc of granitoid plutons.

The end of the compressive phase in the arc region is shown by the mafic magma ascent from lower crustal reservoirs, due to stress relaxation. Thus, the basic rock bodies associated with granitoids are characteristically small, similar to the dioritic Rio Grande and any dioritic enclaves included in them. These enclaves represent basic inclusions in the granitoid that have been affected by different degrees of mixing and/or mingling and resulted in dioritic rocks. The inclusion interpretation has been favored by the mechanical displacement and ascent of the granitic fluids toward higher crust levels.

In summary, this setting is characterized by extension with formation of basic melts behind the arc, granitic emplacement, and acidic to mesosilicic volcanic flows in the arc. When compressive conditions ended, the stress relaxation permitted local interactions (mixing or mingling) of some volumes of granitic melts with the mafic melts, which generated the rock enclaves.

9. Conclusions

Much of the granitic outcrops of the Macon area were originally mapped as Precambrian, Silurian, or Carboniferous, but new radiometric dating and paleontological controls have constrained their ages as Ordovician (Koukharsky et al., 2002). The petrographical, chemical, and isotopic information has provided a better understanding of the eruptive cycle. The new evidence includes in this igneous province not only the Macon granitoids, but also outcropping units in Quebrada de Batin and Salar de Arizaro, which share petrographic and chemical similarities. The eruptive belt is made up of rocks with arc affinities and forms a semicontinuous axis that reaches Chile to the northwest and crops out at Cordon de Lila (Mpodozis et al., 1983). To the south, such rocks reappear at Palo Blanco in western Catamarca (27°S). All evidence supports the generation of a broad Ordovician arc in this sector. However, as pointed out by Palma et al. (1986), when defining the western belt, the regional tectonic complexity during the Ordovician requires a careful analysis of the magmatic units, as well as of the geographically and/or temporally associated sedimentary rocks. The present paleogeographic reconstruction of the Ordovician basin, backed by absolute dating, permits us to postulate relationships between the Puna arc rocks and similar suites cropping out to the south within the Sierras Pampeanas and Famatina.

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Appendix. Sample preparation and analytical techniques

Unaltered and homogeneous rock samples were collected and selected for chemical analyses. The analyses were performed at Activation Laboratories Ltd of Canada for major, trace, and isotopic Rb–Sr and Sm–Nd determinations from hand samples, using a lithoresearch package (WRA + trace 4Lithoresearch). The results are shown in Tables 1 and 2. Techniques and procedures can be found at www.actalabs.com.

The major element chemical standards applied were SY3, MRG-1, W-2, DNC-1, BIR-1, NBS 1633b, STM-1, IF-G, and FK-N. Trace element standards were MAG1, BIR1, DNC1, GXR-2, LKSD-3, MICA-Fe, GXR1, SY3, STM-1, and IFG-1. Isotopic analyses were performed using thermal ionization mass spectrometry.

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