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Sr–Nd isotope data of basement rocks from the northernmost argentine Precordillera and its implications for the early Paleozoic evolution of SW Gondwana margin

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ABSTRACT

The Precordillera terrane (Cuyania) in western Argentina is commonly accepted as an exotic fragment derived from Laurentia in the Early Paleozoic. Evidence supporting such an interpretation is manly based on similarities in the sedimentary cover successions and their paleontological content. Little is known about the basement of the Precordillera terrane. Its isotopic characterization is essential to better constrain the present areal distribution of the terrane and it may provide more insight into the pre-rifting evolution of the Precordillera terrane along the Iapetan margin of Laurentia. We present new Sr and Nd isotope data of pre-Late Ordovician meta-igneous rocks from the Río Bonete region in NW Argentina, interpreted as the northernmost extent of the Precordillera. The Nd systematics of the Río Bonete basement rocks including greenschists and metagabbros ($\varepsilon Nd_{(470)} = +2.14 - -0.19$; $T_{DM} = 0.99 - 1.2$ Ga), a garnet-amphibolite ($\varepsilon Nd_{(470)} = -0.53$; $T_{DM} = 1.32$ Ga) and a quartz-phyllite ($\varepsilon Nd_{(470)} = -3.83$; $T_{DM} = 1.55$ Ga), are similar to other pre-Ordovician meta-igneous rocks from Sierra de Umango, Pie de Palo and the Ullum xenoliths, usually interpreted as the basement of the Precordillera terrane. Nd model ages around 1.2 Ga are also typical from the Mesoproterozoic Grenvillian basement of southern North America, currently exposed in the Llano region. In addition, the greenschists and metagabbros show a robust correlation with the Late Neoproterozoic Catoctin volcanics in the central Appalachians. The Sr isotope data (when not disturbed) also supports this novel interpretation and suggests the presence of the Blue Ridge rifting event in Precordillera. According to our interpretation, some lithotypes included within the basement complex of the Río Bonete area belonged to the basement of the Precordillera terrane supporting previous correlation between both regions.

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1. Introduction

Terrane accretion and continental growth are topics of ongoing interest and intense debate in the geosciences (e.g., Coney et al., 1980; Howell, 1989; Pankhurst and Rapela, 1998). Due to the fact that exotic terranes have unique histories prior to collision and share common tectonic events afterward, identification of exotic terranes requires knowledge of basic field relations, geochronology and isotopic composition of different units. The isotope geochemistry is particularly useful for mapping terrane boundaries in metamorphic belts because it allows delineation of large-scale coherent isotopic domains. Such techniques have been widely used in the past (e.g., Tosdal, 1996; Murphy and Nance, 2002; Loewy et al., 2004; Tohver et al., 2004).

The Precordillera terrane (Cuyania) in western Argentina is a good example of an exotic microplate. The most accepted interpretation suggests it consists of a Laurentia-derived block accreted to southwestern Gondwana in the Middle Ordovician (Ramos et al., 1986; Astini et al., 1995; Thomas and Astini, 1996; Kay et al., 1996; Ramos et al., 1998) during the early stages of the Terra Australis orogen (cf. Cawood, 2005). Many different lines of evidences support the exotic origin for the Precordillera terrane (see reviews by Astini and Thomas, 1999; Thomas and Astini, 2003; Thomas et al., 2012) including the juvenile isotopic composition of its Mesoproterozoic basement, as opposed to the typical more enriched signature of the Gondwana basement rocks (Kay et al., 1996; Tosdal, 1996). However, controversial aspects regarding the boundaries and processes related to its accretion remain

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elusive, because the Precordillera terrane, as initially defined by Astini et al. (1995), has a two-fold division as a result of superposed Andean tectonics. A well-known synrift-postrift passive margin succession lies in the present day fold-thrust belt of the Precordillera morphostructural province, mostly cropping out in the Andean foothills between 29° and 32° S, and a much less known basement. This latter is underlying the exotic largely carbonate sedimentary succession and is indirectly known through xenoliths included in Miocene intrusives (see details in Kay et al., 1996) but also crops out to the east as basement inliers in the Western Sierras Pampeanas (Vujovich and Kay, 1998; Vujovich et al., 2004; Rapela et al., 2010; Varela et al., 2011). In this large "basement dominated region" no sedimentary cover had been clearly demonstrated. However, metasedimentary rocks from the westernmost Sierras Pampeanas have been correlated with the sedimentary successions of the Precordillera fold-thrust belt suggesting a direct tectonic linkage between both regions (Martina and Astini, 2009; Naipauer et al., 2010; Van Staal et al., 2011). The presence of dominantly basement rocks east of the Precordillera fold-thrust belt and a thick sedimentary cover within the Precordillera has led to the concept of a composite Cuyania terrane (see Ramos, 2004 and references therein). Nevertheless, recent papers (e.g., Casquet et al., 2008; Mulcahy et al., 2011) have questioned the exotic origin of some basement massifs largely included in the Western Sierras Pampeanas (e.g., the Maz terrane), indicating that various terranes with different provenances may be preserved there. After the accretion of the Precordillera terrane many modifications have overlapped signatures and obscured the original relationships which are seldom difficult to disentangle and unravel (Ramos, 2009). However, we know from combined stratigraphic-structural work that syn-to post-orogenic autochthonous clastic successions overlie the exotic carbonates (Astini et al., 1995; Thomas and Astini, 2003, 2007) and allow interpreting the end of the collisional event.

The Río Bonete region in northwestern Argentina (Fig. 1) is interpreted as the northernmost extent of the Precordillera terrane (Astini and Dávila, 2004; Martina and Astini, 2009). Although this region is largely composed of basement rocks, its stratigraphic correlation with the Precordillera fold-thrust belt relied on subtle lithologic similarities including turbidites and pillow lavas in the Late Ordovician sedimentary cover (Kay et al., 1984; Astini et al., 2000; Fauqué and Villar, 2003), and the presence of fossil remains within these successions (Aceñolaza et al., 1971; Ortega et al., 1991). However, later paleontological work (Mitchell et al., 1998; Brussa et al., 1999) suggested peri-Gondwanan affinities for these latest Ordovician deep-water graptolite assemblages, remaining their original position and relationship with the present surrounding regions relatively controversial. In order to discuss the affinity of the Río Bonete region with the Precordillera terrane and other basement blocks of the Western Sierras Pampeanas whose origin remain contentious (Fig. 1), we present new whole-rock Sr and Nd isotopic data from meta-igneous mafic and intermediate rocks belonging to the basement of the Río Bonete region. In addition, these new data together with a thorough review of existing isotopic data allows discussion about the origin of the Precordillera terrane and its Laurentian affinity. Previous isotopic studies on basement rocks from the northern segment of the Western Sierras Pampeanas were only carried out in Sierra de Maz, Espinal and Umango (Varela et al., 2003; Porcher et al., 2004; Casquet et al., 2008; Rapela et al., 2010), immediately to the south of the study area. These three basement ranges (Fig. 1) without Early Paleozoic sedimentary cover separate the Rio Bonete region, to the north, from the well known Precordillera fold-thrust belt, where the Cambrian-Ordovician carbonate bank is fully developed.

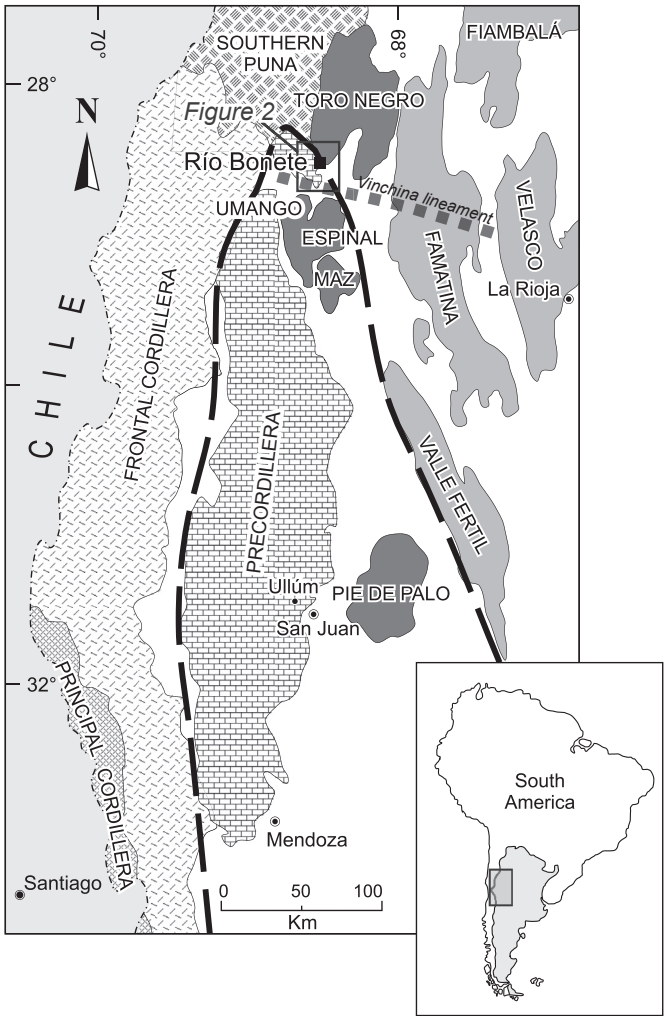


Fig. 1. Location map of the Río Bonete region in the northern Precordillera fold-thrust belt of northwestern Argentina (limestone pattern). Dark gray: Western Sierras Pampeanas; Light gray: Eastern Sierras Pampeanas. Vinchina lineament according to Porcher et al. (2004). Dash line outlines the Precordillera terrane (Cuyania) following Van Staal et al. (2011).

2. Geological framework

The Precordillera morphostructural province is a north-south trending mountain belt exposed along the Andean foreland region of Argentina between 28°30′ and 33° S. It has a distinctive geological character and contrasts markedly with the adjacent Famatina and Sierras Pampeanas regions located to the east (Fig. 1). The Precordillera consists largely of thick Late Cambrian-Early Ordovician, passive margin carbonates overlain by Middle-Late Ordovician siliciclastic rocks including turbidites and mafic lava flows and sills mainly developed to the west (Astini et al., 1995). On the other hand, the contiguous Western Sierras Pampeanas (Fig. 1) consist of metabasic and calc-silicate basement rocks with minor but distinctive Mesoproterozoic granitoids (Casquet et al., 2001; Vujovich et al., 2004; Rapela et al., 2010). The Mesoproterozoic rocks of the Western Sierras Pampeanas have been interpreted as the basement of the Precordillera terrane (Astini et al., 1995; Kay et al., 1996; Ramos et al., 1998; Casquet et al., 2001; Van Staal et al., 2011; Varela et al., 2011) or as part of the Early Paleozoic accretionary margin of Gondwana in an upper plate position (Rapela et al., 2010; Mulcahy et al., 2011). The latter interpretation is

consistent with the less documented idea that the western Sierras Pampeanas formed a single major terrane with the Arequipa-Antofalla massif (Drobe et al., 2009).

The NNW-trending Jagüé shear-zone in the río Bonete area (Fig. 2) separates a basement domain to the east from a region with basement and a sedimentary cover to the west, respectively the Western Sierras Pampeanas, represented by the Sierra del Toro Negro, and the Precordillera (Astini and Dávila, 2004; Martina and Astini, 2009). It consists of ~800 m-thick steeply dipping mylonites and ultramylonites with development of subhorizontal stretching lineations. Most kinematic indicators point to left-lateral strike-slip movements with top-to-the SSW sense of shear (Martina and Astini, 2009). Rock types in the mylonite include strongly foliated garnet amphibolites, abundant meta-igneous greenschists and metagabbros, diverse granitic gneisses and marbles, with minor quartz-phyllites and meta-sandstones. They are grouped in the Río Bonete Metamorphic Complex and constitute the basement of the region (Martina and Astini, 2009). A metagranite sample provided a primary zircon U–Pb age of 1118 ± 17 Ma for this unit (Martina et al., 2005). The marbles may tentatively represent relicts of the Cambrian-Early Ordovician carbonate platform, as suggested by Aceñolaza et al. (1971) and Martina and Astini (2009). However, strongly deformed marbles are also recorded in Sierra de Umango where preliminary Sr and C isotope data suggest a Late Neoproterozoic age (Varela et al., 2001). Although no geochronological data are available, the Jagüé shear-zone should be older than the overlying >3500 m-thick Late Ordovician ophiolites and pillow lavas (Kay et al., 1984; Astini et al., 2000; Fauqué and Villar, 2003) that were not affected by the mylonitic deformation. In this region of South America a Middle Ordovician orogeny has been widely recorded (e.g., the Ocloyic orogeny; Thomas and Astini, 2003, 2007; Astini and Dávila, 2004; Casquet et al., 2001, 2006; Lucassen and

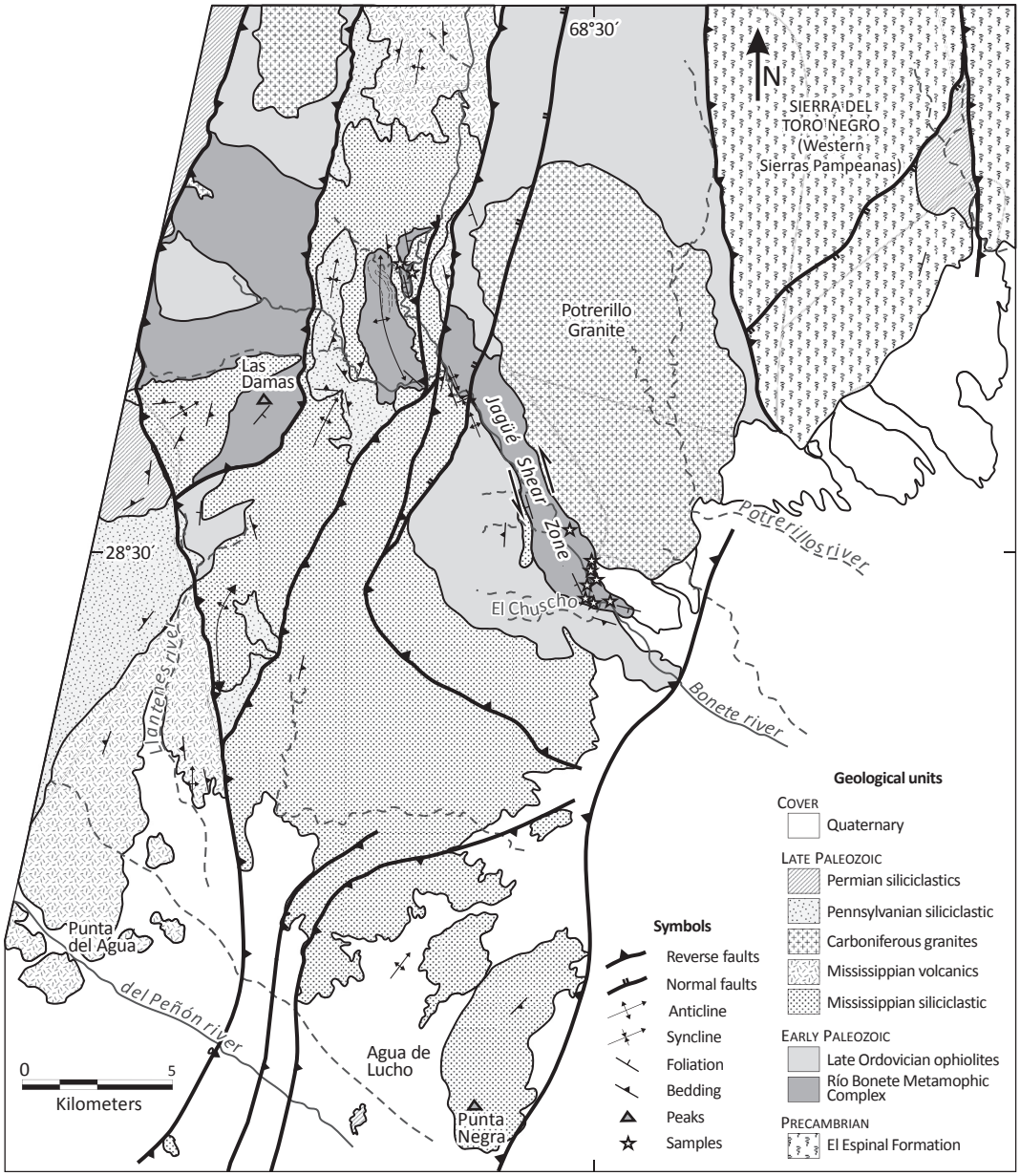


Fig. 2. Geological map of the Río Bonete region (centered at 28°30′S – 68°30′W) showing the Jagüé Shear Zone and surrounding areas in the northernmost Precordillera and Sierra del Toro Negro.

Becchio, 2003; Varela et al., 2003, 2011; Buttner et al., 2005; Collo et al., 2008) that may tentatively bracket the age of the Jagüé Shear Zone.

3. Sampling and petrography

Mafic rocks are ubiquitous throughout the Río Bonete Metamorphic Complex where they form the country rocks and lenses within the mylonite as interlayered with the marbles. Samples were collected from different outcrops exposed along the Bonete river (Fig. 2). Although they commonly preserve relict fine-grained igneous texture, most of the analyzed samples are overprinted by a middle green-schist facies metamorphism as evidenced by the mineral assemblage (Act − Hbl − Ep − Pl − Qtz ± Bt) and deformation microtextures observed in the mafic mylonites. However, the garnet amphibolites also show evidence of an earlier amphibolite facies metamorphism.

The greenschists contain subhedral to anhedral porphyroclasts of plagioclase, epidote and hornblende set in a medium-grained nematoblastic to nematogranoblastic matrix. This texture defines a continuous S1 mylonitic foliation. Two generations of amphiboles are recognized; one less abundant and represented by non-oriented ~0.5 mm long hornblende porphyroclasts. The other, dominant in the groundmass, is largely composed of oriented actinolite possibly resulting from the replacement of the hornblende. Epidote is often closely associated with actinolite and appears to be absent in the hornblende-rich lithologies. Plagioclase occurs both in the matrix and as up to 3 mm-sized porphyroclasts with development of polysynthetic twins and undulating extinction. Quartz is mainly present in the asymmetric pressure shadows around porphyroclasts.

The garnet-amphibolite consists of euhedral to subhedral poikilitic hornblende and tremolite porphyroclasts (up to 12 mm) and anhedral to subhedral garnets (up to 3 mm) enclosed in an essentially equigranular, sutured granolepidoblastic groundmass defined by the preferred orientations of small-sized biotite blasts and quartz and plagioclase grains. Tremolite usually replaces and encloses the hornblende porphyroclasts and chlorite appears to replace biotite. The epidote is usually associated with the amphibole and garnet porphyroclasts.

The quartz-phyllites show porphyroclastic texture with scarce subhedral plagioclase porphyroclasts up to 1.5 mm in size, embedded in a fine-grained (<0.15 mm) granolepidoblastic matrix defined by the preferred orientation of micas and grains of sutured quartz and plagioclase. The porphyroclasts usually display sigma-type asymmetric morphologies with tails of quartz and curved twin lamellae, typical of mylonites. A distinctive feature of these rocks is the high epidote and titanite content throughout the entire unit. According to the mineral composition they are interpreted as intermediate meta-igneous rocks.

4. Analytical methods

Sr and Nd isotope analyses were performed at the Universidade de Brasilia following the methods described by Gioia and Pimentel (2000). Whole-rock samples were crushed and then powdered in a tungsten-carbide vibratory disk mill. Approximately 50–80 mg aliquots of sample powders were mixed with a mixed ^{149}Sm-^{150}Nd spike solution and dissolved in Savillex capsules with HF–HNO_3 solution followed by digestion with HCl 6N. Sr and REE were extracted and purified by conventional cation-exchange procedures. Sm and Nd were further separated in Teflon columns containing LN-Spec resin. Isotopic ratios were measured using a Finnigan MAT-262 multicollector mass spectrometer operated in a static mode. Sr and Nd isotopic ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$ to correct for mass fractionation bias. Estimated uncertainties (2σ) on $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are lower than 0.003% and 0.005%, respectively. At the time of the analyses the NBS-987 Sr standard yielded an average $^{87}Sr/^{86}Sr$ value of 0.71024 ± 5 and the BCR-1 Nd standard yielded a $^{143}Nd/^{144}Nd$ ratio of 0.512647 ± 8. The decay constants used are 0.0142 Ga^{-1} for ^{87}Rb and 0.00654 Ga^{-1} for ^{147}Sm. Sm and Nd concentrations were determined by isotope dilution. Nd model ages were calculated using the depleted mantle model of DePaolo (1981). However, caution must be taken when working with mafic rocks because they usually have high $^{147}Sm/^{144}Nd$ ratios >0.15 resulting in unreliable Nd model ages (Dickin, 2005). In such cases it seems reasonable to use the two-stage Nd model ages (T_{DM2}) where the measured $^{147}Sm/^{144}Nd$ ratio of the sample is used to correct the isotopic composition to the estimated age of the disturbance beyond which the sample follow the same isotope evolution as the average continental crust (DePaolo et al., 1991).

Data for comparison were compiled from the literature and unpublished theses and are listed in Table A1 (electronic supplementary material). The database contains Nd isotopic data of more than 200 pre-Ordovician basement samples from NW and western Argentina and SE North America including the Grenville province and Neoproterozoic mafic rocks. In addition, we also include Early Ordovician juvenile mafic rocks from SW Sierra de Valle Fértil (Fig. 1) and Sierra de San Luis (SE of the mapped area in Fig. 1) in order to test our tentative stratigraphic correlations.

5. Isotopic data from the Río Bonete basement

Sr and Nd isotopic ratios for 10 samples collected from the eastern outcrops of the Río Bonete Metamorphic Complex (Fig. 2) are given in Table 1. Only meta-igneous basement rocks were analyzed, including greenschists (metabasalts and matagabbros), a garnet-amphibolite and a quartz-phyllite. The sample FRB 8 is a less deformed mafic sill that intruded the Río Bonete Metamorphic Complex parallel to the mylonitic foliation. For comparison, initial Sr and Nd isotopic ratios were calculated at 470 Ma according to the suggested metamorphic age.

The $\varepsilon Nd_{(470)}$values of the Río Bonete samples range from −3.83 to +6.65. The greenschists exhibit $\varepsilon Nd_{(470)}$values between −0.53 and +2.14, with an average of +1.10, typical of slightly depleted mantle sources. In contrast, the $\varepsilon Nd_{(470)}$ of the garnet-amphibolite is −3.83 whereas the quartz-phyllite is between the two groups with an $\varepsilon Nd_{(470)}$ value of −1.80. Negative εNd values are usually explained by melting of an ancient crust or by addition of sediment/fluids into the subduction zone (e.g., Rapp et al., 2008). The basic sill, on the other hand, has an $\varepsilon Nd_{(470)}$ of +6.65 which represents the highest value of Río Bonete. This $\varepsilon Nd_{(t)}$ is consistent with an origin from a depleted mantle reservoir without evidence of crustal contamination.

In those cases where the crystallization age is unknown, the Nd model age (T_{DM}) is useful for comparison because they represent the time elapsed since a parental magma was extracted from the depleted mantle (DePaolo, 1981). However, if the T_{DM} is significantly older than the crystallization age of the rock, contamination by ancient crustal material would be expected (e.g., Arndt and Goldstein, 1987; DePaolo et al., 1991; McNutt and Dickin, 2012). Calculated T_{DM} values (after DePaolo, 1981) for the greenschists of the Río Bonete range from 0.99 to 1.2 Ga with the exception of the sample FRB57 which is 1.55 Ga, likely as a result of its high Sm/Nd fractionation ($f_{Sm/Nd} = -0.18$). These are unusually young Nd T_{DM} ages for pre-Ordovician basement rocks sourced in the SW margin of Gondwana as shown by the Nd isotopic composition of the Eastern Sierras Pampeanas (Fig. 3). By contrast, the garnet-amphibolites and quartz-phyllites exhibit T_{DM} values ranging

Table 1
Sr and Nd isotope data for the meta-igneous basement rocks from the Río Bonete area.

Sample	Location (S latitude, W longitude)	Lithology	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr_m$	$^{87}Sr/^{86}Sr_m$ (±2σ)	$^{87}Sr/^{86}Sr_t$	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd_m$	$^{143}Nd/^{144}Nd_m$ (±2σ)	$^{143}Nd/^{144}Nd_t$	εNd	εNd$_t$	T_{DM} (Ga)
FRB8	28°30′20.7″, 68°30′54.1″	Metabasalt	25	569	0.127076	0,70416 (2)	0.703309	6.44	29.6	0.1316	0.512778 (7)	0.512373	2.73	6.65	0.51
FRB57	28°29′55.6″, 68°30′53,5″	Metagabbro	11	433	0.073503	0,70801 (1)	0.707518	3.612	13.561	0.161	0.512501 (8)	0.512005	−2.67	−0.53	1.55
FRB56	28°30′31.9″, 68°30′40.8″	Metagabbro	50	506	0.286065	0,71375 (2)	0.711834	5.321	22.156	0.1452	0.512557 (12)	0.512110	−1.58	1.51	1.07
FRB55	28°30′33.2″, 68°30′40.8″	Greenschist	24	361	0.018622	0,70972 (3)	0.709595	6.367	26.992	0.1426	0.512581 (13)	0.512142	−1.11	2.14	0.99
FRB44	28°30′42.5″, 68°30′23.4″	Foliated Greenschist	5	777	0.018623	0,71046 (2)	0.710335	5.66	23.47	0.1459	0.512586 (15)	0.512137	−1.01	2.04	1.02
FRB4	28°30′26.4″, 68°30′40.3″	Greenschist	61	977	0.180677	0,70963 (2)	0.708420	6.610	29.505	0.1354	0.512357 (18)	0.511940	−5.48	−1.80	1.32
FRB18	28°30′14.0″, 68°30′41.3″	Garnet amphibolite	15	129	0.336473	0,70916 (2)	0.706907	6.31	30.99	0.123	0.512215 (7)	0.511836	−8.25	−3.83	1.38
FRB14	28°30′22.8″, 68°30′33.2″	Quartz-schist	7	129	0.156956	0,70502 (3)	0.703969	5.458	22.574	0.1462	0.512573 (6)	0.512123	−1.27	1.77	1.05
FDJ7	28°24′49.4″, 68°34′34.5″	Foliated greenschist	20	329	0.176115	0,72116 (1)	0.719981	5.523	22.062	0.1513	0.512546 (10)	0.512080	−1.79	0.93	1.2
FDJ10	68°24′42.8″, 68°34′23.5″	Foliated greenschist	44	340	0.374923	0,72131 (2)	0.718799	10.752	46.810	0.1388	0.512450 (8)	0.512023	−3.67	−0.19	1.2

t = Time corrected initial values calculated using the preferred metamorphic age of 470 Ma.
m = measured value.
Sm and Nd concentrations determined by isotope dilution.
Rb and Sr concentrations determined by FRX at Universidad Nacional de Salta.

from 1.32 to 1.38 Ga. These Nd model ages suggest reworking of an early Mesoproterozoic crust or mixing of mantle-derived magmas with an older source. The basic sill (sample FRB 8) is excluded from these groups of rocks because of its extremely low T_{DM} value of 0.51 Ga. This sample may represent a different magmatic event of a younger age.

Calculated initial $^{87}Sr/^{86}Sr_{(470)}$ ratios for the greenschists and metagabbros range from 0.70397 to 0.71998. The highest values correspond to strongly foliated greenschists samples collected from the northernmost outcrops of Río Bonete (Fig. 2). The large data dispersion at relatively constant $\varepsilon Nd_{(470)}$ values may indicate either (1) hydrothermal alteration or (2) disturbance of the Rb–Sr isotopic system during deformation and metamorphism, as suggested for other mylonitic zones (e.g., Su and Fullagar, 1995). Likely only the lowest value represents the primary isotopic composition of the magma as depicted in Fig. 4 where it plots on the depleted mantle array. On the other hand, the garnet-amphibolite has an $^{87}Sr/^{86}Sr_{(470)}$ ratio of 0.70691 and the quartz-phyllite of 0.70842 suggesting a more enriched source or crustal contamination (Fig. 4). The sample FRB 8 shows an $^{87}Sr/^{86}Sr_{(470)}$ ratio of 0.70331, slightly lower than the less evolved greenschists and compatible with a depleted mantle origin in accordance with Nd isotope data.

6. Discussion regarding the isotopic domains

In a recent review of the Río Bonete region, Martina and Astini (2009) grouped the metamorphic rocks of mafic composition included within the Río Bonete Metamorphic Complex as "amphibolites". However, the trajectories of Nd presented here suggest the presence of at least three different protoliths (Fig. 3). This is consistent with the petrography. The garnet amphibolites and quartz-phyllites have negative $\varepsilon Nd_{(t)}$ values and T_{DM} ages older than 1.32 Ga. In contrast, the widespread greenschists and metagabbros essentially show positive $\varepsilon Nd_{(t)}$ values and T_{DM}'s younger than 1.2 Ga, with most around ca. 1.0 Ga. As mentioned above, there is probably another group of rocks represented by the sill sample FRB 8 given its strongly depleted Nd and Sr isotope composition very similar to MORB.

Compared with other Mesoproterozoic meta-igneous rocks from NW Argentina (Fig. 3), the quartz-phyllite and garnet-amphibolite from the Río Bonete Metamorphic Complex show Nd isotope compositions similar to felsic and intermediate rocks from the Juchi Ortogneiss in Sierra de Umango and a few samples from Sierra de Maz/Espinal, which yield T_{DM} ages of 1.29–1.44 Ga and $\varepsilon Nd_{(470)}$ of −7.91–−2.92 (reprocessed data from Porcher et al., 2004; Rapela et al., 2010; Varela et al., 2011). Similar Nd model ages are observed in Mesoproterozoic rocks from the heterogeneous basement of Sierra de Pie de Palo (Morata et al., 2010; Rapela et al., 2010) and in some Ullum xenoliths' of Precordillera (Kay et al., 1996), although the metabasic rocks usually display a more juvenile isotopic composition ($\varepsilon Nd_{(470)} = -0.19$ to $+0.12$; Table A1).

By contrast, the T_{DM} values of the greenschists and metagabbros of the Río Bonete are younger than those commonly recorded in Sierra de Maz/Espinal (Porcher et al., 2004; Casquet et al., 2008; Rapela et al., 2010) and any other pre-Ordovician units of northwestern Argentina usually included in the basement of the Eastern Sierras Pampeanas (Fig. 3), such as the Puncoviscana Formation and associated metamorphic rocks (Bock et al., 2000; Lucassen et al., 2000; Drobe et al., 2009). The low-grade basement rocks of Famatina (Collo et al., 2009) and their equivalents in Sierra de San Luis (Steenken et al., 2004; Drobe et al., 2009, 2011), which formed part of the Gondwana margin during the Ordovician are also included within this basement. Even the basement rocks of the southernmost Sierra del Toro Negro in the hanging wall of the Jagüé shear-zone (Fig. 2) display $\varepsilon Nd_{(470)}$ values of −6.5 and T_{DM} of

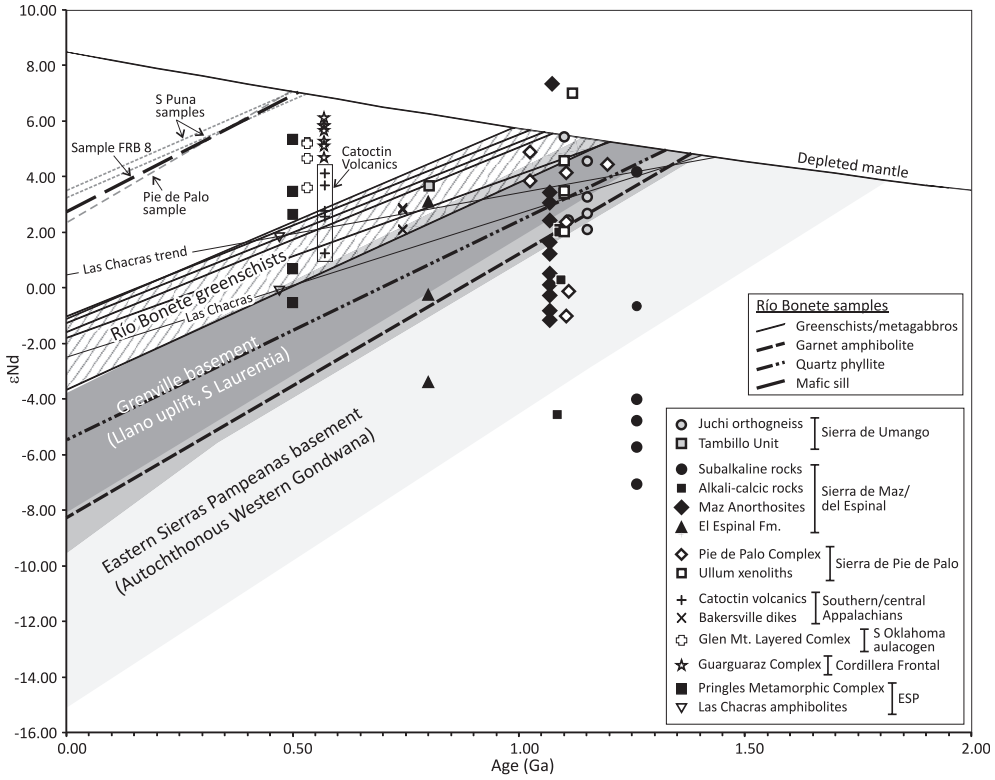


Fig. 3. Nd isotope evolution for the meta-igneous rocks of the Río Bonete area showing the possible crustal sources discussed in the paper. Symbols are initial εNd values for the Mesoproterozoic meta-igneous rocks from Western Sierras Papeanas, calculated using available U–Pb crystallization ages. Also plotted are the initial εNd values of the Late Cambrian and Early Ordovician metabasic rocks from Sierra de San Luis and Las Chacras respectively. Note overlapping between the Río Bonete greenschists field (striped area) and the initial εNd data from the Neoproterozoic mafic rocks of the Southern/Central Appalachians. Depleted mantel curve is after DePaolo (1981). Data from this study and references listed in Table A1.

1.91 Ga (M. Pimentel *pers. comm.*) suggesting a more evolved crustal source. These new isotopic data do not support the correlation of the Río Bonete metabasic rocks with the Mesoproterozoic Sunsas orogen in the SW Amazon craton since the Sunsas orogen shows T_{DM} ages older than 1.6 Ga (Tosdal, 1996; Geraldes et al., 2001; Loewy et al., 2004; Tohver et al., 2004). As shown in Fig. 5 and Table A1, pre-Ordovician igneous protoliths with T_{DM} ages of ~1.1 Ga and positive $\varepsilon Nd_{(470)}$ in this portion of South America have

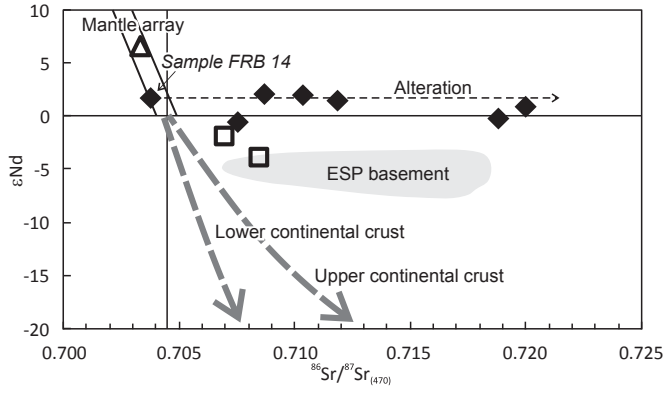


Fig. 4. Initial Sr and Nd isotopic ratios (recalculated at 470 Ma) for the meta-igneous rocks from the Río Bonete region. Dashed lines are illustrative evolutionary curves resulting from the binary mixing between a depleted mantle source and the upper and lower crust, respectively. Field for ESP basement (ESP = eastern Sierras Pampeanas) is from Dahlquist et al. (2008). Symbols denote the greenschists (squares), the amphibolite and quartz schist (diamonds) and the mafic intrusive (triangle).

only been recognized in Sierra de Umango, Pie de Palo and the Ullum xenoliths (Kay et al., 1996; Porcher et al., 2004; Rapela et al., 2010). A similar T_{DM} age has also been locally obtained in an amphibolite sample from the easternmost Sierra del Espinal (Porcher et al., 2004), while the Mesoproterozoic jotunites from Sierra de Maz display an even younger T_{DM} age of 0.94 Ga.

An alternative interpretation would be to consider the greenschists and metagabbros of the Río Bonete as Early Ordovician and related to the Ocloyic orogeny (Fig. 3). However, when compared with the Lower to Middle Ordovician juvenile mafic rocks from the Pringles Metamorphic Complex in western Sierra de San Luis (Steenken et al., 2011) and those recently reported in the SW Sierra de Valle Fertil (Fig. 1; Casquet et al., 2012), they are highly fractionated ($^{147}Sm/^{144}Nd = 0.1535–0.2019$) and only show ~1 Ga T_{DM} ages when calculated with the two-stage model of DePaolo et al. (1991). Furthermore, the Ordovician magmatism usually displays subduction related trace element geochemistry in contrast to the E-MORB nature of the Rio Bonete metabasic rocks (Martina et al., 2014), arguing against a common origin.

Neodymium model ages between 1.0 and 1.4 Ga characterize the Mesoproterozoic Grenvillian basement of southern Laurentia (Fig. 5), currently exposed in the Llano uplift of eastern Texas (Patchett and Ruiz, 1989; Smith et al., 1997; Barker and Reed, 2010), from where most sedimentological and paleontological evidences suggest the Precordillera terrane comes from (e.g., Astini et al., 1995; Kay et al., 1996; Dickerson and Keller, 1998; Thomas et al., 2012). The Nd isotopic compositions of the Llano rocks are a good match for the quartz-phyllite and the garnet amphibolite studied here but contrast with the Grenville rocks of the southern Appalachians (Fig. 5), supporting the interpretation that the

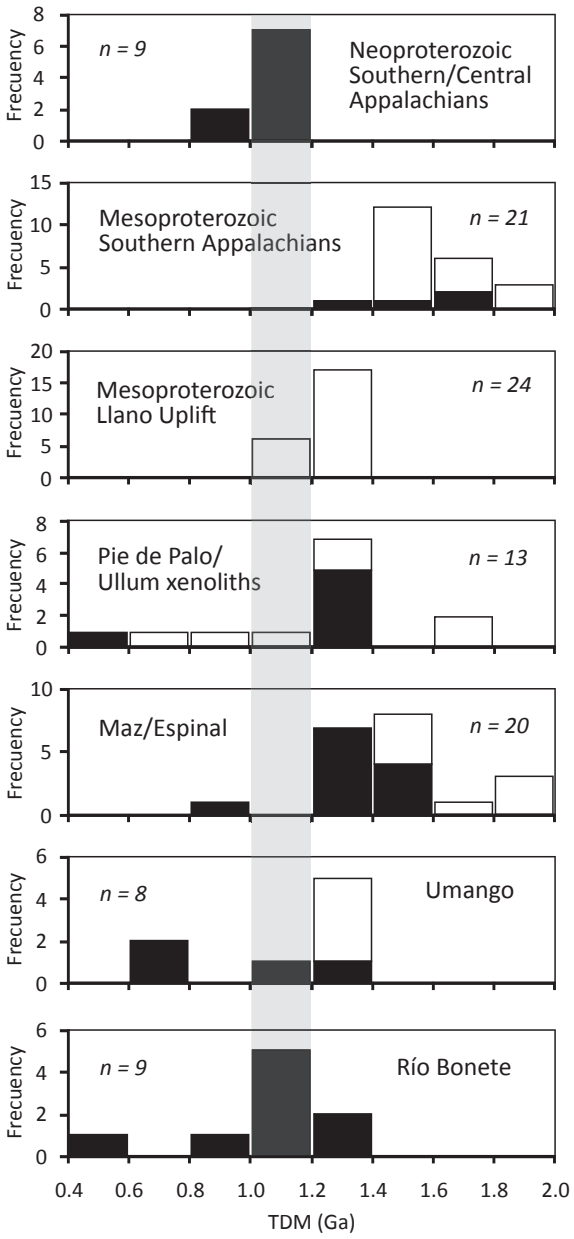


Fig. 5. Histograms of Nd T_{DM} model ages for the different regions with Mesoproterozoic and Neoproterozoic igneous basement discussed in this paper (see Table A1 with expanded data in the electronic supplementary material). Open areas for felsic rocks and dark areas for mafic rocks. The gray bar indicates the overlap between the Neoproterozoic volcanics from the central Appalachians and the greenschists from the Río Bonete area. Note also the correlation between the histograms of the Sierra de Umango, Pie de Palo/Ullúm and the Llano uplift with that of the Río Bonete basement rocks.

Precordillera terrane was rifted from the Ouachita embayment of southern Laurentia. Although many models have been proposed to explain the origin of the Mesoproterozoic basement of the southern and central Appalachians (e.g., Fullagar et al., 1997; Carrigan et al., 2003; Hatcher et al., 2004; Fisher et al., 2010 and reference therein), including a grenvillian connection with Amazonia (e.g., Tohver et al., 2004), the metabasic rocks from the Río Bonete show greater affinities with the Neoproterozoic mafic rocks from this region associated with the Iapetan rifting (Fig. 3). Both the Bakersville dike swarm (ca. 750 Ma; Fetter and Goldberg, 1995; Goldberg and Dallmeyer, 1997) and the Catoctin volcanics (ca. 570 Ma; Badger et al., 2010) display Nd model ages of ~1.0 Ga, suggesting the involvement of a Grenvillian source in their genesis and consistent with our data. In addition, the strontium isotope composition of the Río Bonete sample FRB14 ($^{87}Sr/^{86}Sr_{(470)} = 0.70397$) that strongly correlates with the Catoctin basalts ($^{87}Sr/^{86}Sr_{(470)} = 0.70365–0.70415$; data from Badger and Sinha, 1988) supports our interpretation. This comparison is also in agreement with the whole-rock geochemical data that suggest similar E-MORB signatures (Martina et al., 2014). As shown in Fig. 3 the Nd model ages of the Early Cambrian mafic rocks from the southern Oklahoma rift zone range from 0.67 to 0.82 Ga (Lambert et al., 1988) preventing their correlation with our samples, in accordance with their more juvenile Sr isotope composition ($^{87}Sr/^{86}Sr_{(470)} = 0.70358–0.70362$). The contrasting Nd isotope composition between the basement rocks of Gondwana and Laurentia may be explained by the addition of juvenile material during the Mesoproterozoic Grenville Orogeny (Patchett and Ruiz, 1989; Daly and McLelland, 1991; Whitmeyer and Karlstrom, 2007) whereas the Mesoproterozoic Sunsas Orogeny essentially reworked and homogenized the pre-existing crust (Tosdal, 1996; Loewy et al., 2004; Franz et al., 2006). The continental crust of SW Gondwana would have geochemically rejuvenated only during the Mississippian, as suggested by the Nd (Grosse et al., 2009; Dahlquist et al., 2010; Martina et al., 2011) and Hf isotope data (Dahlquist et al., 2013).

The highly positive $\varepsilon Nd_{(470)}$ value and younger T_{DM} age of the mafic sill FRB 8 suggest derivation from a more juvenile mantle source that is different from the greenschists of the Río Bonete Metamorphic Complex. This interpretation is consistent with the lack of clear mylonitic textures in the sill. Late Ordovician basic volcanic rocks from western Precordillera, including those basalts that cover the basement complex in Río Bonete, show $\varepsilon Nd_{(470)}$values of +6.5–+7.5 (Davis et al., 2000; Kay et al., 2005), more compatible with the composition of the sill. An alternative correlation would be with the basic rocks reported by Kay et al. (1996) in the basement of the Sierra de Pie de Palo, which show a Nd isotope evolution trend strikingly similar to the mafic sill FRB 8 (Fig. 3). This may support the idea that the eastern and western tectofacies (cf., Astini, 1992) overlap in the Río Bonete area (Martina and Astini, 2009). Cambrian T_{DM} ages and strongly positive εNd values have also been recognized in pre-Ordovician metabasic rocks from the southern Puna region (Bock et al., 2000), expanding the possible correlations further north, in which case it is necessary to find an alternative scenario.

7. Tectonic implications

The basement of the Precordillera terrane is only known through the study of Mesoproterozoic metamorphic xenoliths hosted in Tertiary volcanic rocks from western Argentina (Abbruzzi et al., 1993; Kay et al., 1996; Rapela et al., 2010). According to the literature, the xenoliths show juvenile Nd and Pb isotopic compositions, very similar to the Grenvillian basement of southern Laurentia, and different from the more radiogenic basement of SW Gondwana and the southern Appalachians (Fig. 5), supporting the allochthonous hypothesis of the Precordillera terrane (Kay et al., 1996). Other possible outcrops for the basement of the Precordillera terrane are exposed along Sierra de Umango (Porcher et al., 2005) and Pie de Palo (Kay et al., 1996; Vujovich and Porcher, 2008), where preliminary Pb isotopic data from metabasic rocks (Mesoproterozoic?) also show Laurentian affinities. This has been previously suggested by Varela et al. (2003).

As stated above, the meta-igneous rocks from the Río Bonete Metamorphic Complex share some Nd isotopic features with all these regions establishing possible correlations. Given the

overlapping between the studied greenschists and matagabbros with the Late Neoproterozoic Catoctin volcanics in the Appalachians (Figs. 3 and 5), the Río Bonete metabasic rocks are interpreted as potential records of the Blue Ridge rifting event of eastern Laurentia (cf. Thomas, 2011) within the Precordillera terrane, prior to its final separation from the Ouachita embayment at ~530 Ma (Thomas et al., 2012). As pointed before, the mafic rocks from Río Bonete cannot be associated with the rifting of the Precordillera because they show older Nd model ages (Fig. 3) than those from the southern Oklahoma aulacogen (Lambert et al., 1988). According to recent paleogeographic reconstructions (e.g., Thomas et al., 2012), the southern Appalachians formed the continuation of the Precordillera terrane north of the Alabama–Oklahoma transform fault. The Catoctin volcanics are currently located ca. 600 km further north of this boundary. If true, the mafic rocks of Río Bonete may relate to the Blue Ridge rifting event that predates the separation of the Precordillera terrane. This interpretation agrees with the present position of the Río Bonete region in the northernmost Precordillera (Fig. 1). Late Neoproterozoic mafic rocks with juvenile Nd isotope composition and E-MORB geochemistry in Argentina are also present in the Cortaderas area in western Precordillera (576 Ma; Davis et al., 2000) and intercalated within the metasedimentary rocks of the Guarguaraz Complex, further south in Cordillera Frontal (López et al., 2009). These show a maximum depositional age of 563 Ma (Willner et al., 2008) and were previously suggested as part of the Chilenia terrane (cf., Willner et al., 2011). According to our comparison, they could be interpreted as the leading edge of the Precordillera terrane like the greenschists and metagabbros of Río Bonete. Such extension-related rock types would be expected in the earliest stages of the Precordillera terrane in the allochthonous hypothesis and, therefore, support this interpretation.

The meta-igneous rocks from Sierra de Maz and del Espinal show a greater data dispersion although most of them display isotopic compositions also present in the Gondwana basement (Fig. 3), characterized by Paleoproterozoic to early Mesoproterozoic Nd model ages and strongly negative εNd (t) values (e.g., Rapela et al., 1998, 2010; Lucassen et al., 2000; Steenken et al., 2004; Collo et al., 2009; Drobe et al., 2009), suggesting a more protracted geological history. Further north, in the southern Puna region (Fig. 1), two contrasting basement blocks have been suggested based on geochemical data from Andean volcanic rocks strongly related to major fault systems (the Valle Ancho-Laguna Verde lineament; Mpodozis et al., 1997). These deep faults may represent the NW extension of the Jagüé shear-zone (Astini and Dávila, 2004). According to petrological analyses by Lucassen and Becchio (2003) the basement rocks north of the Jagüé – southern Puna lineations show upper-amphibolite to granulites facies metamorphic conditions. This contrasts with the middle greenschist facies metamorphism recorded in the Río Bonete Metamorphic Complex indicating a shallower structural level in the footwall of the Jagüé shear-zone (Martina, 2009). This is also consistent with the different Nd isotope data recorded between the Río Bonete basement rocks and that in the Sierra del Toro Negro. Aeromagnetic geophysical data also shows strong differences between the basements north and south of the Vinchina lineament (29°00′S-67°32′W and 28°33′S-69°32′W; Porcher et al., 2004), in accordance with the NW trend of the Jagüé shear-zone (Fig. 1). The different nature of the basements at both sides of the Jagüé shear-zone indicates an important structural boundary in NW Argentina. Most metamorphic ages in the region allow constraining deformation to the Ordovician (Lucassen and Becchio, 2003; Porcher et al., 2004; Casquet et al., 2006, 2008; Varela et al., 2011). Therefore, the Jagüé shear-zone may be interpreted as a result of the docking of the Precordillera terrane (Ocloyic orogeny), in agreement with structural evidences (Martina and Astini, 2009). The recent recognition of a major Ordovician shear zone also affecting marbles and basic rocks in the western side of the Sierra de Umango (Varela et al., 2011; Meira et al., 2012) supports such an interpretation.

8. Conclusions

Three different isotopic domains were recognized in the basement of the Río Bonete area, NW Argentina, based on Sr and Nd data of meta-igneous rocks. The greenschists/metagabbros are characterized by having a juvenile isotopic composition and Late Mesoproterozic model ages. In contrast, the garnet amphibolite and quartz-phyllite show less radiogenic compositions and older T_{DM} ages. A separate group of rocks is probably represented by a mafic sill that intrude the Río Bonete Metamorphic Complex parallel to the mylonitic foliation given its strongly depleted Nd and Sr isotope composition and Early Cambrian T_{DM} age. According to our data, the basement rocks of Rio Bonete show a good correlation with other pre-Ordovician meta-igneous rocks from the Western Sierras Pampeanas and differ from the basement of the Eastern Sierras Pampeanas (Fig. 3). Similarities to the Nd isotopic compositions of some Ullum xenoliths and the Grenvillian to Late Neoproterozoic basement rocks of the southern North America allows the inclusion of the Río Bonete basement rocks within the basement of the Precordillera terrane and supports the allochthonous hypothesis. The garnet amphibolite and quartz-phyllite correlate with the Mesoproterozoic rocks of the Llano uplift and support previous assertions for the provenance of the Precordillera terrane from the Ouachita embayment. In addition, the overlapping between the Río Bonete metabasic rocks and the Neoproterozoic Catoctin volcanics in the Appalachians suggests a strong relationship with the well-known Blue Ridge rifting event of eastern North America that predates separation of the Precordillera and the Southern Oklahoma Aulacogene event. This has been previously pointed out for the Neoproterozoic mafic rocks of the Cortaderas region further south (Davis et al., 2000). This interpretation also agrees with previous assertion that the Río Bonete region constitutes the northernmost extent of the Precordillera terrane (cf., Astini and Dávila, 2004; Martina and Astini, 2009). According to our analyses, contrasts between basement rocks to both sides the Jagüé shear-zone highlight the importance of this region as a major early Paleozoic tectonic boundary.

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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.2014.08.006.

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