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Puna (Argentina) and northern Chile Ordovician basic magmatism: A contribution to the tectonic setting

B. Coira [a,*], M. Koukharsky [b], S. Ribeiro Guevara [c], C.E. Cisterna [d]

[a] Instituto de Geología y Minería, UNJu-CONICET, C.C. 258, (4600) S.S. de Jujuy, Argentina
[b] Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, UBA-CONICET, C.Universitaria, Pabellón 2, Piso 1, (1428) Buenos Aires, Argentina
[c] Centro Atómico Bariloche, (8400) Bariloche, Río Negro, Argentina
[d] Facultad de Ciencias Naturales, UNT-CONICET, Miguel Lillo 205, (4000) San Miguel de Tucumán, Argentina

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ABSTRACT

Geochemical characteristics of Ordovician basic volcanic rocks help to define the evolving tectonic setting of the Argentine Puna and northern Chile. Four spatially distinct magmatic groups are defined on geological, petrographical, geochemical and isotopic bases, each associated with particular geodynamic environments.

The Tremadoc western group of subalkaline low K tholeiites with arc and modified MORB like signatures represent early stages of a back-arc basin, where spreading was incipient.

The Arenig western group, medium K calc-alkaline basalts to andesites have volcanic arc in transition to back-arc signatures.

The Tremadoc subalkaline basalts of the eastern group have REE patterns similar to E-MORB and at the same time weak subduction characteristics suggesting a rather mature supra-subduction zone (SSZ) basin. In contrast, the Late Tremadocian-Arenig basalts of the same group have intra-plate signatures, interpreted as magmas that ascended along pull apart regions associated with a transtensional regime.

The geochemical patterns were applied to correlate basic sequences of doubtful geological setting. So, basalts from Chile were related to the Tremadocian western group, where they represent a slightly more mature stage of spreading of the basin. Basic rocks from Pocitos and part of Calalaste represent pre-Ordovician records of a back-arc system similar to that of the Tremadoc western group. Clearly similar arc patterns to those of the Arenig western group allow extending the arc environment to the southern Puna. The Tremadocian basalts from the eastern group were related to metabasites from the southern Puna, as part of a back-arc environment at that time.

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1. Introduction

The geodynamic evolution of southern Central Andes and particularly of the Puna during the Early Paleozoic has been the subject of continual debate. A popular postulate states that part of northwestern Argentina and northern Chile are allochthonous or parautochthonous terranes accreted to the southwestern Gondwana margin during the Late Proterozoic and Early Paleozoic (e.g., Coira et al., 1982; Dalziel and Forsythe, 1985; Ramos 1986; Ramos et al., 1986; Forsythe et al., 1993; Conti et al., 1996; Bahlburg and Hervé, 1997). More recently, Lucassen et al. (1999, 2000) on the basis of petrological similarities and age relationships in high grade basement units between 21° and 26° S postulated a wide "mobile belt" geodynamic scenario for the Late Proterozoic-Early Paleozoic development of what represents the present Andean continental margin and what was then the continental margin of Gondwana. Also Bock et al. (2000), Zimmermann and Bahlburg (2003), Kleine et al. (2004) conclude that the geochemical and isotopic data support the homogeneous makeup of that margin, excluding allochthonous and parautochthonous accreted terranes.

Looking for additional constraints on the Early Paleozoic models, this paper focuses on the study of basic magmatic rocks to evaluate mantle characteristics beside the previous information on crustal nature and its evolution (Damm et al., 1986; Koukharsky et al., 1989; Becchio et al., 1999; Coira et al., 1999; Lucassen et al., 1999, 2001; Bock et al., 2000; Kleine et al., 2004).

A suite of basic magmatic rocks representing the Puna's Ordovician has been selected along transversal profiles between 22° and 26°30′S for petrological study. Their mineral, geochemical and isotopic compositions, textures and structures, deformation and metamorphism, together with their radiometric ages or paleontological correlations have been considered. Newly obtained data on established magmatic types have been interpreted with existing

* Corresponding author. Fax: +54 388 4232957.
E-mail address: bcoira@idgym.unju.edu.ar (B. Coira).

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data on basic rocks of the region (e.g., Breitkreuz et al., 1989; Damm et al., 1986, 1990; Coira and Koukharsky, 1991; Coira and Barber, 1989; Coira et al., 1999; Zimmerman, 1999; Becchio et al., 1999; Lucassen et al., 2001; Bock et al., 2000; Coira and Darren, 2002; Coira et al., 2005). Among the analyzed samples are an important number from the southern Puna, where amphibolite and greenschist facies metamorphic grade sequences containing magmatic rocks are in tectonic contact with Ordovician sedimentary successions. The geochemical inconsistences among the analysis of magmatic rocks from these localities reflect their uncertain chronostratigraphic position. The magmatic typing obtained in this study provides a useful correlation tool.

New geological, petrographic, geochemical and isotopic data of the Puna basic Ordovician sequences presented in this paper, along with previous results contribute to constrain the origin and evolution of these magmas and help constrain a postulated geodynamic setting for the Puna and northern Chile region during the Early Paleozoic.

2. Geological setting

Ordovician magmatism has an extensive distribution in the Puna (see Fig. 1) with units as old as Early Tremadoc and with magmatism continuing and reaching its maximum expression in the Arenigian. The magmatic rocks comprise two submeridianal striking magmatic belts known as Western Puna Eruptive Belt (Palma et al., 1986) and Eastern Puna Eruptive Belt (Méndez et al., 1972).

The western belt includes volcano-sedimentary sequences with trilobite faunas of Lower Tremadoc age (Moya et al., 1993), as well as others with trilobite, brachipod and particularly graptofaunas of Arenig s.l. to Middle Late Arenig ages and of Early Llanvirn. Magmatic rocks are mainly dacite-rhyolite pyroclastics and lavas with less abundant basaltic to andesitic lavas associated with volcanoclastic turbiditic sequences (Coira and Barber, 1989; Coira et al., 1987; Koukharsky et al., 1989, 1996). Granite-granodiorite-monzodiorite plutons also occur in this belt. The reported K/Ar, Ar/Ar and $^{207}Pb/^{206}Pb$ model ages (502–476 Ma, 450–440 Ma and 420–425 Ma, Palma et al., 1986; Mpodozis et al., 1983; Koukharsky et al., 2002; Kleine et al., 2004) reflect at least three main magmatic episodes.

Lavas and subvolcanic intrusives of the Eastern Puna Eruptive Belt, in the north sector, are bimodal (dacitic lavas, hyaloclastites, domes-cryptodomes and minor basic-spilitic lavas, massive and in pillows (Coira and Koukharsky, 1991), with gabbro-basalt sills and dikes (Coira et al., 1999) They are associated with fossiliferous clastic sequences assignable to Late Tremadoc to Early-Middle Arenig, where they occur in the Magmatic-Sedimentary Cochinoca-Escaya Complex (Coira et al., 1999, 2004). Granitoids with U/Pb (476 Ma, Lork and Balhburg, 1993) and K/Ar (428 Ma, Linares and Gonzalez, 1990) ages belong to the northern portion of the belt. Towards 24°S, the Eastern Puna Eruptive Belt magmatism continues through a group of granitoids and orthogneisses with U/Pb and K/Ar ages of 500–462 Ma, 450–440 Ma and 420 Ma (Linares and Gonzalez, 1990; Lork and Balhburg, 1993; Lucassen et al., 2000). These plutons intrude medium to high grade metamorphic basement with Sm/Nd ages ca. 500 Ma and TDM (Depleted Mantle Model Ages) of 2.2–1.36 Ga (Becchio et al., 1999). Lithological and structural characteristics of the metamorphic basement allow Hongn (1994) to distinguish three belts: (a) a western belt with medium to high metamorphic facies which record three superimposed tectonic events; (b) a central belt characterized by low to very low-grade of metamorphism and evidence of two tectonic events and (c) an eastern belt with medium to high grade of metamorphic rocks and related granitoids. The Pachamama Igneous–Metamorphic Complex name was proposed on a petrological basis by Viramonte et al. (1993) for these metamorphic and igneous sequences.

Also occurring in the southern Puna, to the south of Salar de Pocitos (as in Sierra de Calalaste) are mafic–ultramafic complexes originally assigned to ophiolitic successions (Allmendinger et al., 1982; Blasco et al., 1996). All of them have been interpreted by Zimmerman et al. (1999), who recognized their tectonic relation with Early Ordovician sedimentary sequences, to be remnants of a pre-Ordovician tectonomagmatic event with magmas having arc-back-arc signatures. This consideration, applied to Pocitos ultramafic (cumulatic) rocks intruded by the Pocitos Igneous Complex (PIC), is in agreement with the Proterozoic age indicated by Kleine et al. (2004) for them, on the basis of the low initial $^{87}Sr/^{86}Sr$ determined from the "contact blackwall" isochron significantly lower than those for the PIC. However in Calalaste, Seggiaro et al. (2002) define the Tramontana Basic-ultrabasic Complex as a group of basic to ultrabasic rocks, where at least the basalts are intercalated with sedimentary to volcanic Ordovician sequences (Arenig to Llanvirn and even Tremadoc), while the ultrabasic rocks and some of the gabbros have tectonic contacts.

3. Magmatic types, mode of occurrence and petrography

3.1. Ordovician basic rocks: selected suites of the Western Puna Eruptive Belt

3.1.1. Pinato and Lari

Sedimentary marine sequences bearing Early Tremadoc fossils (Moya et al., 1993; Koukharsky et al., 1996; Rao et al., 2000; Waisfeld et al., 2001) with an important volcanic component (rhyolitic to dacitic lavas, hyaloclastites and tuffs with minor basaltic rocks) crop out in Pinato and Lari creeks (W of Salar del Rincón, sites 6 and 7 in Fig. 1). These rocks are moderately deformed (Coira and Koukharsky, 2002). The sedimentary facies together with the fossiliferous content indicate a shallow marine environment in which submarine to partly subaerial volcanism took place. At Lari, a conglomerate and light colored sandstones with a marine Silurian fauna, unconformably overly the folded Tremadoc sequence.

The volumetrically subordinate mafic members correspond to several meter thick basalts conformably intercalated with a folded sedimentary volcanic sequence. They are composed of albitized and saussuritized plagioclase intergrows with partly chloritized mafic minerals, abundant opaques and interstitial granophyre with frequent variolitic textures. Typical greenschist facies metamorphic mineralogy (chlorite, actinolite, albitized plagioclase) is incompletely developed.

Acid volcanic debris flows and volcaniclastic rocks associated with marls with an Arenigian trilobite and brachipod fauna (Benedetto, 2001; Coira and Koukharsky, 2002) lies unconformably over the Tremadoc volcanics at Pinato creek.

3.1.2. Quebrada Honda

Mafic flows, sills and discordant bodies (0.80–70 m thick) are present in a low-grade metamorphic sequence of wackes, siltstones and shales with chert and limestone levels in Quebrada Honda (site 8 of Fig. 1). They are microgabbros and in some cases meladiorites and basalts and basaltic andesites. The more coarse grained facies are composed of clinopyroxene in ophitic to subophitic relation with albitized plagioclase. Granophyric aggregates (2–15%) used to be interstitial. Pigeonite shows partial inversion to hypersthene with exsolution of augite lamellae. Opaque oxides included in the clinopyroxene constitutes up to 10%. Basalts and basaltic andesites are aphiric to poorly porphyritic. Phenocrysts (up to 2%) are mostly of albitized plagioclase and scarce pigeonite

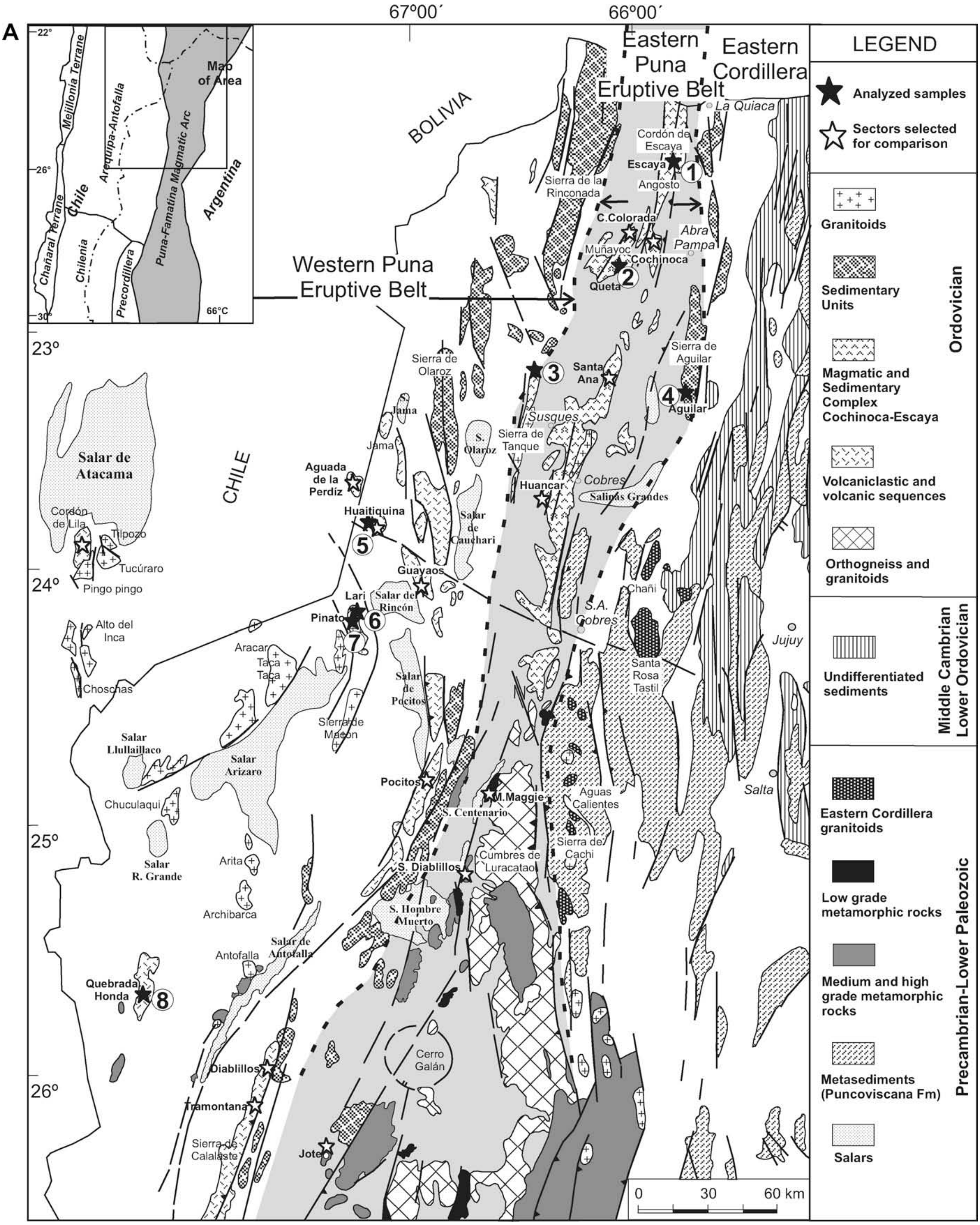

Fig. 1. (A) Map of part of northern Argentina and Chile showing the distribution of Ordovician sedimentary and magmatic rocks and the location of studied sections in the region of the Central Andean Puna plateau. Generalized boundaries between the western magmatic belt (Faja Eruptiva Occidental-FEOC), eastern magmatic belt (Faja Eruptiva Oriental-FEOR) and Eastern Cordillera are shown as heavy dashed lines. Analyzed samples: 1-Escaya, 2-Queta, 3-Tanque, 4-Aguilar, 5-Huaitiquina, 6-Lari, 7-Pinato, 8-Qda. Honda. Selected sectors for comparison: Escaya, C. Colorada, Cochinoca, Sta. Ana, Huancar, Guayaos, Pocitos, M- Maggie, Diablillos, Sierra Calalaste (Qdas. Diablo and Tramontana), B. Lower Paleozoic magmatic events and records in Puna (Argentina), northern Chile. For references see text. Time scale from International Commission on Stratigraphy (2004).

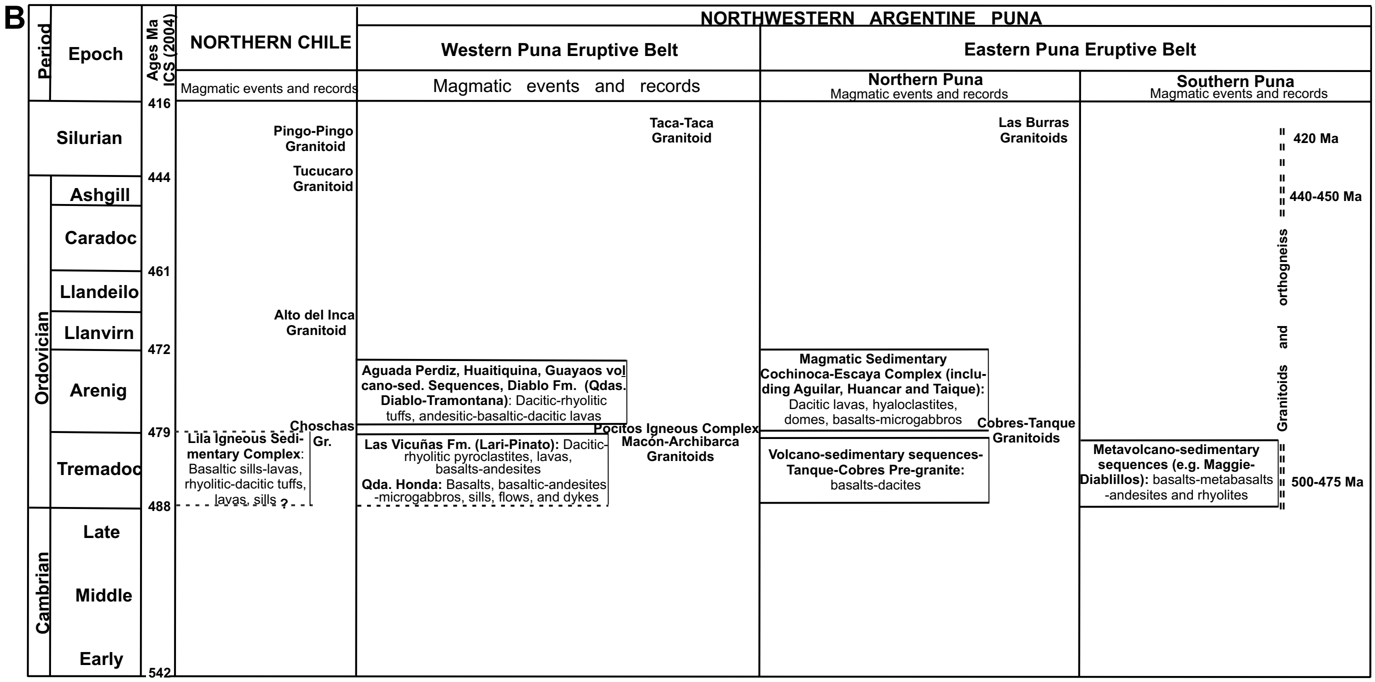

Fig. 1 (*continued*)

microphenocrysts. Variolitic groundmass is common. Some hyaloclastite (1.5–3 m) levels occur at the top of basalts. They show angular to subangular basalt fragments (up to 0.12 m) with jigsaw fit texture in a vitroclastic groundmass partly replaced by chlorite–serpentine–carbonate and quartz. The whole sequence is affected by an intense deformation. It is overlain by conglomerates and light colored sandstones assigned to the Devonian (Palma et al., 1990) that could be correlated to the Cordón de Lila sequence of the same age in Chile (Niemeyer et al., 1985; Niemeyer, 1989).

3.1.3. Huaitiquina–Guayaos

In the Huaitiquina section (site 5 in Fig. 1), massive to brecciated basaltic andesites to andesite lava flows and pillow breccias with algal carbonates characterize the basal unit A distinguished by Coira and Barber (1989). On top, dacitic to rhyolitic partly resedimented tuffs were followed by andesitic–basaltic and dacitic lava flows, pillow breccias and debris flows. Finally, it was followed by a turbidite volcaniclastic sequence with graptofauna from the Late Middle to Upper Arenig (Monteros et al., 1996), marks the end of volcanism in the region. Deformed basanite dikes intrude the above described sequence.

Basaltic andesites are phenocryst poor (less 20%), with partly albitized plagioclase phenocrysts (An^{48-52}), augite and in some cases olivine, in a groundmass of chlorite with opaques, carbonates, and sometimes interstitial scarce quartz. Basanitic dikes of 0.30–2.5 m thick, and (15–20%) porphyric, are composed of plagioclase (An^{50-54}), olivine (Fo^{82-85}) and augite in an intergranular groundmass.

In the Sierra de Guayaos (Fig. 1) there are volcaniclastic turbiditic sequences with dacitic to rhyolitic pyroclastic flows and tuffs and scarce basaltic hyaloclastites. In this succession, an Arenigian-Llanvirnian graptofauna was recognized (Coira et al., 1987; Koukharsky et al., 1989). The hialoclastites are characterized by their fragmental texture and composed of phenocrysts of albitized plagioclase, augite and minor serpentinized olivine in a hyalopilitic to formerly glassy groundmass replaced by prehnite and calcite. The sequence is moderately to intensely deformed.

3.2. Ordovician basic rocks: selected suites of the Eastern Puna Eruptive Belt

In the northeastern Puna, magmatic activity comprises dacitic lavas, autoclastic breccias, hyaloclastites, extrusive domes-cryptodomes and minor basic-spilitic lavas, massive and in pillows (Coira and Koukharsky, 1991), with gabbro-basalt sills and dikes. Syndepositional with the magmatic units are arenaceous-pelitic turbiditic sequences, some representing a platform setting influenced by storms. All of these magmato-sedimentary assemblages were grouped by Coira et al. (1999, 2004) into the Magmatic-Sedimentary Cochinoca-Escaya Complex, whose extent included rock units towards the south in the Huancar and Tanque regions.

Based on graptolite fauna (Martinez et al., 1999; Vaccari et al., 1999; Benedetto et al., 2002), it was possible to recognize diachronism in the magmatic records along the northeastern belt with an earlier event during Late Tremadoc in the south (e.g. Huancar), and during Early to Middle Arenig in the north (e.g. Escaya-Cochinoca). Likewise earlier records of a basic magmatism are identified in the Ordovician sedimentary volcanic sequence which host the plutonic complexes of Cobres (476 ± 1; Lork and Balhburg, 1993) and Tanque (479 ± 1.7 Ma; Coira et al., unpublished) as well as minor members of those complexes (Kirschbaum et al., 2005, 2006; Coira et al., 2005).

3.2.1. Queta–Escaya

Basic rocks are represented in Sierra de Queta (site 2 in Fig. 1). They comprise laccoliths and 1–30 m thickness sills. It is possible to differentiate among them:

(a) Fine grained basalts with greenschist facies groundmass (up to 60%), plagioclase microlites altered to albite in a chloritic mesostasis with titanite granules (up to 5%), skeletal Ti–Fe oxides (2%) and apatite. They are generally vesiculated with quartz, carbonate and chlorite amigdales. In less deformed sections, it is possible to observe peperites at the contacts with the sedimentary host rocks, which testifies to their synchronism with the sediments.

(b) Fine to medium grained basalts composed of clinopyroxene and plagioclase phenocrysts in a groundmass (20%), transformed to greenschists facies mineralogy (chloritic aggregates, albite, occasional tremolite–actinolite). Leucoxene (after titanite) is relatively abundant (2–10%).

Both rocks types are schistose, having been deformed together with their clastic host rocks. They constitute decametric folds and show a strong cleavage in fine rocks.

Pillow and massive lavas (15–25 m thick) are intercalated into the sedimentary sequence in Sierra de Escaya (Coira and Koukharsky, 1991). The pillow lavas have concentric chilled borders controlled mainly by differential concentration of vesicles filled with chlorite and quartz. These pillow lavas, as the massive facies, are poorly porphyritic (10–12%) with plagioclase and pyroxene (titanoaugite) phenocrysts, intensely transformed to greenschists facies mineralogy (albite, chlorite and epidote in a chloritic groundmass with opaque skeletal crystals). In the coarse facies, the massive lavas show variolitic and sometimes ophitic textures.

3.2.2. Sierra de Tanque

In this sector (site 3, Fig. 1), basic and silicic lava flows and sills, and laccoliths, are represented in an Early Ordovician sedimentary–volcanic sequence which host the Tanque Granite (Perez and Coira, 1998). These pre-granite basaltic to microgabric laccoliths and sills are tabular to lenticular (2–6 m and occasionally 30 m thick). Usually, they have boudinage structures as a result of the rhelogical contrast with the sedimentary host rock during deformation. They are composed of plagioclase and clinopyroxene or hornblende, in both cases partly replaced by tremolite–actinolite, and with titanite, apatite and opaques. On the other hand gabbros show mingling and mixing relation with the granite. They form small bodies (<200 m lengthwise) usually foliated and elongated in concordance with the granitoid foliation. The gabbros are essentially constituted by plagioclase and titanaugite replaced by hornblende to which abundant titanite and acicular apatite crystals associate.

The post-granite microgabro-microdiorite dikes are mainly composed of plagioclase and hornblende phenocrysts, in a fine to medium grained groundmass made of plagioclase, titanite, opaques, apatite and secondary tremolite–actinolite.

3.2.3. Aguilar

In this region (site 4, Fig. 1) are recorded the furthest east Ordovician magmatic rocks in the northeastern belt. They constitute a group of (0.4-1.10 m thick) tabular bodies concordant with a sedimentary sequence which bears graptofauna of Early Arenig age (Lopez, 2001; Martin et al., 1987; Toro, 1997). Peperites are clearly recognized in the host rock contacts.

They are ultrabasic to basic alkaline rocks, belonging to the alkaline lamprophyre clan, as monchiquites to sanaites (Coira and Jones, 2002). They are aphiric to poorly porphyric rocks frequently autoclastic brecciated with microgranular to panidiomorphic texture, (2–3%) scarce olivine phenocrysts altered to serpentine and carbonates are included in a groundmass of olivine (20%), augite (40%) and kaersutite (15%), opaques (10%) and scarce biotite. Alkali feldspar, stilbite and carbonates aggregates are irregularly distributed in that groundmass.

4. Geochemical characteristics

The analyzed basic rocks were altered in the submarine environment and metamorphosed up to greenschist facies. As a consequence they have undergone mineralogical and geochemical changes from their original compositions. Success has been achieved in determining the primary magmatic characterization of this kind of modified rock by the use of elements such as Ti, Zr, Hf, Nb, Ta, REE, Th, Sc, Hf, Cr and Ni that are considered to be immobile during these processes (Winchester and Floyd, 1977; Pearce, 1996). Mobile elements are considered only as complements.

In general, the Ordovician basalts show subalkaline or alkaline characteristics, as is reflected in their Nb/Y ratios (Fig. 2A) accompanied by TiO_2 variations, which classify them into two types: low Ti type (0.4–2% TiO_2) and high Ti type (2.5–3.5% TiO_2). SiO_2 content varies between 42% and 57.5% (Table 1).

4.1. Western Puna Eruptive Belt

The western older mafic Ordovician rocks in the Puna are represented by the Pinato-Lari and Quebrada Honda basalts. They plot in the subalkaline field (Fig. 2A), are low K tholeiites with K_2O 0.2–0.6%, FeO/MgO 1.2–3.3% and TiO_2 < 2%. Their extended trace element diagrams normalized to MORB show Th and LREE enrichment (La/Yb = 0.9–3.5; La/Th = 1.3–6.7) and Ta and Nb depletion (La/Nb = 2.7–6) (see Fig. 3A), denoting arc basalts characteristics (Saunders et al., 1980; Thompson et al., 1984). Simultaneously, they show MORB-like HFSE values and REE patterns very similar

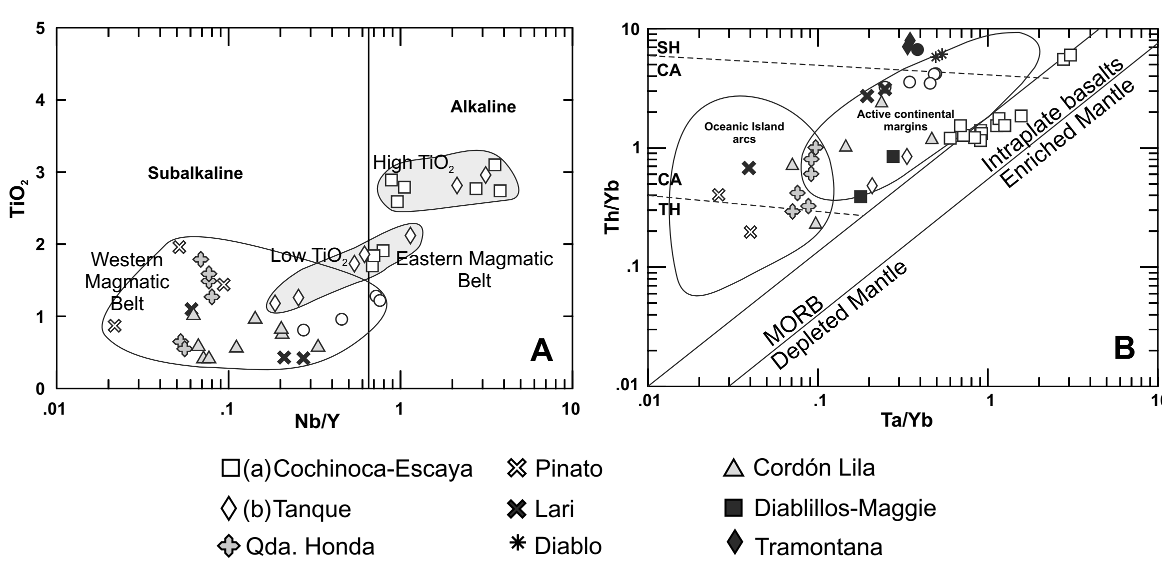

Fig. 2. (A) Plots of TiO_2 wt% vs. Nb/Y showing distribution of Early Paleozoic basic rock samples in subalkaline and alkaline fields and (B) Th/Yb vs. Ta/Yb (after Pearce, 1983) to show sources and geotectonic settings of the samples.

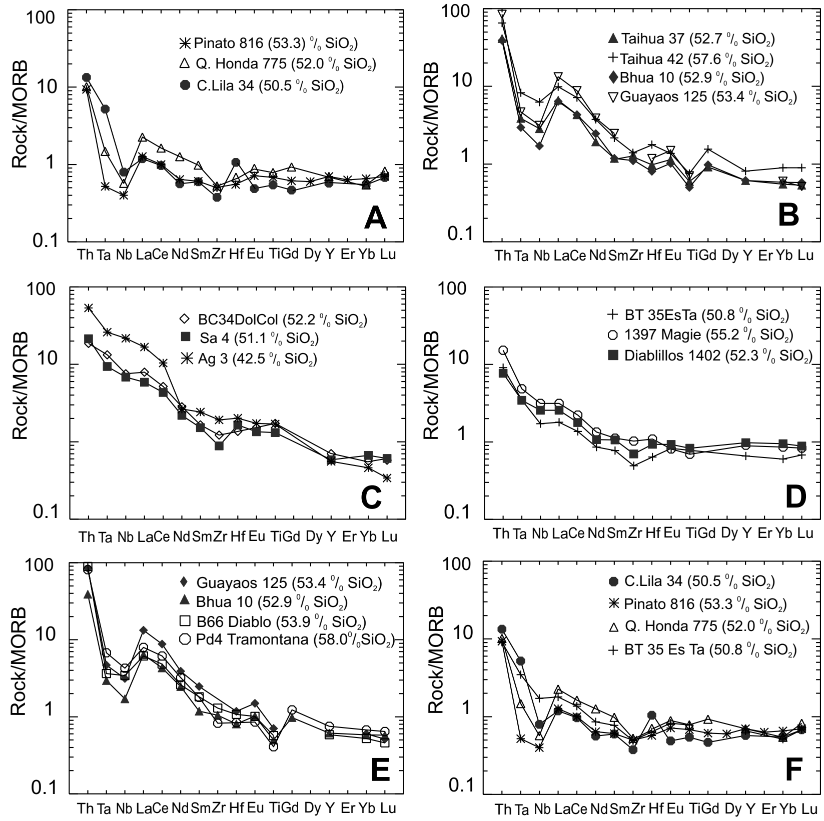

Fig. 3. Extended trace element plots for representative basic rocks from: (A) Pinato, Qda. Honda, C. Lila, (B) Haitiquina (Taihua-Bhua) and Guayaos, (C) Queta-Escaya (BC34), Aguilar (Ag3), Sta Ana (SA4), (D) Samples southern Puna: 1397 Maggie, Diablillos 1402 and northern Puna: Tanque (BT35), (E) Guayaos, Huaitiquina (Bhua), Srra. Calalaste (Diablo and Tramontana), (F) C. Lila, Pinato, Qda. Honda and Tanque, Normalization N MORB after Hofmann, 1988. Data from Table 1 and for comparison: C. Lila 34 from Damm et al. (1986), Guayaos 125 from Coira et al. (1999), Sta Ana (SA4) from Coira et al. (1999), 1397 Maggie and Diablillos 1402 from Viramonte et al. (1993), B66 Diablo and PD4 Tramontana from Zimmermann and Van Staden (2002).

to E-MORB. Applying the tectonic discrimination diagrams for basalts, for example Zr–Nb–Y (Meschede, 1986) and Th/Yb vs Ta/Yb (Pearce, 1983), the Pinato-Lari and Quebrada Honda samples plot in the field of N-MORB and volcanic arc basalt (Fig. 4A) and in the oceanic island arc field or in the overlap zone between this field and the active continental margin field (Fig. 2B). Similar indications are given by the ThHfTa (Fig. 4B; Wood, 1980) and Ti–Zr (Fig. 5; Vermeesch, 2006) diagrams. In the former these basalts plot in the island arc tholeiites to calc alkaline arc fields, whereas in the second one they plot in both fields, MORB and IAB. This composite geochemical characteristic, already recognized by the analysis of the extended element diagrams, is distinctive of supra-subduction

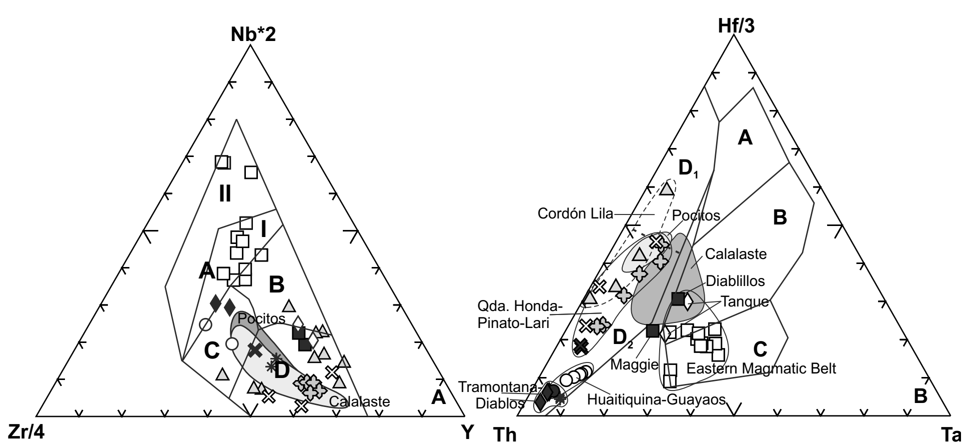

Fig. 4. (A) Ternary Zr–Nb–Y discrimination diagram after Meschede (1986) for the basic analyzed samples and complementary ones for comparison. Fields are: AI, within-plate alkali basalts; AII, within-plate alkali basalts and within-plate tholeiites; B, E-type MORB; C, within-plate tholeiites and volcanic arc basalts; D, N-type MORB and volcanic arc basalts. (B) Th–Hf–Ta discrimination diagram after Wood (1980). Fields are: A, N-MORB; B, E-type MORB and within-plate tholeiites; C, alkaline within-plate basalts; D, volcanic arc basalts. Island arc tholeiites plot in field D where Hf/Th > 3.0 and calc-alkaline basalts where Hf/Th < 3.0. Data from Table 1 and for comparison from: C. Lila from Damm et al. (1986) and Breitkreuz et al. (1989); Maggie and Diablillos from Viramonte et al. (1993); Calalaste and Pocitos (as light and dark grey fields) from Zimmerman (1999). Symbols as in Fig. 2.

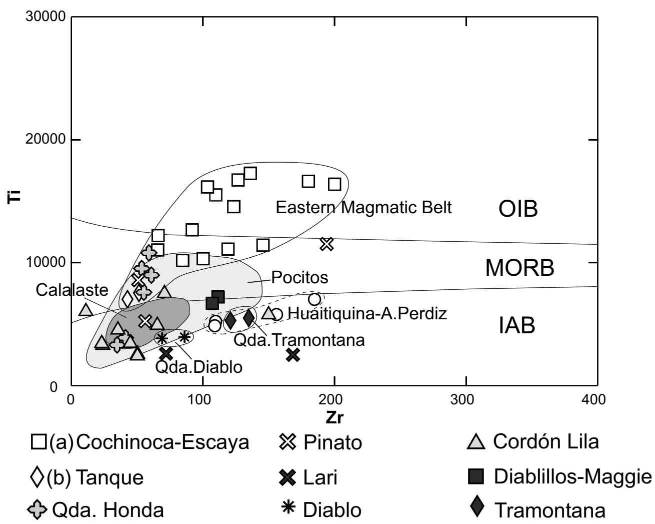

Fig. 5. Ti–Zr discrimination diagram for representative basic rocks of the study region. Data details as in Fig 4.

zone (SSZ) magmas (Pearce et al., 1984; Saunders and Tarney, 1984). It reflects the contribution from a subduction component to mantle derived melts, which takes place during extension above subducting oceanic lithosphere. It is suggested that all these geochemical characteristics resulted from selective contamination of the mantle wedge by LIL enriched hydrous fluids, together with sediments both from descending dehydrated oceanic lithosphere (Saunders and Tarney, 1984; Clift and Dixon, 1994; Hawkins, 1995).

Huaitiquina, Aguada de la Perdiz and Guayaos basalts to basaltic andesites, basic representatives of the western magmatic belt during the Arenig, have medium K calc-alkaline to shoshonitic chemical characteristics. Huaitiquina basalts and andesites have high Al_2O_3 (17–18 %), relatively low TiO_2 (<1.3%) concentrations, low FeO/MgO ratios (<2) La/Th = 2–4 and high La/Ta (44–24); thus they have a calc-alkaline arc signature (see extended trace element plot Fig. 3B and tectonic discriminant diagrams; Fig. 4A; Meschede, 1986; Fig. 2B; Pearce, 1983 and Fig. 4B, Wood, 1980). Huaitiquina alkaline dikes exhibit within-plate signature La/Ta = 10–11 and Ba/Ta = 102–105, which supports a back-arc evolution for this sector.

Agua de la Perdiz basaltic andesites have also arc-like incompatible immobile trace element ratios (La/Ta 32, Ba/La = 58, Breitkreuz et al., 1989). Guayaos basaltic andesites have Th/Yb and Ta/Yb ratios, which place them in the shoshonitic field (Fig. 2B), in concordance with their high K_2O (3%) content, with high La/Ta = 58 and Ba/La (24) ratios indicating their arc signature.

On the other hand the εNd (450 Ma) and fSm/Nd values determined in basic rocks from Huaitiquina (Bierlein et al., 2006) and plotted in Fig. 6 reflect a possible origin, by mixing source components from a moderately depleted mantle similar to eastern magmatic belt mafic members (see below) with a low proportion of crust with a Nd isotope composition, similar to that plotted in the pre-Ordovician rocks field (see Fig. 6) presented by Bock et al. (2000), as well as in the Ordovician sedimentary rocks of northwestern and northeastern Puna field (Zimmermann and Bahlburg, 2003). Similar εNd (450 Ma) and fSm/Nd values observed in the Early Paleozoic metabasites of southern Puna (Fig. 6) indicate that this enrichment process often operated in generating basic magmas during that time.

4.2. Eastern Puna Eruptive Belt

In contrast to the Western Puna Eruptive Belt, the eastern belt basalts (including gabbros, spilites and microgabbros) are alkaline or subalkaline (Fig. 2A). At the Escaya-Queta and Tanque localities there are non-arc alkaline and subalkaline types with 46–52% SiO_2 content. Typifying their non-arc (intraplate) geochemistry are high Ta/Yb = 0.6–2 and Th/Yb = 1–2 ratios (Fig. 2B) and low La/Ta ratios (10–15). Among them are both low and high Ti groups (Coira et al., 1999). The first one is subalkaline, light REE enriched, with TiO_2 1.1–2.1%, FeO/MgO 1.3–1.4, low K_20 (<0.7%) concentrations and

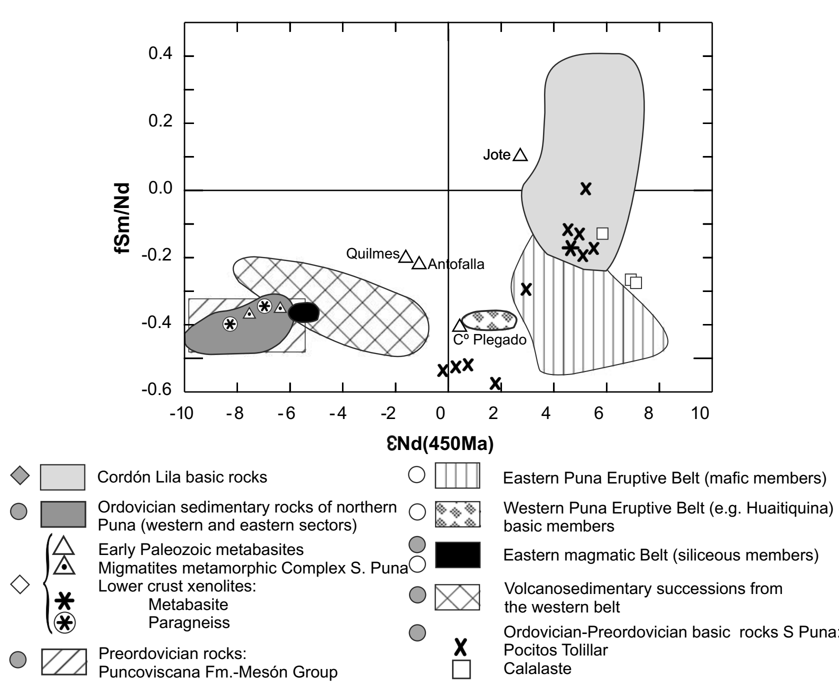

Fig. 6. Plot of fSm/Nd vs. εnd(450 Ma) fSm/Nd = [^{147}Sm/^{144}Nd.sample/0.1967]-1. Data from ● Bock et al., 2000; ♦ Damm et al., 1991; ○ Bierlein et al., 2006; ◇ Becchio et al., 1999.

La/Th ratio 6.5–11. The second one is mainly represented by dikes, minor sills and the Tanque gabbro that plot in the alkaline field (Fig. 2A) and are characterized by their lower SiO_2 (42–51%), higher TiO_2 (>2.1 %) and K_2O (0.3–2.2%) concentrations, FeO/MgO 0.8–1.8. They have steeper REE patterns than the other group (Fig. 3C), with similar low La/Ta rations (10–13). Aguilar alkaline lamprophyres are also in the high Ti group. They have 42–44% SiO_2, the highest TiO_2 (2.85–2.9%) contents, alkalies 3.5–3.76, K/Na 1.1–1.36, FeO/MgO = 0.8–0.9 and the steepest REE patterns (La/Yb = 35–36, see Fig. 3C).

Among the Tanque basic members (see Sections 3.2 and 3.2.2), the pre-granite basalts and microgabros (Bt34, Bt35) along with Cobres pre and syngranite basic rocks integrate a subalkaline group characterized by their lower TiO_2 (0.2–1.25%), low K_2O (0.3–1.2%), FeO/MgO (0.6–1.1), Ta/Yb < 0.6, Th/Yb = 0.5–1 and lower Nb/Y < 0.4 (Coira et al., 2005; Kirschbaum et al., 2005). They show a REE pattern very similar to E-MORB with LREE and Th enrichment but with a slight depletion in Nb and Ta relative to adjacent Th and La. Neither Nb–Ta anomalies nor the LREE enrichment is extreme. This fact may indicate that those rocks formed in a mature rather incipient SSZ basin, but not so mature given the detectable subduction signature. This group plots in the E-MORB and MORB fields in the tectonic discriminant diagrams (Figs. 4A, B and 5), whereas the Late Tremadoc- Middle Arenig Escaya-Cochinoca, Santa Ana, Huancar and part of Tanque magmatic type plot in the within-plate field in the previous diagrams. In the Ti–Zr diagram some low Ti group samples match in the MORB field, but the high Ti group samples in the OIB field.

Nd Isotopic composition of the mafic members of the eastern magmatic belt (Bierlein et al., 2006) is characterized by positive εNd (450 Ma) = 2.2–7 values similar to those from Cordón de Lila basalts (Chile) with lower fSm/Nd values (data from Damm et al., 1986), and also similar to basic lower crust xenoliths from Salta rift (Becchio et al., 1999) and to basic rocks of Pocitos and Calalaste (Bock et al., 2000), (see Fig. 6). These isotopic compositions also suggest an origin by melting a moderately depleted mantle. Their lower fSm/Nd values than Cordón de Lila basic rocks can be explained by melting the mantle at a deeper level where garnet was fractionating the REE. The radiogenic Pb isotopes composition of one sample of this group determined by Bock et al. (2000) indicates a mantle source enriched in U and Th relative to Pb.

4.3. Ordovician basic rocks: their correlation along the Puna

Keeping in mind the four well-established groups of basic rocks (illustrated in Fig. 3A–D), their geochemical analyses are compared with those from the southern part of the Western and Eastern Puna Eruptive Belt to find their most probable relationships.

Similar geochemical patterns (Figs. 3A, 4A, B and 5) are exhibited by basalts of Cordón de Lila in Chile (Damm et al., 1990), which can be correlated with the Pinato, Lari and Quebrada Honda group of basic rocks, albeit the Cordon de Lila basic rocks show lower La/Nb = 0.44–1.06 and Th/Nb = 0.5–0.7 ratios and La/Th = 1.5–1.7 than Quebrada Honda, Pinato and Lari basalts and microgabbros (Fig. 3A). The latter are not easily distinguished from island arc tholeiites and, like many basalts of the western Pacific back-arc basins, could represent early stages, where spreading was incipient (e.g., Mariana through basalts – Gribble et al., 1996, 1998; Japan Sea – Allan and Gorton, 1992). In contraposition Cordon de Lila basalts are more E-MORB like and could be assigned to a more mature stage of spreading in the basin, but not so mature as to exhibit MORBs without any subduction zone signature.

The Nd isotope compositions of Cordón de Lila mafic rocks provide additional information related to the nature of the mantle contribution. Their determined εNd (450) = 1.9–6.5 values (Damm et al., 1991) indicate an origin by melting of a depleted mantle. An important spread of fSm/Nd values of those rocks is observed in Fig. 6, probably developed in mantle during melting. Furthermore, their Pb isotopic composition indicates an unradiogenic signature for the source (Bock et al., 2000), limiting the amount of crustal contaminant.

Sierra de Calalaste andesites (see Fig. 1) in the Quebrada Tramontana and basalt-andesites in the Quebrada Diablo were described as volcanic arc derived rocks by Zimmermann and Van Staden (2002). Their geochemical patterns are most like those of the Huaitiquina-Guayaos basaltic andesites to andesites group (see Fig. 3E). These compositional characteristics, together with the temporal correlation between the last group (Late Middle to Upper Arenig-LLanvirn, see Section 3.1c) and the Quebrada Diablo basalt-andesites, of Diablo Formation (Arenig to Lower Llanvirn; Zimmermann et al., 1998; Zimmerman, 1999) allows extension of the length of the magmatic arc at that time, at least to the Sierra de Calalaste, in the southern Puna, including, based on their geochemical characteristics, the Quebrada Tramontana basic rocks.

On the other hand, geochemical characteristics of Sierra de Calalaste and Pocitos mafic and ultramafic (cumulate) rocks assigned to the pre-Ordovician have been described as consistent with a back-arc basin origin (Zimmermann et al., 1999; Zimmermann, 2000). As we plot for comparison data fields for those rocks from Zimmerman et al. (1999), Zimmermann (2000) and Zimmermann and Van Staden (2002), together with the geochemical data from Quebrada Honda, Pinato-Lari and Cordon de Lila (see Figs. 4A, B and 5), they are comparable and plot overlapping arc basalts and MORB (N and E) fields, characteristics that are distinctive of supra-subduction zone (SSZ) magmas.

Likewise, some of the Calalaste and Pocitos samples have positive εNd (450 Ma) and negative fSm/Nd values (Bock et al., 2000), similar to some of the Cordón de Lila samples (Damm et al., 1991), suggesting an origin for those rocks by melting a moderately depleted mantle. But for the Pocitos samples, their εNd (450 Ma) and fSm/Nd spread values (see Fig. 6) probably reflect different ages among them in correspondence with trace element patterns indications of different groups. This consideration is in agreement with the Proterozoic age indicated by Kleine et al. (2004) for Pocitos ultramafic (cumulatic) rocks intruded by the Pocitos Igneous Complex, on the basis of the low initial $^{87}Sr/^{86}Sr$ determined from the "contact blackwall" isochron, significantly lower than those for the CIP. Geochemically (see Figs. 4A, B and 5) and petrographically comparable rocks crop out in Sierra de Calalaste. So it seems that basic-ultramafic (cumulatic) rocks of Pocitos and probably part of Calalaste represent Pre-Ordovician records of a back-arc system in which, considering their geochemical characteristics, the depleted mantle derived melts (MORB) have been enriched by a subduction component and transferred to that system. These conditions operated again during Ordovician times in the western belt as indicated by Cordon de Lila, Pinato and Quebrada Honda geochemical characteristics.

Comparing selected metabasites from the metasedimentary-magmatic assemblage of low to medium grade metamorphic rocks that characterize an eastern belt (Hongn, 1994) of the southern Puna metamorphic basement (NE Salar de Diablillos and NE Salar Centenario-Mina Maggie), with the described group of basalts and microgabbros from Tanque Granite and Cobres Granite host rock, a good concordance can be established among their trace element patterns (see Fig. 3D, data from Viramonte et al., 1993 and this paper). They show very similar REE patterns with light enrichment in LREE and Th and slight depletion in Nb and Ta relative to adjacent Th and La (see Fig. 3D) in accordance with an origin in a mature supra-subduction zone basin. They fall in the Ta/Yb vs. Th/Yb diagram (Fig. 2B) near the mixing array between a depleted mantle source (MORB) and an enriched–mantle source (OIB), but at higher Th/Nb ratios, which may indicate a subduction addition to the mantle component.

The good geochemical concordance and temporal correlation recognized among the group of Tanque and Cobres (host of granitoids of 476–479 Ma) and the metabasites of the NE of Diablillos salar and Centenario salar (part of a correlative metavolcano-sedimentary unit dated in 485 ± 5Ma U–Pb; Viramonte et al., 2005) allows an establishment of the continuity of the East Magmatic Belt in southern Puna at that time under an extensional back-arc tectonic setting.

5. Concluding remarks

During the Early Paleozoic magmatic evolution of Argentine Puna and adjacent northern Chile, juvenile (basaltic) inputs, not really voluminous in relation to the siliceous contribution, occurred during the Early Tremadoc and Middle to Upper Arenig in the Western Puna Eruptive Belt and during the Tremadoc-Middle Arenig in the Eastern Puna Eruptive Belt.

The geochemical and isotopic characteristics of the analyzed basic Ordovician magmatic rocks from the northern and southern Puna make it possible to constrain the mantle contributions during Early Ordovician times to: (a) depleted mantle melts, MORB type, with a non-radiogenic Pb isotope signature variably enriched by a subduction component, and (b) LIL enriched mantle sources which were enriched in U and Th relative to Pb, that ascended associated with a transtensional regime that affected the eastern Puna. Enrichment processes resulting from mixing melts from a moderately depleted mantle with a variable contribution of a crustal component with εNd (450 Ma) = −10 to −5.5 (field of pre-Ordovician Puna rocks) were important in generating basic magmas at that time in the Puna region.

Among those Ordovician basic magmatic rocks four spatially distinct magmatic groups are defined on their geological and geochemical characteristics, each one associated with a particular geodynamic environment.

(a) The Tremadoc western group of mafic rocks is represented by Quebrada Honda, Pinato-Lari subalkaline basalts and microgabbros. They correspond to low K tholeiites with arc and modified MORB like signatures. Their similar geochemical patterns allow a correlation with the Cordon de Lila basalts in a northern sector of the western magmatic belt. Those characteristics are consistent with basic inputs of magmas in a supra-subduction setting, where depleted mantle derived melts (MORB) were produced and enriched during subduction events associated with the evolution of a marginal basin system at that time. The Cordon de Lila basalts denote a more weak subduction zone signature than the rest of the group and could represent a more mature spreading stage in the basin.

A depleted mantle source for those magmas is supported by their εNd (450 Ma) values ranging from 7 to 4 and a non-radiogenic Pb isotope composition (Bock et al., 2000).

Similar geochemical signatures to the group of Quebrada Honda, Pinato–Lari subalkaline mafic rocks are recognized in Pocitos and in a group of mafic rocks of the Sierra de Calalaste. These characteristics support a marginal basin geological setting for Pre-Ordovician times in that region, conditions that operate again during Tremadoc in the western belt.

(b) The Arenig western group of basalts to andesites is represented by Huaitiquina, Guayaos and Aguada de la Perdiz members in northern Puna. They have medium K calc-alkaline chemical characteristics and show arc signatures. Andesites and basalts of the Qda del Diablo and andesites of the Qda Tramontana, in the Sierra de Calalaste, are correlated with the former group based on their clearly comparable geochemical patterns. This correlation allows an extension of the volcanic record of the magmatic arc at that time, at least to the Sierra de Calalaste, in the southern Puna.

The εNd(450 Ma) = 0.98–2.17 and fSm/Nd = −0.39 values of basalt-andesites of Huaitiquina section (Bierlein et al., 2006) indicate that those rocks could originate by mixing of a moderately depleted mantle with a low proportion of a crustal component having εNd (450 Ma) = −10 to −5.5, as in the field (see Fig. 6) of Pre-Ordovician Puna rocks (Bock et al., 2000), whereas the voluminous silicic to intermediate volcanic and volcaniclastic rocks that are associated to those basalt and andesites are practically indistinguishable by Nd isotopes from an old crustal component. They may be interpreted, considering their geochemical characteristics, as melts of arc-like crust.

(c) The Tremadoc eastern group is represented by the Tanque pre-granite subalkaline basalts and microgabbros, and both pre- and syngranite gabbros and basalts of Cobres, in the north sector of the eastern magmatic belt. They are characterized by their low TiO_2, and K_2O and show a REE pattern very similar to E-MORB with LREE and Th enrichment and slight depletion in Nb and Ta. These geochemical characteristics are in concordance with an origin in a mature rather incipient SSZ basin. The Nd isotope composition of these rocks is characterized by εNd (450 Ma) = +4.08 (Bierlein et al., 2006), compatible with a depleted mantle source (see Fig 5) and in the range of Cordón de Lila mafic rocks εNd (450 Ma) = 1.9–6.5 values (Damm et al., 1991).

The good geochemical concordance and temporal correlation recognized among the rocks of the previous group, a host of granitoids that yielded U/Pb ages of 479–476 Ma, and the metabasites of the NE of Diablillos and Centenario salars, correlative with a metavolcano-sedimentary unit dated in 485Ma U/Pb, allows the establishment of a continuation of the Eastern Puna Eruptive Belt in southern Puna at that time as part of a back-arc basin.

(d) The Late Tremadoc-Arenig alkaline basalt–microgabbro group of the northeastern Puna (Queta-Cochinoca-Aguilar-Tanque) integrates a bimodal assemblage with voluminous dacitic members. They have an intraplate signature and include low and high Ti types. This group denotes a mantle source enriched in LIL elements, which is also enriched in U and Th relative to Pb. The associated silicic magmatic types are practically indistinguishable by Nd isotopes from an old crustal component. They may be interpreted, considering their geochemical characteristics, as melts of a sedimentary crustal component with weak arc type signature.

For this time, the geodynamic setting of the Puna region proposed by Coira et al. (1999), an oblique left-lateral transpressional subduction zone in the south that changes to the north into an oblique strike-slip fault system, would account for the important crustal melting processes that took place along this belt and were associated with the basic alkaline magmatism related to mantle decompression in pull apart settings.

The magmatic typing established in this paper provides, as shown above, a useful tool to apply to correlate Early Paleozoic basic rocks of the Puna of uncertain chronostratigraphic position with superimposed tectonic and metamorphic events, as in the case of southern Puna occurrences.

Those correlations allow an improvement of the reconstruction of the geodynamic settings and better constrained interpretations of the magmatic evolution during the Ordovician in this sector of the western margin of Gondwana. So it is possible to recognize in the western magmatic belt during Tremadoc the evolution of a marginal basin where depleted mantle derived melts (MORB) were produced and enriched during extension above the eastward dipping subducting slab. A range of compositions found among the mafic rocks suggests basin variations in the spreading from incipient, as in the Quebrada Honda-Pinato-Lari sectors with a more island arc tholeiites signature, to a more mature stage of basin spreading as in the Cordon de Lila. Meanwhile, the basic magmatic

Table 1
Geochemical analyses of basic Ordovician rocks of the Puna, Argentina.

Sample	Pinato and Lari			Huaitiquina			Qda. Honda					Queta - Escaya - Tanque							
Major oxides (wt%)	MKP210	MKL816	MKL826	Taihua37	Taihua42	Bhua10	775	776	NQH14	NQH37	853	CB30 EsQue	CB50 DolQue	CB54 DolQue	BC32 DolCol	BC34 DolCol	BT35 EsTan	BT76 dqdioTa	Ag3 Aguilar
SiO_2	50.91	51.76	57.48	50.73	55.11	51.39	50.78	50.43	49.48	49.64	50.02	47.36	50.25	49.18	48.98	49.09	50.16	51.29	42.04
TiO_2	1.44	1.10	0.43	0.96	1.22	0.81	1.27	0.55	1.59	1.79	1.49	2.21	1.84	1.76	1.70	2.84	1.26	1.86	2.85
Al_2O_3	12.88	13.41	15.97	18.28	17.79	18.54	13.86	15.68	13.17	13.70	13.17	13.53	16.36	15.19	16.75	14.83	15.87	16.14	10.15
FeO		12.88																	11.76
Fe_2O_3	14.58		6.43	7.22	5.14	7.56	13.03	8.57	14.99	15.45	14.43	10.59	8.07	8.30	8.35	10.11	10.05	8.99	
MnO	0.22	0.45	0.07	0.09	0.12	0.13	0.17	0.13	0.19	0.20	0.19	0.23	0.14	0.15	0.16	0.19	0.20	0.15	0.18
MgO	6.24	6.93	1.75	6.66	2.57	6.80	5.92	8.40	5.97	5.62	6.38	4.75	7.35	8.14	6.07	5.33	8.71	6.73	13.97
CaO	7.79	6.61	5.77	5.97	3.50	5.73	9.60	12.55	8.79	8.00	8.23	9.25	9.99	12.08	12.75	10.88	9.48	10.03	9.49
Na_2O	2.92	3.28	9.32	4.40	5.27	4.50	2.69	1.56	3.72	3.75	2.80	3.13	4.10	3.27	0.82	4.11	1.81	3.37	1.59
K_2O	0.66	0.52	0.02	1.96	4.79	1.44	0.18	0.30	0.42	0.19	0.33	0.21	0.55	0.01	1.07	0.02	1.13	0.44	2.17
P_2O_5	0.09	0.10	0.09	0.28	0.40	0.23	0.10	0.05	0.11	0.13	0.11	0.36	0.27	0.22	0.22	0.43	0.14	0.36	0.68
LOID	3.15	1.01	3.26	3.93	4.41	3.37	2.40	1.92	2.18	2.22	2.85	8.61	1.85	2.03	2.90	2.69	1.19	1.20	4.98
Total	100.88	98.05	100.59	100.48	100.32	100.50	100	100.14	100.61	100.69	100.00	100.23	100.77	100.33	99.77	100.52	100.00	100.56	99.86
Trace elements (ppm)																			
La	2.60	4.94	12.00	25.80	38.50	24.90	8.80	6.10	5.50	6.60	6.70	36.60	25.98	22.09	16,00	30.80	7.00	23.50	65.00
Ce	10.2	12.00	29.6	51.8	86.1	51.7	19.6	14.9	15.5	17.3	18.2	72.1	52.3	44.9	36.6	62.1	16.4	50.0	125.0
Nd	23.0	7.1	18.2	21.6	42.0	27.6	14.1	8.7	23.0	16.1	23.0	32.7	38.4	33.9	23.5	31.6	9.6	35.5	21.3
Sm	3.65	2.27	3.41	4.44	8.14	4.44	3.68	2.06	3.70	3.79	3.78	6.99	5.34	4.67	3.66	6.19	2.90	5.96	9.10
Eu	1.302	0.955	0.852	1.522	1.830	1.361	1.190	0.680	1.357	1.389	1.424	1.750	1.790	1.800	1.172	2.040	1.100	1.930	2.300
Tb	1.13	0.57	0.41	0.67	1	0.63	0.76	0.40	0.79	0.90	0.82	1.00	0.84	0.66	0.63	0.85		0.99	0.60
Gd	6.07	3.12	3.06	4.64	7.89	4.97	4.71	2.57	8.44	6.77	7.52	8.86	5.76	3,64					
Yb	4.81	2.56	1.31	2.15	3.50	2.27	3.12	1.73	3.35	3.39	3.44	2.09	2.28	1.73	1.65	2.27	2.00	3.01	1.8
Lu	0.796	0.412	0.211	0.315	0.528	0.341	0.483	0.266	0.533	0.523	0.499	0.264	0.317	0.272	0.244	0.341	0.400	0.471	0.200
Ba	220	110	84	792	705	368	158	106	181	145	169	232	740	109	337	189	232	90	756
Rb	21	21	5	68	86	48	7	10	16	7	9	15	18	9	44	9	52	24	73
Sr	97	185	103	427	186	555	115	99	117	78	179	165	683	240	330	269	166	278	750
Cs	0.99	2.00	0.30	1.40	15.60	3.55	0.82	0.44	9.75	0.82	2.82	0.71	2.02	0.10	2.68	1.95	6.00	0.91	47.00
U	0.2	0.2	0.7	1.7	2.6	1.7	0.4	0.2	0.1	0.3	0.3	1.0	0.8		0.7	1.0	1.0	0.9	1.0
Th	2.0	1.8	3.6	7.7	12.2	7.3	1.9	1.4	1.4	1.1	1.0	3.7	3.2	2.0	2.1	3.5	1.7	3.6	10.0
Hf	3.2	1.7	2.6	2.9	5.3	2.4	3,0	1.5	3.0	2.9	3.0	5.1	4.0	3.1	2,9	4.0	1.9	4.5	6.0
Nb	3	1	4	10	22	6	2	1	2	2	2	23	19	14	14	26	6	17	76
Y	32	23	19	22	29	22	25	18	26	29	26	24	24	20	20	25	24	28	20
Ta	0.064	0.100	0.255	0.743	1.590	0.567	0.284	0.159	0.254	0.298	0.244	2.430	2.080	1.570	1.192	2.550	0.668	1.770	5.000
Sc	50.4	46.0	22.1	23.9	21.8	25.4	45.7	39.1	47.9	51.3	52.7	31.9	36.2	45.9	37.7	30.3		31.7	21.0
Cr	82	79	12	149	75	211	57	652	114	66	170	59	289	715	1539	26	465	213	423
Ni	29	42	16	109	36	123	46	140	44	23	66	17	95	158	144	14	94	53	340
Co	58	39	25	34	23	35	60	45	54	57	56	46	44	53	50	55	42	51	72
Zr	51	51	72	156	51	109	55	35	53	59	61	110	146	66	85	127	51	120	200
V	404		176	35	116	164	363	221	468	456	485	271	265	245	251	320	213	262	210
Ratios																			
FeO/MgO	2.10	1.86	3.31	0.98	1.80	1.00	1.97	0.92	2.26	2.47	2.04	2.01	0.99	0.92	1.24	1.71		1.20	0.84
K_2O/Na_2O	0.23	0.16	0.00	0.45	0.91	0.32	0.07	0.19	0.11	0.05	0.12	0.07	0.13		1.23		0.62	0.13	1.36
Ba/La	84.6	22.3	7.0	30.7	18.3	14.8	18.0	17.4	32.9	22.0	25.2	6.3	28.5	4.9	21.1	6.1	33.1	3.8	11.6
La/Th	1.3	2.8	3.3	3.4	3.2	3.4	4.6	4.4	3.9	6.0	6.7	9.9	8.1	11.2	7.6	8.8	4.1	6.5	6.5
La/Sm	0.7	2.2	3.5	5.8	4.7	5.6	2.4	3.0	1.5	1.7	1.8	5.2	4.9	4.7	4.4	5.0	2.4	3.9	7.1
La/Yb	0.5	1.9	9.2	12.0	11.0	11.0	2.8	3.5	1.6	1.9	1.9	17.5	11.4	12.8	9.7	13.6	3.5	7.8	36.1
Sm/Yb	0.8	0.9	2.6	2.1	2.3	2.0	1.2	1.2	1.1	1.1	1.1	3.3	2.3	2.7	2.2	2.7	1.5	2.0	5.1
Ba/Ta	3438	1100	329	1066	443	649	556	667	713	487	693	95	356	69	283	74	347	51	151
La/Ta	41	49	47	35	24	44	31	38	22	22	28	15	12	14	13	12	10	13	13

Major element and trace element (Rb, Ba, Sr, Y, Zr, Hf, Nb, Th, U, Co, Cr, Ni, V) analyses were done by X-Ray fluorescence (XRF) on a Rigaku FX2000 spectrometer with a Rh tube operating at 50 Kv and 45 mA, at Instituto de Geología y Minería-Univ. Nacional de Jujuy-US Geological Survey and Japanese Geological Survey standards were used. REE and other trace elements were analyzed in the LAAN, Centro Atómico Bariloche. Samples were irradiated in RA-6 reactor. Gamma spectra were measured on an HPGe detector with 12.3% relative efficiency and on a multichannel (40%) analyzer. In the analysis the absolute parameters method was used. The samples were analyzed with certified standards of similar matrix.

records in the eastern magmatic belt indicate the beginning of an extensional back-arc regime in this belt by that time.

During the Arenig the magmatic records in the Western Puna Eruptive Belt point to the existence of a magmatic arc to back-arc which evolved on attenuated continental crust from the Aguada de la Perdiz, Huaitiquina-Guayaos area to at least the Sierra de Calalaste in southern Puna.

In other hand, in the Eastern Puna Eruptive Belt the extensional conditions continued during the Late Tremadoc-Middle Arenig. The bimodal magmatism, represented by within-plate basic rocks and voluminous siliceous members with a crustal signature (Coira et al., 1999), supports a tectonic setting where alkaline magmatism is produced in association with mantle decompression along pull-apart regions, while crustal melting took place due to the thermal anomaly related to thinning. Transpressive (Hongn and Mon, 1999) and transtensive (Coira et al., 1999) models had been proposed for the origin, emplacement and deformation of this magmatic event.

Despite the reduced volume of juvenile inputs of Ordovician magmas in the study region, the best comprehension of their characteristics was the key to reconstructing the geodynamic settings and to interpreting the magmatic evolution during the Ordovician in this sector of the western margin of Gondwana.

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Appendix Analytical methods

See Table 1.

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