Extensional Carboniferous magmatism at the western margin of Gondwana: Las Lozas valley, Catamarca, Argentina

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ABSTRACT. The Las Lozas volcanic sequence, which crops out at northwestern border of the Famatina belt-southeastern Puna, NW Argentina, is constituted mainly by rhyolites and a lesser volume of basalts and trachytes, and volcanoclastic deposits. These rocks, previously considered of Early Paleozoic age, are now assigned to the Lower Pennsylvanian (320 Ma U-Pb age). They represent a bimodal volcanic succession that plot in the subalkaline/tholeiitic (rhyolites), alkaline basalts (basalts) and alkaline (trachytes) fields on the total alkali-silica diagram. The basalts display features comparable to transitional MORB and within-plate tholeiites, with contributions from a mantle source affected by crustal contamination. The acid members also show geochemical affinities to within-plate magmas, and their composition suggest a derivation from continental crustal material with mantle source interaction or a juvenile essentially mantle derived crust. The 320 Ma age from the Las Lozas volcanic succession as well as the 342 and 348 Ma U-Pb ages, from rocks in the nearby Cazadero Grande section, to the south, and the U-Pb ages from Sierra Pampeanas granites (332-357 Ma) highlight the importance achieved by Carboniferous magmatic activity in that region, framed between 320 and 350 Ma. Low strontium initial ratios from the Las Lozas (0.70479-0.70164) indicate a predominant contribution by a juvenile component, while the ratios in the nearby Cazadero Grande (0.71433-0.71233) and Sierras Pampeanas granites (0.717 to 0.7124) point to an input by enriched sources with restricted contribution of a mantle component. Nd isotopes from a basalt from the Las Lozas section ($\varepsilon_{Nd(320)}$ with +3.11, T_{DM} with 774.6 Ma) indicates a possible asthenospheric source, with evidence for some mixture between juvenile and reworked crustal material. In contrast Sr-Nd isotopes in a rhyolite from Cazadero Grande ($\varepsilon Nd_{(t)}$ of -2.91 and -0.3, T_{DM} of 1.09 and 1.1 Ga) and of Sierra Pampeanas granites ($\varepsilon Nd_{(t)}$ of -0.6, T_{DM} of 1.19 and 1.1 Ga) suggest a crustal source with minor juvenile input. Taking in account the age difference in the region between Mississippian and the Lower Pennsylvanian magmatism, this would indicate a change in the magma source consistent with a more pronounced extensional tectonic regime for the Lower Pennsylvanian. This assumption need to be considered together with observations along a transect at 27º30'S, where the Carboniferous Eastern Sierras Pampeanas granitic rocks show, regardless of age, a greater contribution of juvenile material of mantle character to the west. Among these rocks, with a major juvenile component, are those of the Las Lozas succession as well the Cerro Gloria Granite, the eastern manifestations of the Carboniferous Eastern Sierras Pampeanas magmatism. From the foregoing emerges that the contribution of juvenile material could be continuously varied in the region through the Carboniferous, due to varying lithospheric extension. An example of this arise from the presented data of the Lozas succession, which indicate that this rocks resulted from reworking of supra-crustal material with input of juvenile magmas, linked to the change in the lithospheric extension.

Keywords: Carboniferous post-orogenic volcanism, Geochemistry, Sr-Nd isotopes, Northwestern Argentina.

RESUMEN. Magmatismo carbonífero en régimen extensional en el margen occidental de Gondwana, valle de Las Lozas, Catamarca, Argentina. La sucesión volcánica que aflora en Las Lozas, noroeste del Sistema de Famatina-sureste de la Puna (noroeste Argentina), está constituida principalmente por riolitas y en menor volumen por basaltos, traquitas y depósitos volcanoclásticos. Estas rocas, previamente consideradas de edad paleozoica inferior, son asignadas actualmente al Pensilvaniano Inferior (edad U-Pb 320 Ma). Representan una sucesión volcánica bimodal encuadrada en los campos subalcalino/toleítico (riolitas) y alcalino (basaltos y traquitas) sobre la base álcalis-sílice. Los términos básicos muestran características comparables y transicionales a MORB-toleitas de intraplaca, con una fuerte contribución mantélica y contaminación cortical. Los miembros ácidos también muestran afinidades con magmas de intraplaca, sugiriendo su derivación de la interacción de material cortical con una fuente mantélica o de una corteza juvenil esencialmente derivada del manto. La edad U-Pb de 320 Ma obtenida para la sección de Las Lozas, al igual que las edades de U-Pb 342 y 348 Ma reportadas para rocas aflorantes en la zona de Cazadero Grande, hacia el sur; junto con las edades U-Pb reportadas para granitos de las Sierra Pampeanas (332-357 Ma) confirman la importancia alcanzada por la actividad magmática carbonífera, encuadrada entre 320 y 350 Ma, en dicha región. Las bajas razones iniciales de estroncio en las rocas volcánicas de Las Lozas (0,70479-0,70164) indican contribución de un componente juvenil, mientras que las mismas relaciones observadas en las riolitas de Cazadero Grande (0,71433-0,71233) y en los intrusivos graníticos de Sierras Pampeanas (0,717-0,7124), apuntan a magmas con participación de componentes corticales. Los valores isotópicos de Nd sobre un basalto en Las Lozas ($\varepsilon_{Nd (320)}$ con 3,11, T_{DM} con 774,6 Ma) permiten argumentar una fuente astenosférica, con evidencia de mezcla entre elementos juveniles y corticales. Los isótopos Sr-Nd determinados, en cambio, para una riolita que aflora en Cazadero Grande ($\varepsilon_{Nd (t)}$: 2,91 y -0,3, T_{DM}: 1,09 y 1,1 Ga) y en granitos de las Sierras Pampeanas ($\varepsilon Nd_{(t)}$: -0,6, T_{DM}: 1,19 y 1,1 Ga) sugieren participación cortical. Dada la diferencia de edades en la región entre el magmatismo misisipiano y pensilvaniano inferior, dichas variaciones indicarían un cambio en la fuente magmática, consistente de un régimen tectónico extensional más pronunciado durante el Pensilvaniano Inferior. Esta presunción debe ser considerada teniendo en cuenta las observaciones a lo largo de una transecta a los 27°30'S, donde las rocas graníticas carboníferas de las Sierras Pampeanas Orientales muestran, sin importar la edad, un mayor aporte hacia el oeste de material juvenil de carácter mantélico. Entre estas rocas, con una mayor componente juvenil, se encuentran: la sucesión de Las Lozas y el Granito Cerro Gloria, manifestaciones occidentales de dicho magmatismo. De lo anterior se desprende que la contribución de material juvenil podría variar continuamente durante ese tiempo como respuesta a una extensión litosférica variable. Un ejemplo de esto surge de los datos de la sucesión de Las Lozas presentados, los que indican a la misma como resultado del retrabajo de material supracortical, con el aporte de magmas juveniles asociados a cambios extensionales de la litósfera.

Palabras clave: Volcanismo carbonífero posorogénico, Geoquímica, Isótopos Sr-Nd, NW de Argentina.

1. Introduction

The present study deals with the volcanic-volcanoclastic section that outcrops along the Las Lozas Valley at the northwestern of the Famatina System-southern Puna (Fig. 1), to the north of the Mississippian rhyolites reported in Cazadero Grande by Martina *et al*. (2011) and to the west of the coeval granites of the Sierras Pampeanas (Dahlquist *et al*., 2006, 2013; Grosse *et al*., 2009). The Las Lozas rocks, previously mapped as Ordovician and considered to be part of the Famatinian magmatic system (Turner, 1967; Mpodozis *et al*., 1997; Rubiolo *et al*., 2001; Coira *et al*., 2005), were recently assigned by Cisterna *et al*. (2013) and Zappettini *et al*. (2015) to the Lower Pennsylvanian based on a zircon U-Pb SHRIMP age (320±2 Ma). Both, lower Pennsylvanian and Mississippian successions are new records of the Carboniferous magmatism in the region, locate west of the small and scattered A-type granites distributed

along more than 1,000 km in the Sierras Pampeanas (Dahlquist *et al*., 2010). The geodynamic setting of the Carboniferous magmatism in the region remains controversial. It has been considered product of crustal reheating during final phase of Famatinian orogeny (*e.g.,* Grissom *et al*., 1998; Llambias *et al*., 1998; Höckenreiner *et al*., 2003; Grosse *et al*., 2009) or part of the Achalian orogen (*e.g.,* Sims *et al*.,1998; Siesgesmund *et al*., 2004; Dahlquist *et al*., 2006, López de Lucchi *et al*., 2004). Meanwhile Dahlquist *et al*., 2010 proposed that those Carboniferous granites represent a new tectonothermal event, considering their field and geochemical characteristics, indicative of an extensional within-plate setting and non-compressive tectonic regime and not syn-kinematic emplacement as has been invoked for Devonian granite of Sierras de Cordoba or San Luis (Sims *et al*.,1998; Siesgesmund *et al*., 2004).

In this paper we present, a detailed petrographic, structural, geochemical and complementary isotopic
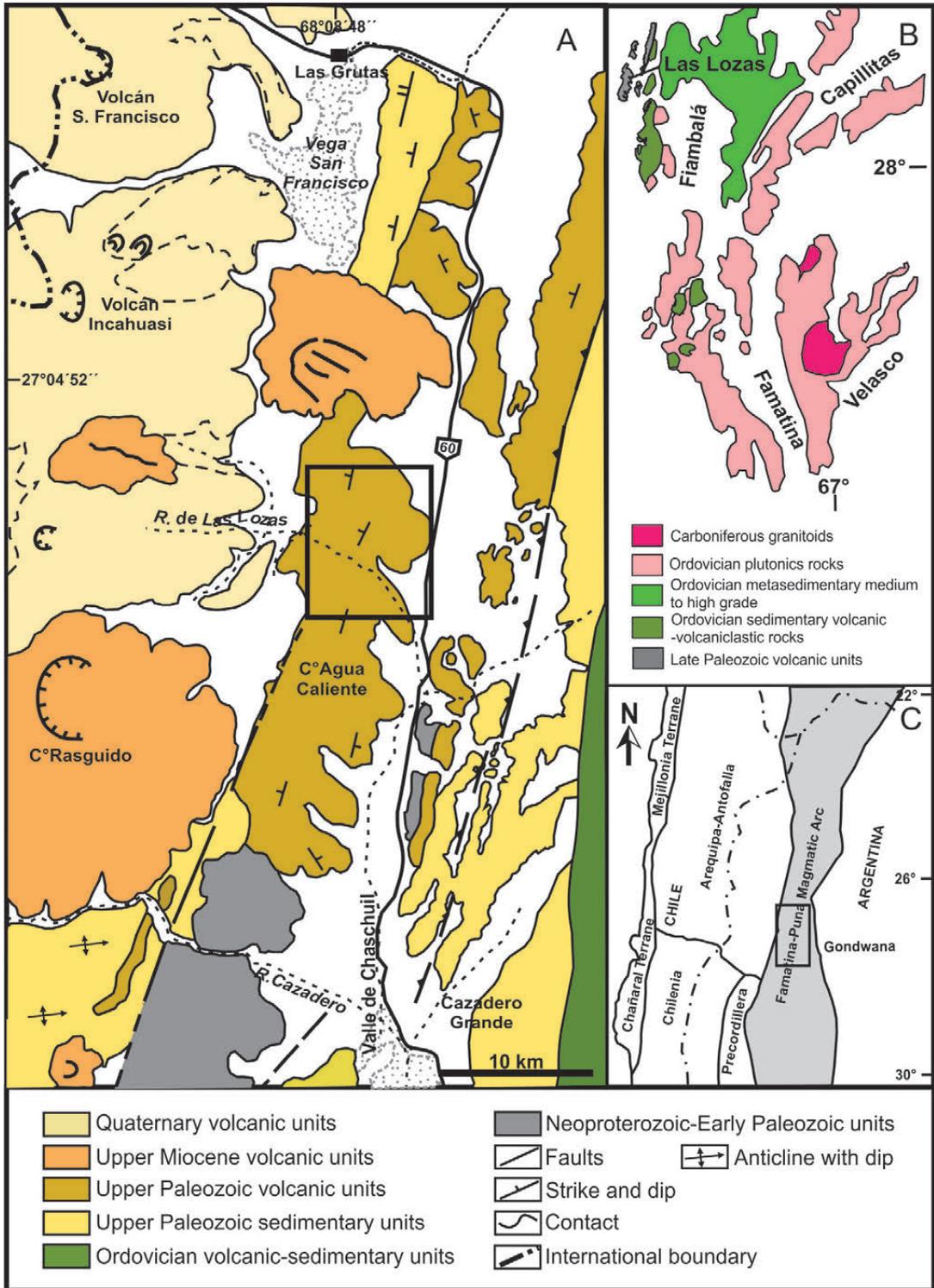
FIG. 1. **A.** Geological map of Las Lozas Valley showing the location of the studied area; **B.** Regional geological map comprising the studied area and the Sierras Pampeanas region; **C.** Geological setting of the Puna-Famatina-Sierras Pampeanas System, NW Argentina.

data of the Las Lozas rocks to place constraints on their possible sources and geotectonic setting and to analyze them in relation to A-type granites from Sierras Pampeanas and to Mississsippian Cazadero Grande rhyolites, to thereby evaluate the compositional variations in time and space through the region and so contribute to improve geodynamic models in the Proto-andean margin of Gondwana during Late Paleozoic.

2. Geologic setting

Late Paleozoic formations overlie uncomformably a deformed Precambrian to Early Paleozoic metamorphic basement, as well as Early Ordovician granitoids (*e.g.*, the Las Angosturas granodiorite) and Ordovician volcanic deposits (*e.g.*, the Suri and Las Planchadas formations) at the northwestern border of the Famatina belt in the southern Puna (NW Argentina).

The formations usually identified in this region as Late Paleozoic deposits are composed mainly by extensive siliciclastic beds (the Agua Colorada and Patquia formations, members of the Paganzo Group), assigned to the Carboniferous and Permian (Turner, 1960; Cuerda, 1965). Nevertheless a Carboniferous volcanic succession has been recently identified to the west of Chaschuil valley (Fig. 1), in Cazadero Grande, where Martina *et al.* (2011) reported U-Pb SHRIMP ages of 348±3 and 342±1 Ma and Cisterna *et al.* (2013) and Zappettini *et al.* (2015) a U-Pb SHRIMP age of about 320±2 Ma, obtained in a sample from the nearby the Las Lozas section (Fig 1). Those Carboniferous volcanic successions outcrop underlying Permian sedimentary rocks of the Paganzo Group (Seggiaro *et al.*, 2000).

3. Las Lozas section

The present paper focuses mainly on the volcanic deposits exposed along the Las Lozas Valley at the southwestern limit of Catamarca province (27º10'38.1''-27º10'115.9'' and 68º07'16.3''-68º07'11.9''; Fig. 1). The outcrops are well-preserved, allowing the detailed mapping and identification of many different volcanic rocks, lying discordantly above a metamorphic basement and covered by Late Paleozoic siliciclastic continental sequences. Our studies were centered on a profile with a thickness of about 550 m, running east to west, considered

to be free of structurally induced repetitions and characterized by the abundance of rhyolite lavas and their fragmented equivalents, together with minor intercalated occurrences of basalts-trachybasalts and also trachytes-dacites (Fig. 2).

Las Lozas section rocks are deformed, displaying rock cleavage result of ductile shear processes (Cisterna *et al.*, 2006) and on top, were gently folded and faulted during the Cenozoic (Andean) deformation. The majority of these outcrops, however, display preserved primary depositional structures (*e.g.*, spherulites, flow bands, banding) and textures some units still retain near-glassy (cryptocrystalline) domains and mafic and felsic minerals, including phenocrysts, that appear as preserved pseudomorphs variably altered to chlorite and sericite.

3.1. Lithofacies

The studied profile is characterized by an abundance of rhyolite lavas and their fragmented equivalents, together with minor intercalated occurrences of basalts-trachybasalts and also trachytes-dacites. The rocks are affected by low metamorphic grade with structures indicating localized ductile deformation (Cisterna *et al.*, 2006).

3.1.1. Effusive lithofacies
3.1.1.1. Rhyolites. This facies is present along the entire profile as flows reaching a thickness of about 25 m, bordered by brecciated monomicitic equivalents both at the top and bottom of the lavas flows. Color is brown to reddish or grey to dark grey. Predominant texture is porphyritic, with plagioclase, K-feldspar and quartz euhedral megacrysts set in a glassy, partially spherulitic microcrystalline groundmass showing well-developed flow banding. Plagioclase megacrysts, 2-5 mm in length, are blocky to lath-like, variably altered to sericite. K-feldspar may reach up to 2 cm in some rocks, showing alignment parallel to the flow direction. Quartz megacrysts (0.5 to 5 mm) are euhedral to rounded, commonly presenting resorption textures. Mafic minerals, mostly oxidized biotite as small and irregular lamellae, are scarce (<1%). Some rhyolites also present fine prismatic disoriented grains of arfvedsonite.

The groundmass consists of a finely microcrystalline quartz-feldspar mosaic, with abundant randomly oriented feldspar laths (Fig. 3a). It shows a primary banding with devitrification textures,
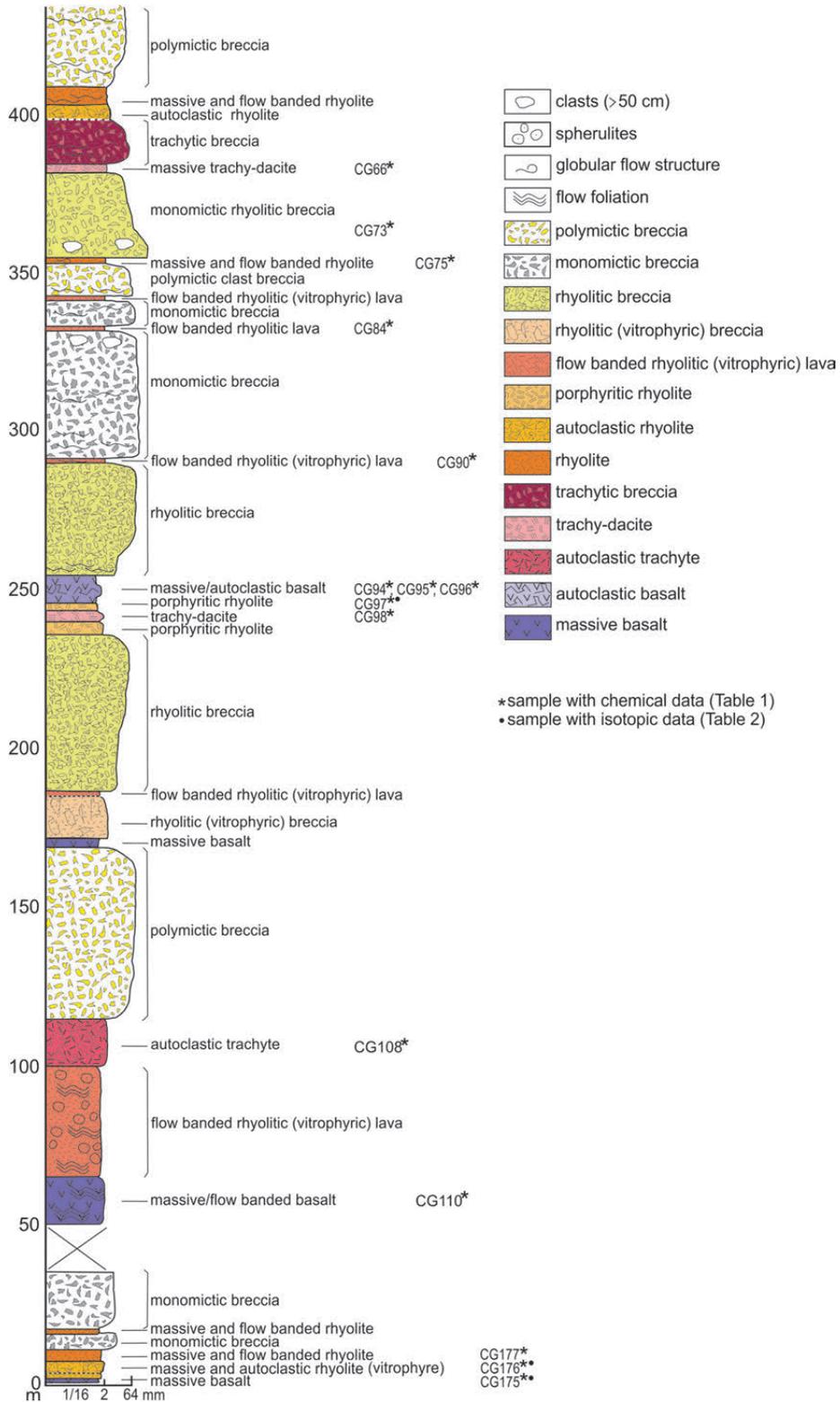
FIG. 2. Schematic log showing the internal organization of the Las Lozas section and location of studied samples.
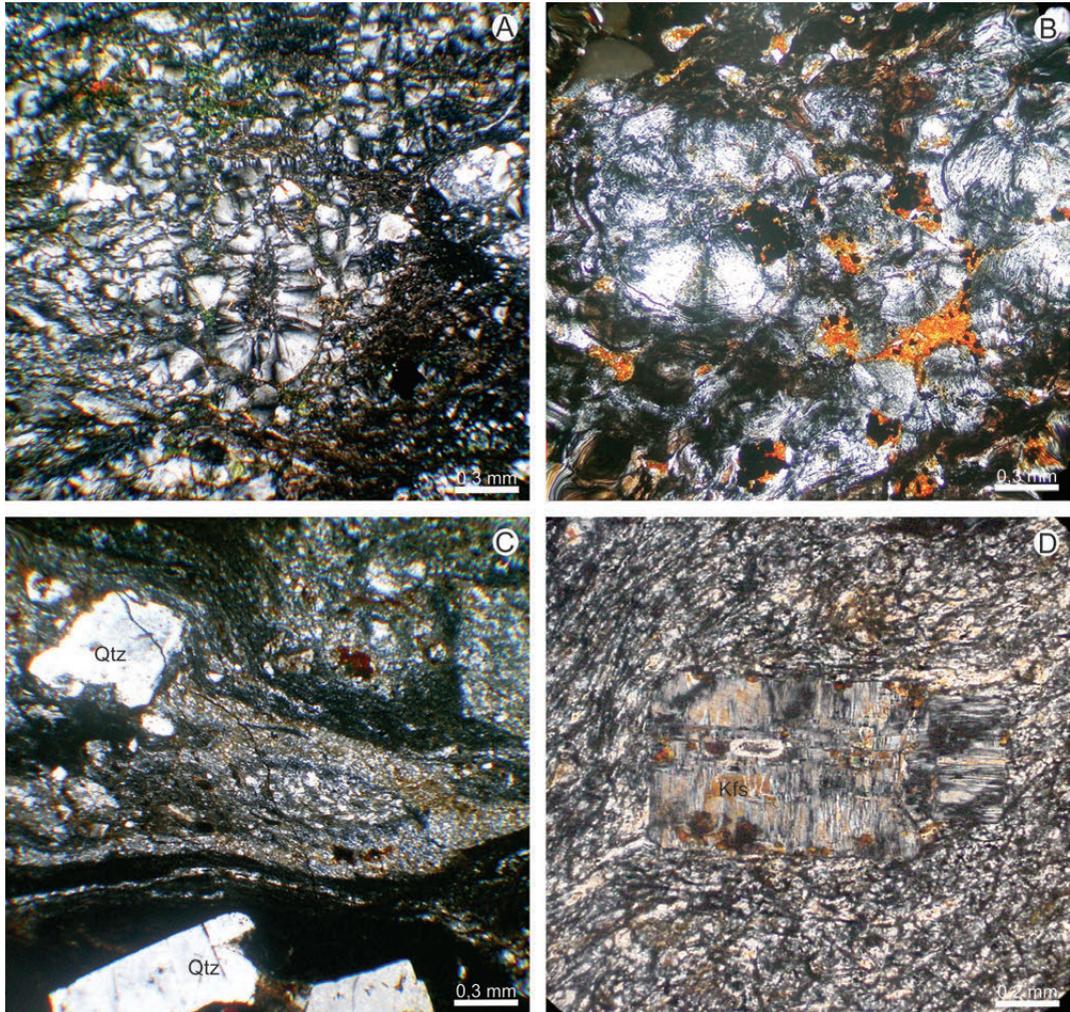
FIG. 3. Microphotograph of rhyolites *s*howing: **A.** spherulitic groundmass; **B.** displaying cryptocrystalline to glassy groundmass with flow banding; **C.** groundmass of a finely microcrystalline quartz-feldspar mosaic; **D.** phenocryst with chessboard texture, according tofoliation. Cross polarized light.

and spherulites with microcrystalline quartz and K-feldspar as micrographic intergrowths (Fig. 3b). The rhyolites presenting predominantly spherulitic texture (with or without micrographic intergrowth) probably crystallized at higher temperatures than the rocks displaying cryptocrystalline groundmass, with a smaller degree of undercooling (cf. Allen *et al.*, 2008). The last texture probably results from a devitrification process of a rapidly cooled glassy precursor (Lofgren, 1971; Murphy and Marsh, 1993). On the other hand, the formation of spherulitic to granophyric textures is consistent with a process of slower cooling (Lofgren, 1971).

Rhyolitic vitrophyres exhibit a cryptocrystalline or glassy groundmass with flow banding (Fig. 3c); in some cases showing vitrophyric layers alternating with others presenting devitrification features (fine granophyre together with spherulites).

Clear indications of deformation are distributed irregularly in several rhyolitic flows, attesting to the activity of localized ductile shear, also probably linked to different hydration conditions of the lavas. Some of the deformed rhyolitic layers present an altered groundmass with finely crystalline quartz, white mica, chlorite, opaque minerals and minor epidote, zircon and titanite, or show stretching of phenocrysts

along the direction of an incipient foliation (Fig. 3d). Autoclastic structures can be observed along the profile, coherent lavas grading transitionally into fractured autoclastic beds, always poorly sorted, with a thickness of up to 15 m, with predominance of angular to subangular rhyolitic clasts immersed in a finer-grained groundmass of fragments (Fig. 2). The blocky clasts, about 3 cm or more in size, show an arrangement with a jigsaw texture, presenting curviplanar fractures and non-quenched margins.

The features displayed by the rhyolite lavas and autobrecciated equivalents are consistent with an eruption mechanism through volcanic domes presenting coherent lava cores and brecciated margins (*e.g.*, Allen *et al*., 2008). The groundmass of the breccias, displaying a banded structure, with fragments showing spherulitic and granophyric intergrowths but also glassy and perlitic textures, suggest a high temperature environment active during their emplacement.

3.1.1.2. Trachytes to trachydacites. These rocks outcrop at the upper levels of the Las Lozas section (Fig. 2), presenting dark-colored beds up to 15 m thick. These units are lava flow mainly autobrecciated with angular clasts ranging from 3 to 10 cm in size. Their texture is porphyritic, with predominant K-feldspar phenocryts (10-15%) up to 3 mm in size, and irregular vesicles (1 to 2 mm). K-feldspar show chessboard texture. Mafic minerals are subordinate (subhedral augite and hornblende). The groundmass is greenish-brown, with a trachytic, partly glassy, texture with weakly to moderately oriented feldspar microlaths. Vesicles, filled with iron oxides and quartz, may be aligned parallel to the flow direction. The preexisting glass is converted into quartz-feldspar aggregates and/or altered into chlorite. Inclusions of subrounded to irregular lithic fragments of volcanic rocks with a very fine-grained groundmass, partly flow-banded, are also observed under the microscope.

3.1.1.3. Basalts. These rocks occur at the basal and the middle of the Las Lozas section as concordant tabular bodies, with a thickness varying between 2 and 15 m (Fig. 2). The rocks are greenish to dark grey, generally massive and porphyritic, but also fine-grained. Locally, basalts present flow banding, partly enhanced by the flow orientation of irregular vesicles (2 mm to 1 cm), and filled with chlorites and iron oxides.

The porphyritic basalts show phenocrysts (5-10%) including predominant, partly fractured, plagioclase (1-2 mm; Fig. 4a) and lesser amounts of augite (1 mm). Variolitic textures can be observed in some instances. Titan-augite, as main mafic mineral, is commonly fractured and partly altered, along fractures, to chlorite and opaque phases. The groundmass is green to brownish and the texture is usually ophitic to subophitic (Fig. 4b). Plagioclase microlites, augite grains, apatite and abundant opaque phases are also present in the groundmass, in part altered to chlorite. Glass in the groundmass is altered to palagonite. Vesicles are zoned and filled with chlorite and albite.

The basalts outcropping in the middle of the section are concordant lava flows, generally displaying autoclastic facies (Fig. 2) at their margins. Clasts, sometimes with altered margins, are angular, ranging among 3 to 5 cm, rarely reaching up to 60 cm. The autoclastic facies can be formed as a response to locally high strain rates in an already more brittle lava body, creating fragments, especially at the outer border of the flows, continually being dislodged by the lava movement (*e.g.*, McPhie *et al*., 1993).

3.1.2. Volcanoclastic lithofacies
These deposits, occur as extensive tabular bodies, represent the thickest members in the Las Lozas succession and are almost entirely composed of lavas clasts. We recognized both monomictic and polymicticbreccias (Fig. 2).

3.1.2.1. Monomicticrhyolitic breccia lithofacies. This monomictic facies, present in the entire sequence, is composed by lava clasts and forms tabular bodies with sharp boundaries, up to 50 m in thickness. It consists of poorly sorted rhyolitic angular-subangular clasts. The breccias are dominantly grayish-brown to dark grey, massive, locally with a foliated structure due to alignment of clasts by flow. Sizes of clasts vary among 1 to 5 cm, rarely reaching up to 60 cm: clast proportions may vary between 10 to 45% of the total. Clasts are rhyolitic lava fragments showing textural variations as described for the rhyolites (cf. above; such as: rhyolitic porphyritic fragments; fragments composed by a fine microcrystalline quartz-feldspar mosaic (Fig. 4c); clasts with granophyric or spherulitic textures; sometimes, clasts with flow orientation. Groundmass is microcrystalline, with flow structure, sometimes winding around crystals or lithic fragments, with appearance of pressure
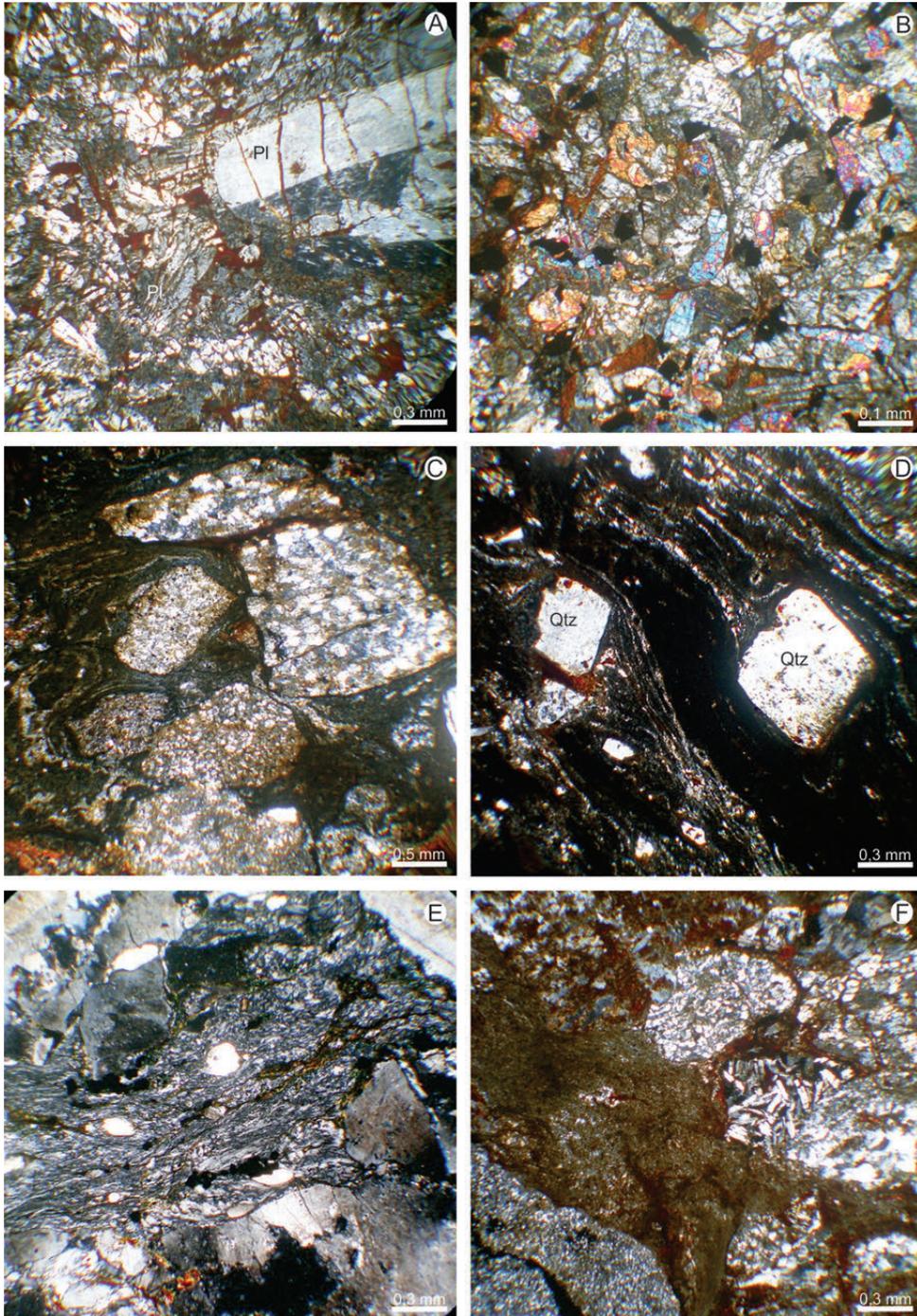
FIG. 4. Microphotograph showing: **A.** porphyritic basalt with plagioclase phenocrysts and lesser amounts of augite immersed in a groundmass of plagioclase microlites, augite grains, apatite and abundant opaque, in part altered to chlorite; **B.** basalt with ophitic to subophitic texture; **C.** Monomictic rhyolitic breccias with rhyolitic lava fragments showing textural variations like porphyritic or fine microcrystalline quartz-feldspar mosaic; **D.** groundmass of monolithic breccia, with flow structures contorting around lithic fragments and crystals with common development of foliation consisting of alternating glassy and devitrified bands; **E.** polimictic breccia with clasts of rhyolitic lavas and minor basalt clasts; **F.** banded structure in polimictic breccias with flow orientation around lithic fragments. Cross polarized light.

shadows and a foliation consisting of alternating glassy and devitrified bands (Fig. 4D). Irregular vesicles are filled with iron ore, quartz, and other secondary minerals. Upper portions of the profile may show breccias with finer clasts.

3.1.2.2. Rhyolitic vitrophyric breccia lithofacies.
This facies is represented by a single tabular body 13 m thick appearing in the upper section of the studied profile (Fig. 2), with a basal transitional contact with the underlying rhyolite and a sharp upper contact. Color is dark grey, showing a foliated structure resulting from compositional banding in the groundmass and the aligned disposition of flat rhyolitic clasts. Clasts constitute about 70 to 80% of the rock; they range in size between 1 to 3 cm, are angular, and mostly flat. Some portions of the breccias are disposed in a jigsaw arrangement, while other are only partially fractured. Under the microscope, the groundmass is frequently flow-banded, with alternating fine-grained quartz-feldspar mosaics and spherulitic bands, in part also perlithic.

3.1.2.3. Polymictic vitrophyric breccia lithofacies.
These rocks constitute the most extensive breccia deposits, crop up as tabular bodies up to 60 m in thickness (Fig. 2), with the basal and upper contacts relatively sharp. They are predominantly brown or dark grey and massive, but show locally a flow-oriented structure, evident through aligned clasts and internal flow banding (Fig. 4E). The breccias are very poorly sorted, with clast proportions reaching between 20 to 50% of the rock. Clasts are 1 to 5 cm in size and may reach up to 60 cm. The beds may show an increase in the clast size in the upper parts of the tabular bodies. Lithic angular to subangular components are usually predominant, composed mainly by rhyolitic lava fragments with minor proportions of basalt clasts (Fig. 4F). Clast proportion in these beds usually increases towards the top. Thin sections show the banded structure with flow orientation (glass or oxidized fragments flowing around lithic fragments), sometimes presenting a foliation constituted by recrystalized quartz and feldspar aggregates, with granophyric textures or with spherulites. Crystal fragments (5 to 10%) are formed by subhedral fractured feldspars and quartz, up to 3 mm in size. Lithophysae (<1%) are also observed, composed of concentric shells of finely crystalline quartz and feldspars. Irregular vesicles,

filled with quartz and iron minerals, are also present in the breccias fragments.

4. Geochemistry and Isotopic Data

The geochemical and isotopic analysis of the volcanic rocks of Las Lozas valley presented here were aimed to define the source of their magmas and to compare with Cazadero Grande rhyolites and coeval granites of Sierras Pampeanas data. As well as to provide new elements to differentiate them from the Ordovician volcanic sequences lacking stratigraphic control, outcropping at the northern portion of the Famatina System and southern Puna.

4.1. Methodology

4.1.1. Rock geochemistry of major, minor and trace elements
Analytical determinations of major, minor and trace elements from Las Lozas valley profile were performed at the XRF and chemistry-ICP laboratories of the Instituto de Geociências, University of São Paulo, Brazil.

The XRF data were obtained from prepared pressed pellets and fused glass discs. Pressed pellets were prepared from rock powders (ground to less than 200 mesh), micronized to less than 5 microns in a vibratory rod mill with ethanol, and dried overnight at 60 °C. An amount of 7,000 grams of the micronized powder was homogenized with 1,400 gram wax, and pressed for 60 seconds at 30 KPa. The fused glass discs were obtained from 1,000 g of the powder sample, weighted with a Claisse commercial flux (mixture of 67% lithium tetraborate and 33% lithium metaborate), positioned in a Pt crucible in a Claisse automatic melting machine and fused at 1,000 °C, then poured into Ptmoulds. Analytical determinations for these elements were performed in Siemens XR fluorescent equipment, using a set of 40 international rock standards to generate a reference line (for more information, see Mori *et al*., 1999).

PerkinElmer ICP equipment was used to analyze the same rock powders for the determination of most trace elements. Preparation of the solutions from powders (ground to less than 200 mesh) uses an amount of 0.04000 g of powder, dissolved with an acid mixture of HF/HNO_3 in a Parr bomb at 200 °C for 5 days. After this, HF is eliminated as SiF_4 on a hot plate and the solution diluted in the ratio 1:2000

in 0.1 N HNO_3. The reference curve was obtained preparing standard materials in the same way, for which the following reference samples were used: granites GA, GH, OU-3, and YG-1 and the basalt BE-N, besides a blank (for details, see Navarro *et al.*, 2008).

4.1.2. Strontium and neodymium isotopes

Rb-Sr analyses were madeon CG-14 (vitrophyre), 97 (rhyolite) and 176 (vitrophyre) samples at the Geochronological Research Center, University of São Paulo, Brazil (CPGeo-USP). Those analyses were made by isotope dilution following the procedures indicated in Tassinari *et al*. (1996), employing a Micromass VG-sector mass spectrometer. For the basalt CF-175, the $^{87}Sr/^{86}Sr$ isotopic ratio was measured in the same instrument, but the indicated total Rb and total Sr values were obtained by XRF. For a similar range of values, the normal precision in the Rb/Sr ratio at the CPGeo is always better than 2%. Basalt sample CG-175 was also analyzed for Sm-Nd isotopes at the CPGeo-USP, using a Finnigan-MAT multi-collector mass spectrometer, with analytical precision better than 0.002% (2σ). The methodology is described in Sato *et al*. (1995).

4.2 Results

4.2.1. Major and trace elements

The majority of the analyzed rocks can be divided into basic (41.83 to 49.97% SiO_2) or high silica (77.13 to 69.00%) groups cf. Table 1, although rocks with some intermediate compositions are also present (Table 1). On the total alkali (Na_2O+K_2O)-silica diagram (Le Bas *et al*., 1986), the felsic members fall into the rhyolite field and the subalkaline-tholeiitic series, the basic rocks plot within the alkaline basalt field and the intermediate types are alkaline trachyte and trahyandesites (Fig. 5a). On the K_2O *versus* silica variation diagram (Peccerillo and Taylor, 1976), most volcanic rocks fall in the high-K calc-alkaline and shoshonite fields (Fig. 5b); they show A/CNK ratios varying between 1.38 and 1.01, and A/NK ratios between 2.98 and 1.35, indicative of a peraluminous tendency, although some basalts have A/CNK ratios between 0.98 and 0.93. Fe_2O_3, MgO, TiO_2, CaO and P_2O_5 decrease with increasing silica. Al_2O_3 is fairly constant, while K_2O and Na_2O show a significant increase in the felsic members in comparison with abundances in the intermediate and mafic rocks. The *mg* number [(mg#=100 x Mg/Mg +Fe^{2+})] ranges from 11.59 to 35.31 in the basalts, 1.19 to 2.96 in the trachytes and trachydacites, and among 0.47 to 8.28 in the rhyolites.

In the ratio Zr/TiO_2 *versus* Nb/Y diagram (Winchester and Floyd, 1977), an effective discriminant for magmatic types, basic samples are classified as basalts, trahyandesites, and commandites/pantellerites, the majority of them lying on the limit between the subalkaline and alkaline fields, while andesites and rhyodacites/dacites, plotted within the subalkaline field (Fig. 5C).

4.2.2. Basalts

These rocks are enriched in TiO_2, Na_2O, K_2O and P_2O and show higher of LILE (K, Rb, Ba), HFSE (Zr, Y) and REE (Table 1) contents in comparison with the values observed in the Ordovician tholeiitic basalts (Cisterna *et al*., 2010) (Figs. 6A and 7A). The average value of *mg*# is 22.03 for the Las Lozas basalts, much lower than the estimated *mg*# for primitive mantle-derived basaltic magmas (Talusani, 2010). In fact, the *mg*# numbers (from 11.5 to 35.3), and contents of Ni (21 to 101 ppm), Cr (23 to 131) and MgO (2.1 to 7.82%) are lower than the ones to be expected for basalts derived from a primitive mantle, an indication of more evolved compositions. Therefore, these basalts were probably modified by fractional crystallization and crustal assimilation processes during their ascent (De Paolo, 1981). They correspond on the other hand, high-Ti types with Ti/Y ratios ranging from 621.93 to 911.7, TiO_2 content between 2.58% and 4.53%, characteristic of high-Ti basalts (Shellnutt and Jahn, 2011). They show an average Fe_2O_3/TiO_2 ratio of 4.43, also presenting abundances of trace elements compatible with high-Ti features (*e.g.*, Zr between 160 to 462 ppm, Nb from 13 to 28.3 ppm, Hf from 3.75 to 6.9 ppm, and Th from 1.71 to 3.18 ppm). Their chondrite-normalized REE patterns (Fig. 6A) are rather flat, with Sm/Yb_N around 3.1-3.3 and with La/Yb_N around 5.7 to 6.7, with a slight enrichment in LREE and no Eu anomaly, thus precluding fractionation of feldspars. The MORB-normalized pattern (Pearce, 1983; Fig. 7A) shows a slight enrichment in LILE (K, Rb, Ba) and a significant depletion of Sr, but also Th enrichment, with a slight depletion of Nb and Ta relative to the adjacent Th and Ce. Nb and Ta anomalies are noted, as well as a moderate enrichment in LREE. These features are

TABLE 1. CHEMICAL ANALYSES OF THE STUDIED VOLCANIC ROCKS FROM LAS LOZAS SECTION.

Sample	CG73	CG84	CG90	CG95	CG97	CG98	CG108	CG110	CG175	CG176	CG177	CG66	CG75	CG94	CG96
Major	*oxides*	*wt%*													
SiO_2	69	75.49	77.12	45.6	76.19	63.51	63.82	46.15	42.83	75.64	76.27	65.64	74.5	49.97	47.63
TiO_2	0.521	0.154	0.173	3.991	0.205	0.658	0.692	2.829	4.326	0.262	0.32	0.562	0.263	2.585	3.954
Al_2O_3	12.33	8.26	10.15	12.97	9.9	14.14	14.01	13.49	13.21	9.46	11	14.38	10.86	12.92	13.28
Fe_2O_3	6.44	6.87	3.15	15.39	4.72	7.94	7.48	13.57	16.86	6.03	3.97	7.18	3.6	14.89	15.26
MnO	0.15	0.07	0.03	0.23	0.85	0.19	0.18	0.19	0.23	0.07	0.05	0.14	0.04	0.32	0.25
MgO	0.25	0.11	0.11	4.43	0.45	0.16	0.24	7.82	4.78	0.03	0.34	0.091	0.04	2.1	4.18
CaO	0.54	0.25	0.21	8.49	0.76	0.85	1.91	7.34	8.42	0.32	0.28	0.4	0.17	6.49	7.08
Na_2O	4.43	3.16	2.9	2.91	3.46	4.65	4.92	2.98	2.79	3.5	4.17	4.45	4.39	2.09	3.54
K_2O	4.32	3.95	4.79	2.31	3.51	5.38	5.01	1.44	2.15	3.25	3.5	6.1	3.61	4.75	2.42
P_2O_5	0.09	0.01	0.02	0.8	0.01	0.11	0.15	0.67	1.34	0.01	0.05	0.01	0.01	1.22	0.83
LOI	0.46	0.38	0.5	2.17	0.36	1.28	0.56	2.94	2.36	0.16	0.4	0.63	0.363	2	2.13
Total	98.53	98.7	99.15	99.21	99.65	98.87	98.97	99.42	99.29	98.74	100.35	99.64	97.84	99.33	100.55
Trace	*elements*	*ppm*													
Ba	917	158	192	569	115	195	940	383	429	92	148	218	88	726	596
Hf	20.3	86	49.1	3.75	63.9	18.3	13.3	4.45	4.63	64	44.6	15	49	6.9	4.91
Nb	70	212	145	17.5	94.5	91.6	51.1	18.3	28.3	177	128	69	124	15	13
Zr	849	3,838	1,838	160	2,766	799	581	191	191	2,758	1,814	574	1,483	462	286
Y	93	379	211	33	257	80.4	78	28	41.7	263	185	78	163	35	26
Sr	41	18	17	478	58	97	57	284	345	34.3	20	10	17	153	512
Rb	83	92	123	65	73	125	98	39	103	68	75	91	78	170	116
Cs	0.73	0.19	0.39	1.69	0.57	2.73	2.03	0.55	2.45	0.28	0.26	1.28	0.51	5.49	2.08
Ni	4	6	4	21	4	3	4	101	39	4	5	-	4	-	2
Co	25	5	5	36	29	28	24	54	41	5	5	0.53	6	28	49
Cr	10	12	12	30	12	4	12	131	51	4	12	3.71	3	0.5	23
Th	17.3	55.7	45.4	1.71	43.6	7.78	10.5	1.75	1.97	38.7	30.9	10.4	34.5	3.18	2.25
U	3.7	12.8	10.2	0.54	9.82	2.28	2.88	0.44	0.7	10.8	8.54	1.58	7.4	0.43	0.48
Ta	4.41	17.9	9.97	0.88	16.2	7.24	3.1	0.89	1.95	12.9	10.5	4.61	9.73	1.7	1.47
Sc	13	13	13	37	3	5	13	27	33	3	13	1.8	0.22	35.9	35
Zn	139	593	217	119	222	160	119	115	135	247	206	189.2	171.7	126	126
Ga	33	42	36	21	22	38	35	19	23	44	44	-	-	-	-
V	14	8	12	12	16	8	9	226	286	2	18	35	18	28	361
La	94.2	359	86.8	21.6	250	83.6	70.1	23.2	29.6	287	90.2	77.5	122.5	42.9	32.8
Ce	208	768	198	48.4	450	164	149	51	62.8	533	228	169	308	104.5	61.5
Nd	96.7	335	102	30.9	236	93	73.4	31.3	42.1	269	100	90.6	135	80.4	44.2
Sm	19.6	70.5	27.9	7.32	49.9	18.4	15.3	6.97	9.83	50.7	25.2	18.4	30.2	14.5	10.7
Eu	3.49	3.93	0.28	3.33	1.09	1.74	4.37	2.54	3.98	1.97	0.86	2.79	1.43	6.23	4.13
Dy	15.9	65.9	34.2	5.98	51.2	16.1	12.7	5.38	7.75	25.37	29.6	18.4	35.4	11.9	7.53
Yb	8.97	35.8	19.7	2.56	30.7	9.2	6.73	2.35	3.06	29.4	17.8	8.9	18	4.66	3.72
Pr	25	88.2	26.3	6.84	59.5	21.7	18.5	7.18	8.81	67.2	26.1	-	-	-	-
Gd	18.2	68.2	31.6	7.63	39.9	14.8	14	6.87	9.05	45.4	27.4	-	-	-	-
Tb	2.77	11.2	5.67	1.09	7.99	2.63	2.22	0.98	1.32	8.66	4.9	2.89	5.32	1.93	1.35
Ho	3.37	14.2	7.48	1.21	11.1	3.24	2.68	1.1	1.6	10.5	6.67	-	-	-	-
Er	9.09	38.4	20.4	3	27	7.73	7.06	2.74	3.77	26.6	18.2	-	-	-	-
Tm	1.41	5.85	3.21	0.44	4.14	1.16	1.09	0.4	0.47	3.97	2.91	-	-	-	-
Lu	1.34	5.06	2.76	0.38	4.64	1.56	1	0.35	0.48	4.38	2.49	1.37	2.63	0.725	0.49
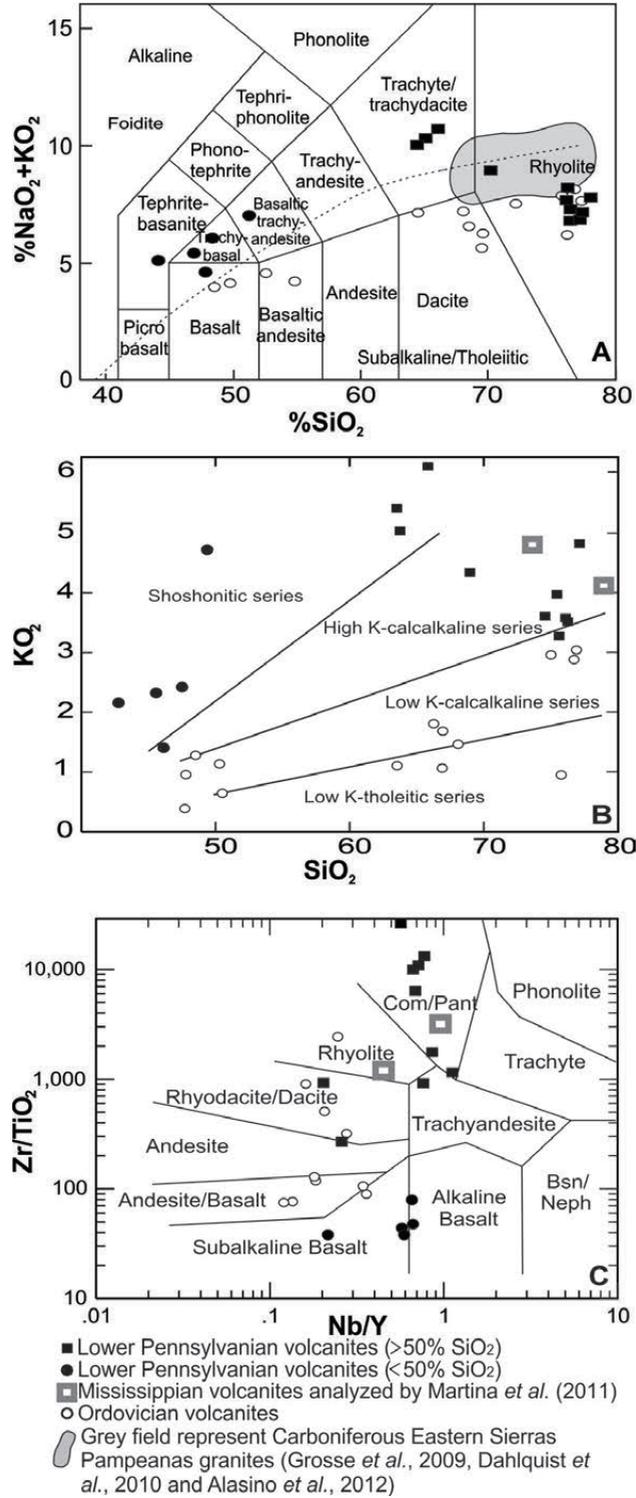
FIG. 5. Diagrams from the Las Lozas volcanic rocks: **A.** TAS (Le Bas *et al*., 1986); **B.** SiO$_2$ *versus* K$_2$O (Peccerillo and Taylor, 1976); and **C.** Diagram Zr/TiO$_2$ *versus* Nb/Y (Winchester and Floyd, 1977). The boundary between alkaline and subalkaline series (dashed line in a) is after Irvine and Baragar (1971).
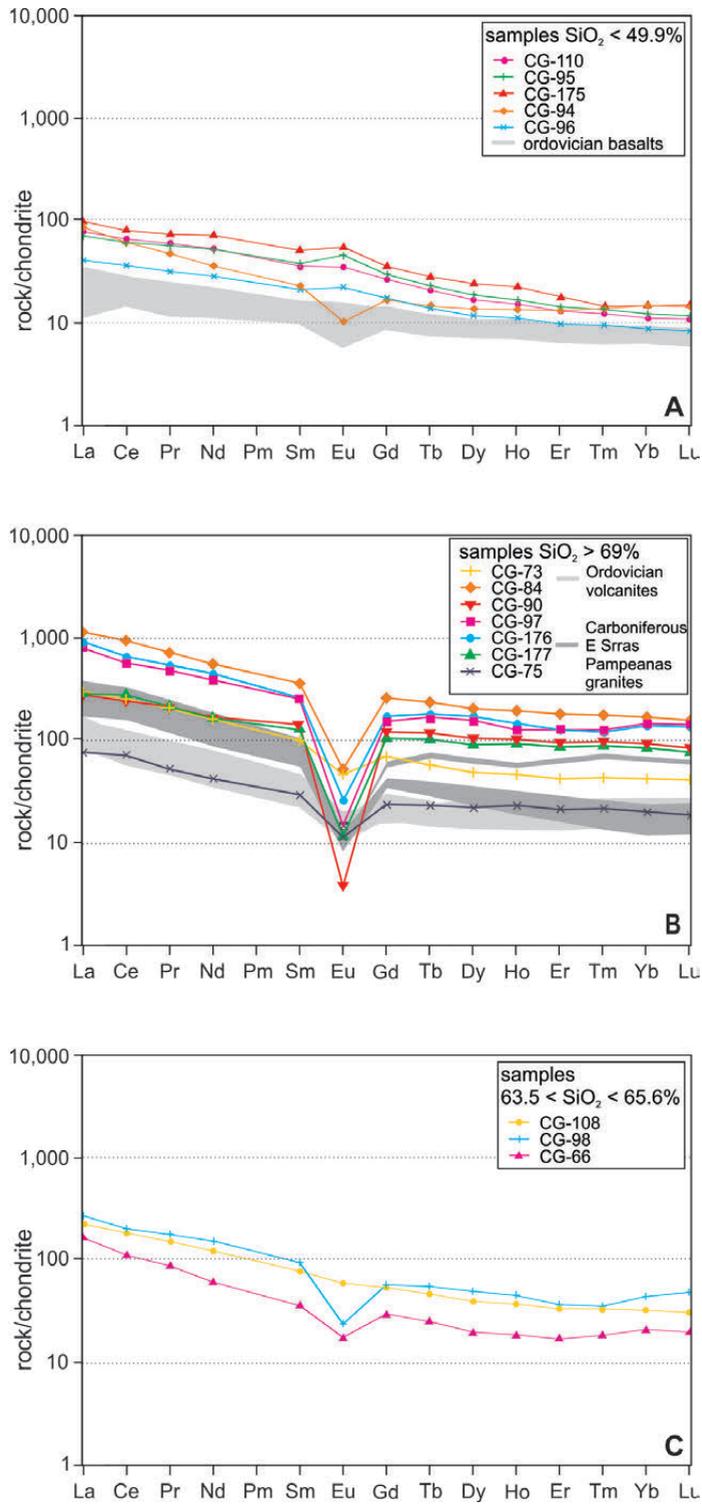
FIG. 6. Chondrite-normalized (after Boynton, 1984) REE diagram of the volcanic rocks of Las Lozas section; **A.** samples <49,9% SiO$_2$; **B.** samples >69% SiO$_2$; **C.** samples 63,5%-65,5% SiO$_2$. Gray shaded areas correspond to Ordovician volcanic rocks of Famatina reported by Cisterna *et al*. (2010) and to Carboniferous E Sierras Pampeanas granites (Grosse *et al*., 2009; Dahlquist *et al*., 2010).
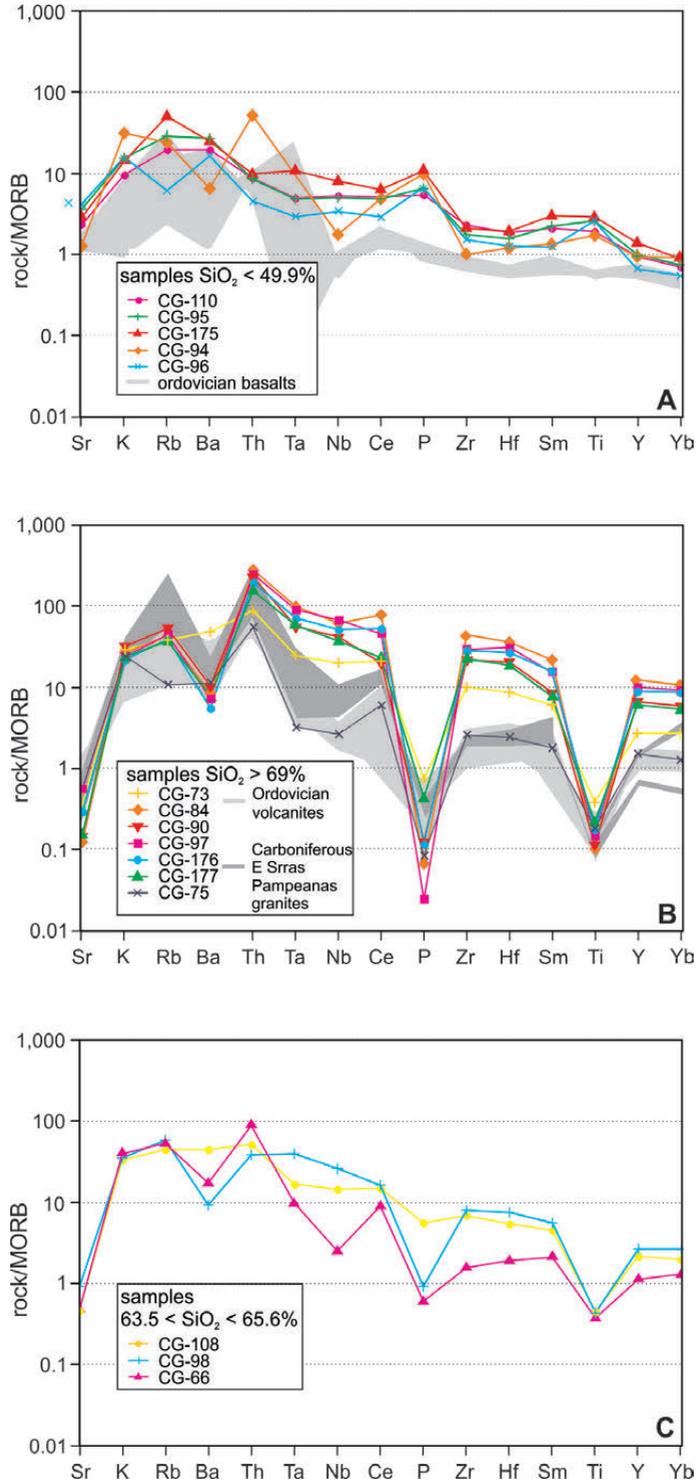
FIG. 7. Multi-element variation diagram, normalized to MORB (Pearce, 1983), of the studied volcanic rocks of Las Lozas section: **A.** samples <49,9% SiO_2; **B.** samples >69% SiO_2; **C.** samples 63,5%-65,5% SiO_2. Gray shaded areas correspond to Ordovician volcanic rocks of Famatina reported by Cisterna *et al*. (2010) and to Carboniferous E Sierras Pampeanas granites (Grosse *et al*., 2009; Dahlquist *et al*., 2010) .

comparable to patterns shown by transitional MORB basalts and within-plate tholeiites from attenuated continental terranes (Pearce, 1996), including contribution of a mantle source affected by crustal contamination during the genesis of magmas. In the case of Ordovician basalts the Nb and Ta depletion relative to Th and Ce is marked giving indication of a subduction component (Fig. 7A).

In the tectonic triangular discrimination diagram Zr/4-Nbx2-Y (Meschede, 1986) the basalts also show a transitional position within the intraplate alkali basalt field (AII), near the limit of the plume-enriched MORB field (B=PMORB). Only one sample lies in the volcanic arc basalt field (D=VAB, Fig. 8A). On the Th-Hf/3-Ta and Th-Zr/17-Nb/16 diagrams (Wood, 1980; Fig. 8B, C), these samples plot within the E-type MORB and WPT fields. The within-plate characteristics are also pointed out by the La/Ta (average of 22.66) and Ba/Ta (average of 433.58) ratios. Meanwhile, the Ordovician basalts plot in the volcanic arc and PMORB fields in the first diagram and in the volcanic arc fields in the other two.

4.2.3. Rhyolites and trachytes

The high silica rocks show an average SiO_2 content of 74.89% (rhyolites) and 64.32% (trachytes) and *mg* numbers of 3.64 for rhyolites and 2.0 for trachytes and contents of Al_2O_3=10.28%, 14.18%, TiO_2=0.27%, 0.64, and Na_2O+K_2O =7.59%, 10.2% respectively. Some trace elements such as Cr, Y and Zr increase with the increase in silica content (Cr, from 6.6 ppm in trachytes to 9.3 ppm in rhyolites; Y, from 78.8 to 185.2 ppm; Zr, from 629 to 2,162.7 ppm), while Ba, Rb and Sr tend to decrease (Ba from 448.6 in trachytes to 247 ppm in rhyolites; Rb from 102 to 86.1 ppm; Sr from 59 to 29.3 ppm).

The chondrite-normalized patterns for rhyolites display an enrichment in LREE (La/Yb$_N$=3.0 to 6.8) relative to the HREE with Sm/Yb$_N$=1.5 to 2.1 (Fig. 6B). They show a strong Eu anomaly (Eu/Eu*=0.03 to 0.53), an indication of significant feldspar fractionation, probably during ascent. In contraposition the Carboniferous Eastern Sierras Pampeanas granites show in most cases high enrichment in LREE (La/Yb$_N$=8.5 to 13.3) and higher HREE with Sm/Yb$_N$=2.5 to 4.1. A MORB-normalized pattern shows in the rhyolites an enrichment in some LILE (Rb and K), but also a significant depletion in Sr and Ba, the last parameters indicating probably also fractionation of feldspars (Fig. 7b). Th and Ce

• Lower Pennsylvanian basalts (49.9 < % SiO2)
○ Ordovician basalts
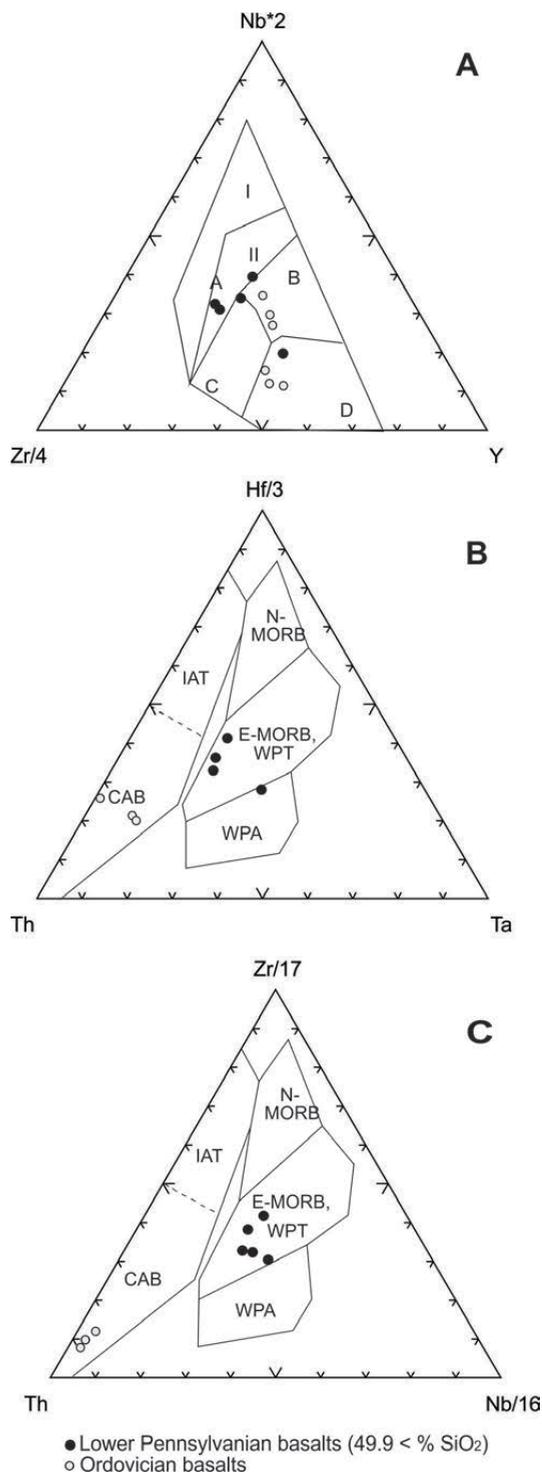
FIG. 8. Basalts from Las Lozas section and Ordovician basalts from Famatina (Cisterna *et al.*, 2010) plotted in the tectonic discrimination diagrams: **A.** Zr/4-Nbx2-Y (Meschede, 1986); **B.** Th-Hf/3-Ta and **C.** Th-Zr/17/Nb/16 diagrams (Wood, 1980).

are relatively enriched, in comparison with Nb and Ta, and is observed enrichment in Zr, Hf, Sm, Y and Yb, as well as strong negative anomalies in P and Ti, signs of interaction of a mantle source with the crust, Meanwhile the Carboniferous Eastern Sierras Pampeanas granites show a lower negative anomaly of Ta and Nb and less enrichment in Zr, Hf, Sm, Y and Yb , with minor negative anomalies in P and Ti, pointing to a less interaction with the mantle.

The chondrite-normalized pattern for the intermediate rocks shows a slight enrichment in LREE (La/Yb$_N$=5.9-7.1) relative to the HREE, with Sm/Yb$_N$=2.1-2.3, and practically no Eu anomaly (Eu/Eu*=0.32-0.91) (Fig. 6c). The MORB normalized pattern for these rocks displays an enrichment in LILE (K, Rb) and a significant depletion in Sr; Ba is variable (Fig. 7c). Th, Ta, Nb and Ce are also moderately enriched, as well as Zr, Hf, Sm, Y and Yb; Nb contents are variable, and may present negative anomalies. Ti and P also show depletion and negative values, but less pronounced than the ones found in the rhyolite members. The intermediate volcanic rocks present characteristics that lie between those observed in basalts and rhyolites.

Both rhyolites and trachytes show very low Th/Ta ratios (1.07 to 4.55), coinciding with values found in within-plate zones (WPVZ; Gorton and Schandl, 2000). The within-plate nature of these magmas is

also indicated by the Th/Yb (1.17-2.3) and Ta/Yb ratios (0.51 on average; cf. Gorton and Schandl, 2000), consistent with the results observed in the tectonic discrimination diagrams of Pearce *et al.* (1984) (Fig. 9a, b). In these last referred diagrams the Carboniferous Eastern Sierras Pampeanas granites and rhyolites, as Cazadero Grande rhyolites, plot in the within-plate field, in contraposition to Ordovician volcanic rocks framed in the field of volcanic arc-syncollision granites (Figs. 9a and b).

4.2.4. Strontium and neodymium isotopes

^{87}Sr/^{86}Sr isotopic ratios of selected samples from Lozas Valley profile as: CG-97 (rhyolite) and CG-176 (vitrophyre) were determined as well as the Sm-Nd ratios for basalt sample CG-175. The analytical work was done in order to pinpoint an additional information on the magma source of the volcanism recorded in Las Lozas valley, for which has been recently obtained an U-Pb SHRIMP age of 320 Ma and Hf data (Zapettini *et al.*, 2015) that signalize a juvenile sources of Cryogenian age for that volcanism. The ^{87}Sr/^{86}Sr and ^{147}Sm/^{144}Nd determined ratios are also supporting data to counterpose Mississippian of lower Pennsylvanian magmatism.

The calculated Sr initial ratios for the rhyolites CG-97 (^{87}Sr/^{86}Sr=0.70164) and CG-176 (^{87}Sr/^{86}Sr=0.70287) and basalt sample CG-175 (^{87}Sr/^{86}Sr=0.70479)
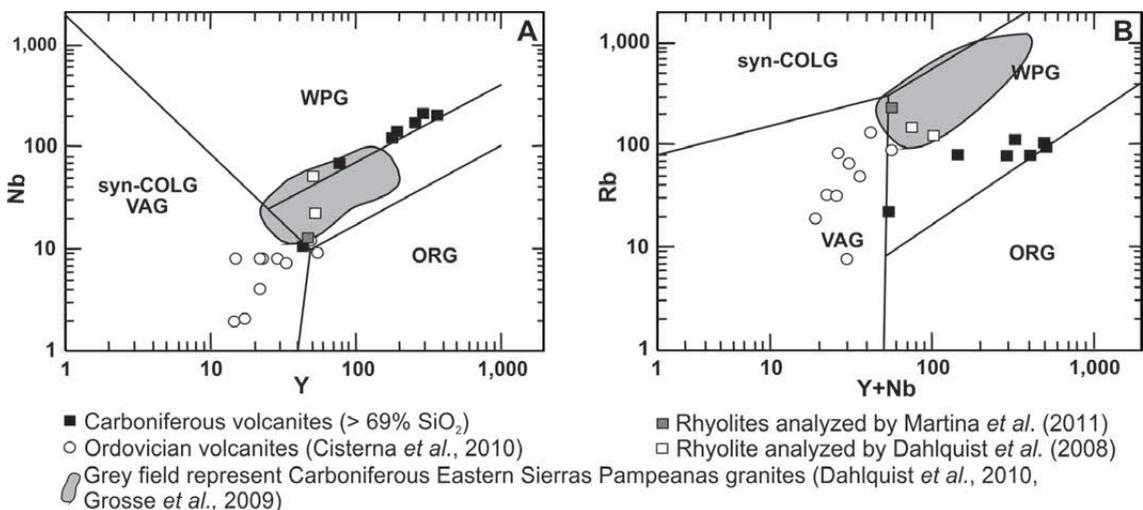
FIG. 9. Y *versus* Nb and Y+Nb *versus* Rb tectonic discrimination diagrams (Pearce *et al.*, 1984) for the analyzed rhyolites. The Lower Pensylvannian rocks and Carboniferous E Sierras Pampeanas granites plot in the within plate granites field (WPG) unlike the Ordovician samples, which mostly plot in the volcanic arc field (VAG). Gray shaded areas are the Ordovician felsic volcanics of Famatina.

for an age of 320 Ma, considering U-Pb SHRIMP age determined in the study section, are very low (Table 2) and could correspond to a mantle source indicating a clear predominance of a juvenile component, in agreement with previous conclusions of Zapettini *et al*. (2015).

Likewise the positive value $\varepsilon Nd_{(320\ Ma)}$=+3.11 of the CG-175 basalt (Table 2) suggests that the parental basaltic magma was originated within the asthenospheric mantle

Moreover if the Sr and Nd parameters of the CG-175 basalt are plotted in a $\varepsilon_{(Nd)}$ *versus* $^{87}Sr/^{86}Sr$ diagram, its parental magma would be located close to the Mantle array (Fig. 10). Moreover, the Sm-Nd model T_{DM} age of 774.6 Ma indicated above is an evidence of assimilation of a minor amount of reworked material during the rise of the magma through the continental crust.

In comparison, Sm-Nd isotopic analyses of the rhyolites from the Cazadero Grande region suggest a crustal source with some juvenile input, showing $\varepsilon Nd_{(t)}$ between -2.91 and -0.3, and T_{DM} ages between 1.09 and 1.1 Ga (Martina *et al*., 2011). Similar conclusions can be drawn (Fig. 10) from data of Sierras Pampeanas Carboniferous granites with $\varepsilon Nd_{(t)}$ between -0.6 and -3.6 and T_{DM} ages of 1.2 to 1.4 Ga, (Groose *et al*., 2009; Dahlquist *et al*., 2013) .

5. Disscusion

The distinctive characteristics of the Las Lozas volcanic sequence formed predominantly by rhyolites, with basalts and intermediate rocks as minor members give indications of the nature of the components,

emplacement and environmental conditions. In this regard the association, within the acid members, of porphyritic and vitrophyric lavic rhyolites with their volcanoclastic breccias (autoclastic lavas; monomictic rhyolite and vitrophyre breccias) is consistent with the eruption mechanism of central lavas domes, consisting of a massive and coherent central part and crumbling outer domains, all mobilized to form extensive flows that resulted in the deposition of large tabular bodies of intermingled coherent and brecciated members. The dominance of rhyolitic lithic clasts in the polymictic breccias lithofacies suggests explosive eruptions that destroyed rhyolite lava domes. In some cases the breccia facies may be inferred that are above or very close to their source vents. The matrix of these breccias, showing spherulitic and granophyric textures, flow banded compositional structures with abundant glass and perlitic fragmentation may suggest high temperatures during their development (cf. Allen *et al*., 2008).

Basalts, together with the equivalent breccias (10% of the mapped section) are present as concordant lava flows, generally displaying autoclastic facies at their margins indicating locally high strain rates in an already more brittle lava body during continuous effusion (cf. McPhie *et al*., 1993). Trachytes to trachydacites and equivalent breccias show similar characteristics.

The association in the stratigraphic column of rhyolites with their volcanoclastic breccias, followed by minor basaltic and intermediate lavas suggest episodic eruption pulses triggering instabilities in the volcanic edifices and degradation of their flanks, with emission of lava and breccia flows and concomitant

TABLE 2. Rb-Sr AND Nd-Sm ANALYTICAL DATA OF FOUR SELECTED SAMPLES FROM THE STUDIED PROFILE (SEE FIGURE 2 FOR LOCATION).

Sample	Whole rock	Lab number	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	2σ error	$^{87}Sr/^{86}Sr$	2σ error	$(^{87}Sr/^{86}Sr)_0$ for 320 Ma
CG-175	Basalt	5664	103.0	345.0	0.864	0.026	0.708526	0.00006	0.70479
CG-176	Vitrophyre	15946	64.39	32.59	5.730	0.045	0.728970	0.00004	0.70287
CG-97	Rhyolite	15947	80.6	57.90	4.037	0.119	0.720024	0.00004	0.70164

Sample	Whole rock	Lab number	Sm,ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	2σ error	$^{143}Nd/^{144}Nd$	2σ error	εNd (zero)	εNd (320 Ma)	f^{Sm-Nd}	T_{DM} (Ma)
CG-175	Basalt	5664	9.830	42.100	0.4412	0.00002	0.512681	0.00001	0.84	[+ 3.11]	[-0.28]	774.6

(1) CG-97 - porphyritic rhyolite; (2) CG-176 - vitrophiric rhyolitic lava; (3) CG-175 - massive basalt.
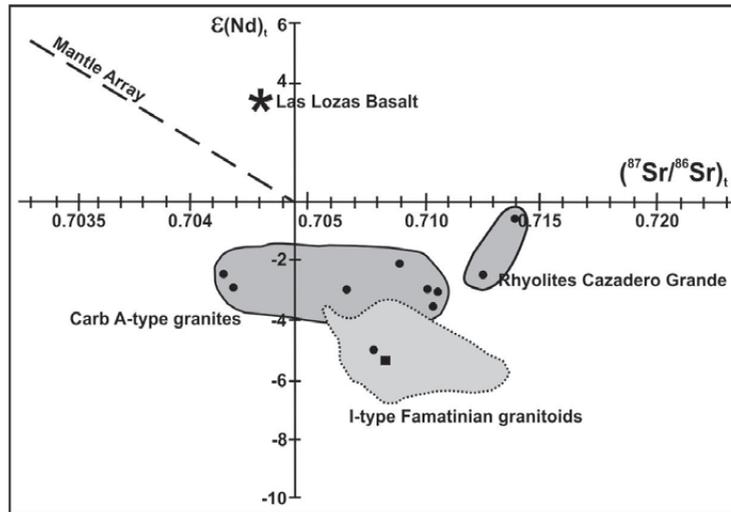
FIG. 10. εNd *versus* (^{87}Sr/^{86}Sr)t for las Lozas Basalt, rhyolites from Cazadero Grande, Carboniferous E Sierras Pampeanas granites and I type Famatinian granitoids. Data from Pankhurst *et al*. (1998), Dahlquist and Galindo (2004), Dahlquist *et al*. (2010), Martina *et al*. (2011).

collapse of the central lava domes. Although the vent sources for these lavas have yet to be identified. By other terranes, Allen and McPhie (2002) suggested that widespread outflow would be promoted by eruption from several vents along a fissure rather than from point-source vents, a relationship that is well demonstrated in flood basalt provinces (*e.g.*, Self *et al*., 1996).

From a chemical point of view, the Las Lozas rocks plot in diagrams in the subalkaline/tholeiitic (rhyolites), alkaline basalts (basalts) and alkaline (trachytes) fields. They are mainly peraluminous, with the exception of a few metaluminous basalts.

The acid terms show chemical affinities with the Mississippian volcanic rocks that outcrop in the Cazadero Grande area and with the Carboniferous Eastern Sierras Pampeanas granites, showing all mainly a subalkaline trend (*e.g.*, Fig. 5).

In regard to the Ordovician volcanic succession, they display a subalkaline trend, with medium to low K and also reach the tholeitic field (Fig. 5); the members basic are characterized by their low content of Ti.

The geochemical characteristics of the basalts are comparable to those of transitional MORB rocks and within-plate tholeiitic basalts from attenuated continental margins, where their mantle source is affected by crustal contamination. Moreover, the average *mg* numbers, as well as the Ni and Cr

contents, are much lower than those to be expected from basalts derived from a primitive mantle and they indicate a more evolved magma type, subjected to fractional crystallization and interaction with crustal material.

In the case of Ordovician basalts they form volcanic arc tholeiitic and MORB series. Such features indicate geotectonic environments linked to marginal basins (Cisterna *et al*., 2010). In addition their Zr-Ti-Y contents suggest a highly depleted mantle as their source but the enrichments in Cs, Rb, Ba and Th and negative anomaly of Nb in relation to Th and Ce reflect a subduction component and/ or crustal assimilation processes.

The geochemical features of the rhyolites are those of within-plate magmas, and their composition suggest a derivation from continental crustal material with mantle source interaction or a juvenile essentially mantle derived crust. The two rhyolite samples from Cazadero Grande presented by Martina *et al*. (2011), as the Carboniferous Eastern Sierras Pampeanas granites show geochemical affinities with Las Lozas rhyolites in the Y *versus* Nb and Y+Nb *versus* Rb tectonic discrimination diagrams (Pearce *et al*., 1984) plotting in the within plate granites field (Fig. 9). Meanwhile the acid Ordovician volcanic rocks lies in the volcanic arc field (VAG).

Calculated ^{87}Sr/^{86}Sr initial ratios of 0.70164-0.70287 for an age of 320 Ma for the rhyolites of

the Las Lozas section suggest a clear predominance of a juvenile component. This is in contrast with the data obtained for the Cazadero Grande Mississippian rhyolites, exhibiting $^{87}Sr/^{86}Sr$ initial ratios of 0.71433 to 0.71233 for an age of 345 Ma (Martina *et al.*, 2011), and for coeval Sierras Pampeanas granites with $^{87}Sr/^{86}Sr$ initial ratios of 0.7044 to 0.7114 for an age of 345-354 Ma (Dahlquist *et al.*,2010). The last two magma types were probably extracted from a strongly enriched reservoir with negligible mantle contributions. It is also possible to differentiate the Pennsylvanian Las Lozas rocks from the Mississippian Cazadero Grande volcanism and the coeval Sierras Pampeanas A-granites in terms of their source, since the $\varepsilon Nd_{(t)}$=+3.11 in a Las Lozas basalt suggests that its parental magma originated within the asthenospheric mantle. In contrast, the equivalent data from Cazadero Grande (*e.g.*, $\varepsilon Nd_{(t)}$ of-0.3 and 2.91 , Martina *et al.*, 2011) and the main Carboniferous Sierras Pampeanas A-type granites (*e.g.*, $\varepsilon Nd_{(t)}$ of -0.5 and -3,6; Grosse *et al.*, 2009, Dahlquist *et al.*, 2013) seem to indicate a crustal source with some juvenile input.

Few isolated cases in a transect at 27º30' S show a greater contribution of juvenil material in their generation as Cerro La Gloria (353 Ma), in the west of the Eastern Sierras Pampenas ($\varepsilon Nd_{(t)}$ between +0,46 and -0,58, Alasino *et al.*, 2012) and Guandacolinos granite (314 Ma, $\varepsilon Nd_{(t)}$ between+1.7 and +0,6, Varela *et al.*, 2004) and Cerro Veladero plutons (311 Ma; $\varepsilon Nd_{(t)}$ between+1,15 and -0,8, Cingolani *et al.*,1993), in the east of the Western Sierras Pampeanas. On this basis, Alasino *et al.* (2012) concluded that the Carboniferous granitic rocks show, in that section, a greater contribution of juvenile material of mantle character to the west.

6. Conclusions

Las Lozas Pennsylvanian volcanic succession belongs to a bimodal magmatic series represented by subalkaline/tholeiitic rhyolites and alkaline basalts and trachytes. The geochemical characteristics of the basalts are comparable to those of transitional MORB rocks and within-plate tholeiitic basalts from attenuated continental margins, where their mantle source is affected by crustal contamination. Alike the rhyolites show within-plate signature, suggesting a juvenile component of their magma source as well as interaction with crustal material or a juvenile essentially mantle derived crust. Their $^{87}Sr/^{86}Sr$ initial ratios of 0.70479 (basalt)-0.70164 (rhyolite) likewise the positive value $\varepsilon Nd_{(320\ Ma)}$=+3.11 of a basalt strengthen that origin for the magmas. Those characteristics point to post-orogenic geotectonic conditions, in a within-plate setting during a regional crustal heating phase, in response to extension of the crust and mantle upwelling. These conditions, as was proposed by Alasino *et al.* (2012) for Carboniferous A-type magmatism, could have occurred in an extensional ensialic region linked to an Andean type margin where the lithospheric mantle played a role in its generation. These authors and Dahlquist *et al.* (2013) propose that the juvenile contribution could be explained by detachment of the lithosphere That conditions contrast with active continental margin setting of the Ordovician volcanism recorded in the study region, which involves a major contribution of pre-exinting old crustal rocks without evident participation of the asthenospheric mantle. In that case their geochemical parameters set themselves up as useful tools for their distinction.

It is possible to establish besides, based on isotopic data, a clear difference in the origin of magmas between the volcanic succession of Las Lozas and the Misisisippian rhyolites of Cazadero Grande and the main coeval Sierras Pampeanas A-type granites. Those data, for the case of Las Lozas, denote a predominance of a juvenile component but affected by crustal contamination, meanwhile indicate that the last two magmatic groups of rocks were probably extracted from a strongly enriched reservoir with negligible mantle contributions.

Taking in account the age difference in the region between Mississippian and the Lower Pennsylvanian magmatism, this would indicate a change in the magma source consistent with a more pronounced extensional tectonic regime for the Lower Pennsylvanian. This assumption need to be considered together with the Alasino *et al.* (2012) observations along a transect at 27º30' S, where the Carboniferous Eastern Sierras Pampeanas granitic rocks show, regardless of age, a greater contribution of juvenile material of mantle character to the west. Among these rocks, with a major juvenile component, are those of the Las Lozas succession as well the Cerro Gloria Granite, the eastern manifestations of the Carboniferous Eastern Sierras Pampeanas magmatism. From the foregoing emerges that the contribution of juvenile material could be continuously varied through time as due to varying lithospheric extension during these

tectono-thermal event. However draws attention the concentration of rocks with greater juvenile contribution near the boundary of A-type and I type magmatic representatives, coincident with Western and Eastern basement blocks, suggesting that that area may have had an important role in detachment of the lithosphere and in the control of the magmatism.

In order to achieve a better definition of a model to discern, if extensional variation was coupled with areas of regional weakness in the control of the juvenil material upwelling, during the Carboniferous magmatism, is necessary to obtain additional geochemical, isotopic and geochronological data across the region.

Regardless of these considerations, the data presented of the Las Lozas succession confirm that Carboniferous magmas in the region, product from reworking of supra-crustal material with variable input of juvenile magmas, are undoubtedly linked to changes in the lithospheric extension.

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