

# The Mesoproterozoic Basement at the San Rafael Block, Mendoza Province (Argentina): Geochemical and Isotopic Age Constraints

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**Abstract** This work provides new petro-geochemical and isotopic information to constrain the crustal evolution of the Precambrian Cerro La Ventana Formation. The Rb–Sr, Sm–Nd, Pb–Pb, and U–Pb isotopic data obtained as well as their

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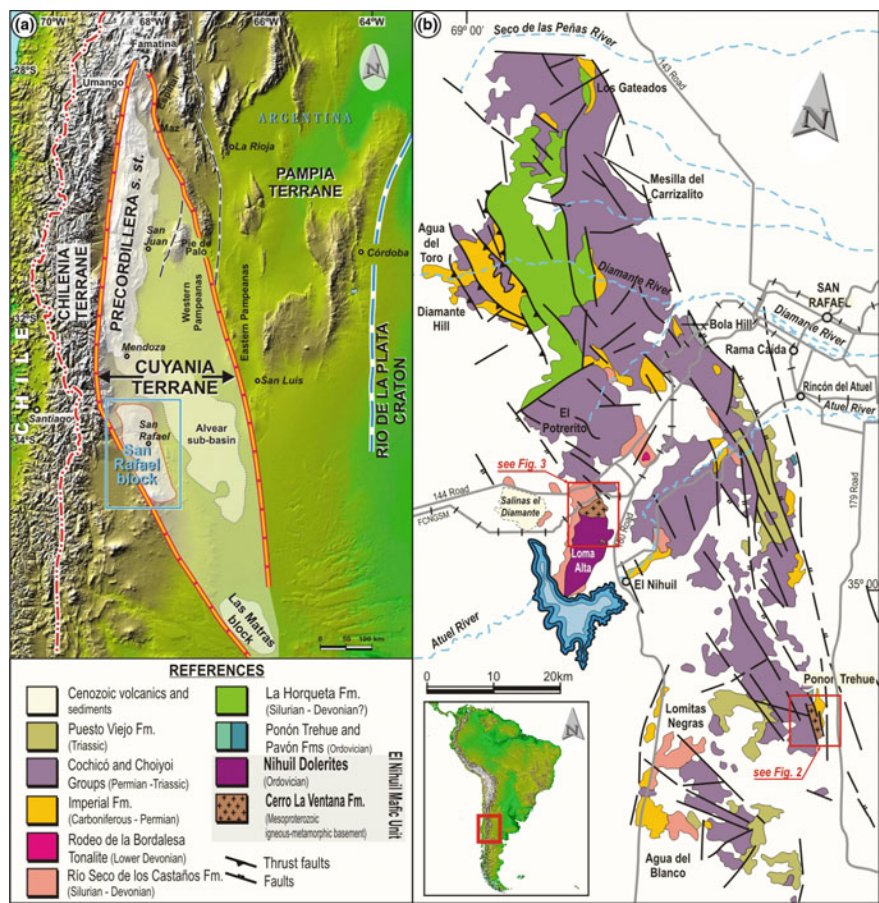
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petrological and geochemical features are reported. These data are useful to discuss relationships with equivalent Mesoproterozoic units located along the Cuyania terrane in the proto-Andean Gondwana margin. The type section of the basement rocks of the Cerro La Ventana Formation is located in the south-eastern part of the San Rafael Block, Mendoza Province known as Leones-Ponón Trehué-La Estrechura region. Equivalent crustal fragments are also included in this basement, such as ductile-deformed rocks of the El Nihuil Mafic Unit that are intruded by Ordovician undeformed dolerites. The basement exposed along the type section corresponds to a metamorphosed volcano-plutonic complex with hardly any sedimentary protolith. Main rocks are tonalites and foliated gabbros and quartz diorites that pass to amphibolites, and minor granodioritic–dioritic orthogneisses, with abundant angular microgranitoid enclaves now deformed and stretched intruded in mafic to felsic metavolcanics with porphyritic relic textures. The studied samples classified as tonalites and some close to the field of granodiorites following a calc-alkaline trend. Gabbroic samples from the El Nihuil mafic unit show a more tholeiitic signature. The bulk of samples from the Cerro La Ventana Formation plot within the field of metaluminous rocks; although a few are in the peraluminous field. Main groups of samples plot as low-Al TTD field; however, some of them show high Sr/Y ratios which are typical of high-Al TTD. The Mg#K ratio is higher in the Cerro La Ventana Formation compared with Las Matras TTG series suggesting a minor differentiated grade for the first one. The chondrite-normalized REE diagrams for Leones samples have Eu anomalies rather positive and gabbros from El Nihuil region display patterns with positive Eu anomalies typical of plagioclase-rich igneous rocks. The Rb–Sr data defined an isochron with  $1148 \pm 83$  Ma, initial  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70292 \pm 0.00018$ . The low initial ratio is indicative of a slight evolved Mesoproterozoic source. An acceptable isochron was obtained using Sm–Nd methodology indicating an age of  $1228 \pm 63$  Ma. The model ages ( $T_{\text{DM}}$ ) are in the range 1.23–1.64 Ga with  $\epsilon\text{Nd}_{(1200)}$  in between  $-0.94$  and  $+4.7$  recording a ‘depleted’ source, less evolved than CHUR for the time of crystallization. In a  $^{207}\text{Pb}/^{204}\text{Pb}$  diagram the samples plot similarly to rocks from the basement of Cuyania Terrane (Pie de Palo Range and crustal xenoliths) showing a distinctive non-radiogenic signature. The tonalitic lithofacies located at the Leones River type section was chosen for zircon U–Pb TIMS dating and the obtained crystallization age was  $1214.7 \pm 6.5$  Ma. The in situ U–Pb (LA-ICP-MS) zircon data done in two different laboratories on samples from El Nihuil mafic unit (tonalitic orthogneisses) plotted in a Concordia diagram, record an intercept at  $1256 \pm 10$  Ma and in Tera-Wasserburg diagram an age of  $1222 \pm 6.9$  Ma. With these isotopic data we confirm the Mesoproterozoic age for the basement of the San Rafael Block. The obtained *ca.* 1.2 Ga is quite similar to those belonging to the basement of other regions from the Cuyania allochthonous terrane.

**Keywords** Cuyania terrane · San Rafael Block · Cerro La Ventana Formation · Mesoproterozoic basement · Geochemistry · Geochronology



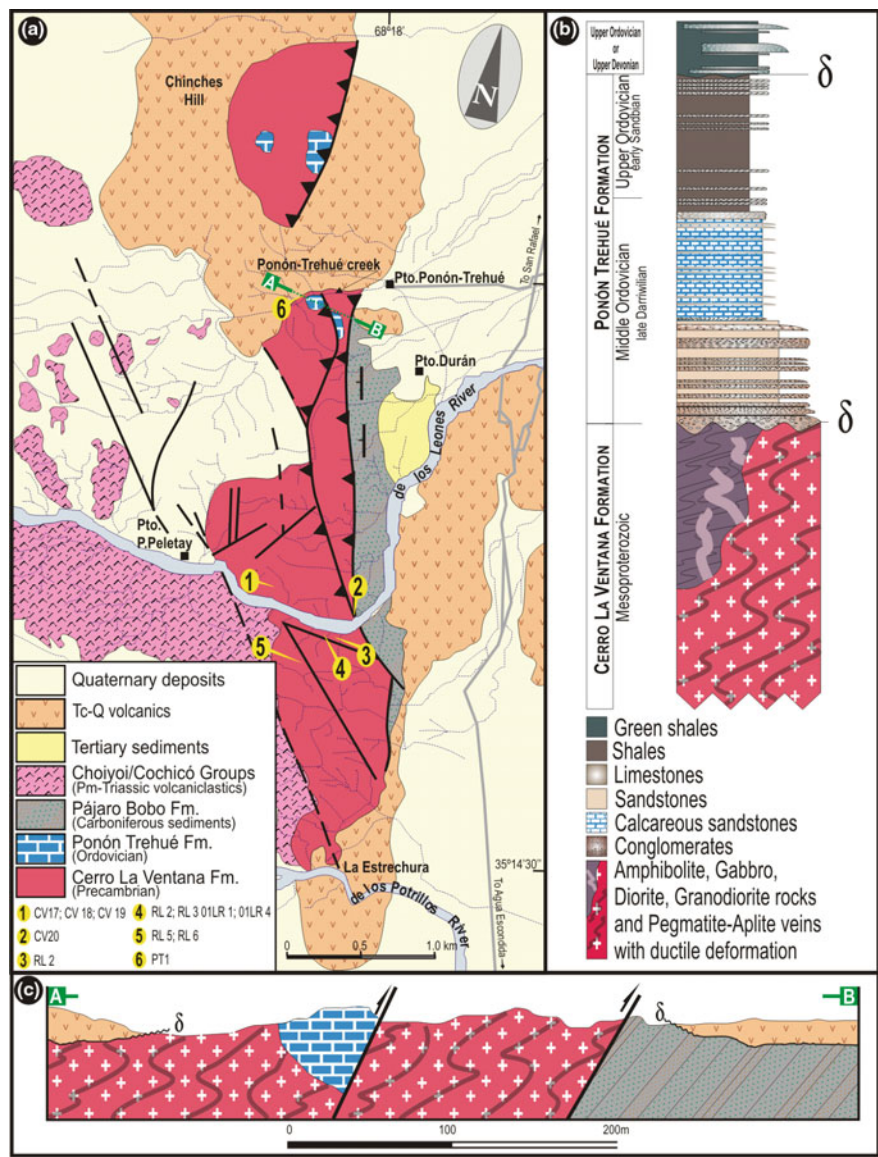
**Fig. 1** **a** Location of the San Rafael Block within the Cuyania terrane along the proto-Andean margin of Gondwana; **b** geological sketch map of the San Rafael Block and the position of the studied regions

## 1 Introduction

The southern South America Paleozoic Gondwana margin (Fig. 1) is characterized by the presence of orogenic belts oriented approximately north-south (Ramos et al. 1986; Dalla Salda et al. 1992). They have been accreted to the cratonic areas during the Cambrian (Pampean), Mid-Ordovician (Famatinian), and Upper Devonian (Gondwanian) tectonic cycles. The Argentine Precordillera or Cuyania composite terrane in the sense of Ramos (2004 and references) is linked to the Famatinian cycle and lies eastward of the present-day Andes. This terrane had been considered from the standpoint of stratigraphy and faunal unique to South America mainly for the Lower Paleozoic carbonate and siliciclastic deposits overlying an igneous–metamorphic crust of Grenville age (Ramos et al. 1998; Sato et al. 2004; Varela et al. 2011). The composite terrane comprises four sectors: The Precordillera (28°–33°S) mainly thin-skinned fold and thrust belt generated by shallow east-dipping flat-slab subduction of the Nazca plate, the Pie de Palo area, and the San Rafael and the Las Matras blocks (Fig. 1).

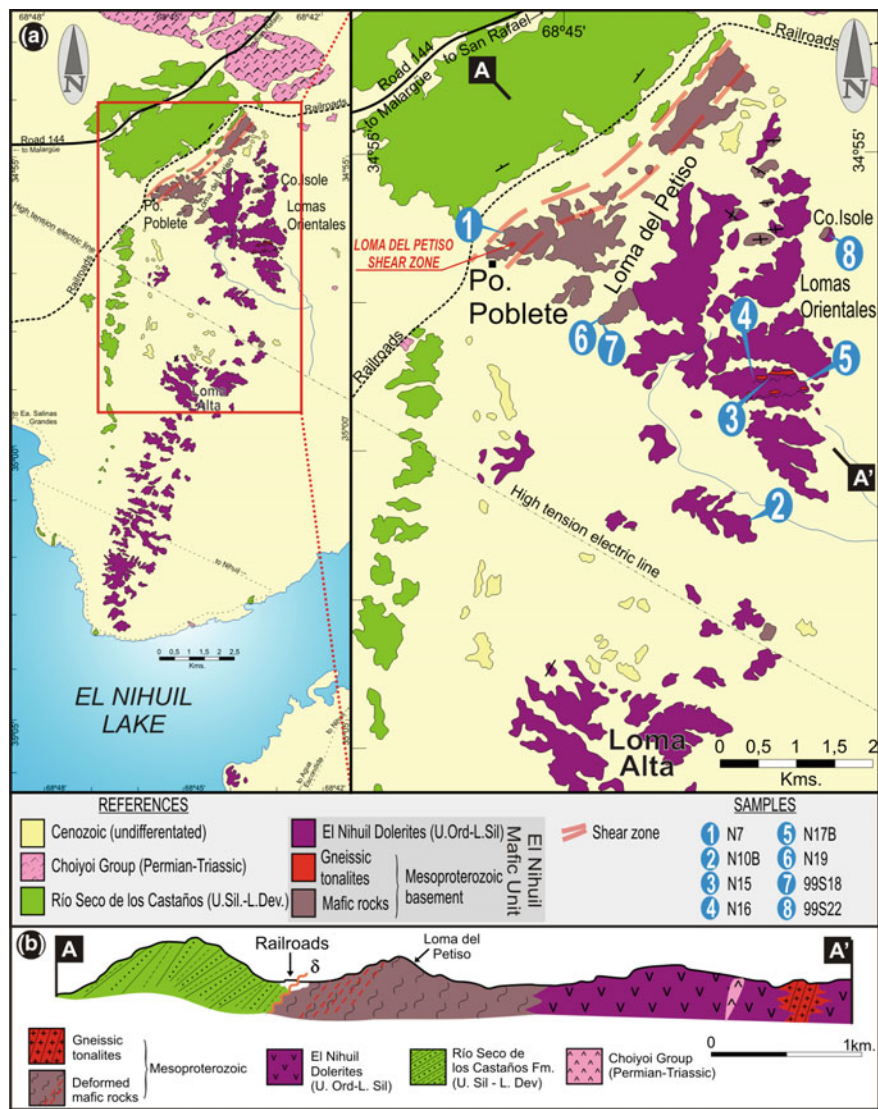
The San Rafael Block (SRB) lies in west-central Mendoza Province, Argentina (35°S–68° 30'W), and has SSE–NNW structural Cenozoic trend in the pre-Andean region. To the North and South the Cuyo and Neuquén sedimentary basins bound it, respectively. Toward East the outcrops of the SRB vanish under the modern basaltic back arc volcanism and sedimentary cover; the Western boundary is defined by the Andean foothill (Fig. 1). The SRB is interpreted as an extension of the Precordillera region on the light of paleontological and geological evidence (Ramos 1995; Ramos et al. 1999; Keller 1999). Diverse igneous–metamorphic and sedimentary units of Precambrian to Middle Paleozoic age, known as ‘pre-Carboniferous units’ due to their clear differentiation below a Carboniferous regional unconformity (Dessanti 1956), crop out within the SRB. Basement crustal rocks known as Cerro La Ventana Formation (Criado Roqué 1972) are exposed in the eastern and central part of the SRB (type section: 35° 12'S–68° 17'W), partially covered by calcareous–siliciclastic sedimentary rocks bearing Ordovician macro- and microfossils (Nuñez 1962, 1976; Heredia 2006; Abre et al. 2011; Heredia and Mestre, this volume).

The main purpose of this work is to provide new petro-geochemical and isotopic information to constrain the crustal evolution of the Precambrian Cerro La Ventana Formation. The Rb–Sr, Sm–Nd, Pb–Pb, and U–Pb isotopic data obtained as well as their petrological and geochemical features are reported in this paper. These data are useful to discuss relationships with equivalent Mesoproterozoic units located along the Cuyania terrane in the proto-Andean Gondwana margin.



**Fig. 2** a Geological sketch map from the Leones-Ponón Trehué creeks toward the south up La Estrechura section (based in Nuñez 1979; Bordonaro et al. 1996; Astini 2002; Cingolani et al. 2005). Locations of the samples are in yellow. b Stratigraphic column showing the Cerro La Ventana basement and unconformity contact with the Ordovician Ponón Trehué Formation (modified from Heredia 2006). c Schematic profile at the Ponón Trehué creek showing the tectonic relationships between basement rocks and other units





**Fig. 3** a Geological sketch map of the El Nihuil mafic unit where the Mesoproterozoic basement is exposed (modified from Cingolani et al. 2000). The locations of the studied samples are in blue; b schematic profile showing the relationships between units

## 2 Geological Setting

The type section of the basement rocks of the Cerro La Ventana Formation (Criado Roqué 1972) or La Ventana Formation (Nuñez 1979) is located in the south-eastern part of the SRB, Mendoza Province (Fig. 2) known as Leones-Ponón Trehué-La Estrechura region (hereafter ‘Leones’), in a NNW-SSE trending belt of about 9 km long and 1.5 km wide. It consists of an igneous–metamorphic complex, acidic to intermediate granitoids, as well as pegmatitic and aplitic veins.

Equivalent crustal fragments are also included in this basement, such as ductile-deformed rocks of the El Nihuil mafic unit outcropping at Lomas Orientales and Loma del Petiso (Fig. 3) intruded by undeformed Ordovician dolerites.

Also we mention the ‘basement rocks’ that were localized in petroleum research wells (Criado Roqué 1979; Criado Roqué and Ibáñez 1979) toward the southeast (‘Alvear sub-basin’ at Triassic Cuyo Basin). The Cerro Las Pacas Formation (Holmberg 1973) was previously considered as part of the basement; however, new isotopic data done by Cingolani et al. (2014) on mica schists with vertical foliation and intruded by Permian magmatism, record U–Pb detrital zircon ages as young as *ca.* 376 Ma, and therefore it no longer can be considered as part of the Proterozoic basement of the Cuyania terrane. Oil exploration carried out before 1970 in the underground of Triassic Cuyo Basin, ‘basement’ rocks correlated with the Cerro La Ventana Formation were recognized to the east of the San Rafael Block, at the Alvear sub-basin (Ramos 2004). The borehole IV-D cut garnet–hornblende–biotite schists that recorded a K–Ar age of 605 Ma (Criado Roqué 1979). Close to Corral de Lorca town the exploration well cut metasedimentary rocks (mica schists) from which Cingolani et al. (2012a) obtained U–Pb detrital zircon ages of 395–410 Ma. These rocks are very different to those from the Mesoproterozoic basement and could be correlated to the La Horqueta Formation (Silurian–Devonian age) instead.

It is important to mention that the Leones type section (Ponón Trehué region) constitutes an interesting study area since it records the primary contact between the basement (Cerro La Ventana Formation) and the Precordilleran Lower Paleozoic platform sedimentary rocks (Fig. 2a, b). After Nuñez (1979), Bordonaro et al. (1996), Heredia (1996), and Astini (2002), the two sedimentary members mapped in the area were genetically related to an episode of extension but deposited in separate areas, although both overlie basement rocks. The first one was interpreted as an accumulation of allochthonous (resedimented) carbonate blocks and olistoliths (limestone and igneous blocks) in the proximal reaches of graben. The second unit comprises a lower section composed of sandy carbonates yielding a well-preserved mid-Ordovician conodont and shelly fauna, and resting unconformably on the basement, while the upper section is siliciclastic in composition. Together they provide a record of extensional history (Astini 2002; Abre et al. 2011 and references).

### 3 History of the Basement Knowledge

Stappenbeck (1913) in his extensive travel from the Sierra Pintada to Cerro Nevado achieved the first reference on basement rocks, and in the La Estrechura (de los Potrillos River) he mentioned the presence of basement gneisses supposedly brought up to the surface by modern basalts. Wichmann (1928) mentioned basement rocks such as gneisses, granites, pegmatites, amphibolites among others, and limestones (outcropping toward west of the Cenozoic volcano Ponón Trehué Hill), which he considered similar to those of the Cerro de la Cal and Salagasta (near the city of Mendoza). Polanski (1949) named the basement as ‘Serie de Ponon-Trehue’. Padula (1949, 1951) mapped the region while working for the oil industry and described granitic orthogneisses supporting Ordovician limestones in unconformity and with tectonic contacts with younger Upper Paleozoic sedimentary and volcanic rocks. Criado Roqué (1972) assigned the igneous–metamorphic complex composed mainly of deformed mafic-amphibolite and granitoid rocks, to the Precambrian and named it as Cerro La Ventana Formation. This unit was correlated based on rock similarities to the Pie de Palo outcrops. The basement along the Seco de los Leones River and Ponón Trehué creek was also referred to as La Ventana Formation by Nuñez (1979). He described the petrographical characteristics of the recognized rocks, affected by heterogeneous ductile shear zones, such as amphibolites, mica schists, metaquartzites, gneisses, amphibolitic schists, granites, diorites, and pegmatitic and aplitic veins. Roller and Criado Roqué (1970) and Roller and Fernández Garrasino (1979) mentioned the presence of high-metamorphic grade ‘Pre-Paleozoic Basement’ with amphibolites, gabbros, mica schists, amphibolitic schists, and quartzites, intruded by granites and pegmatite–aplite veins. The authors pointed out the presence of intercalated mafic rocks recording pre-orogenic magmatism similar to the Cerros Valdivia and Barbosa (near San Juan city). This complex supports in unconformity an Ordovician sedimentary cover and its exposures are characterized by compressive features such as tectonic contacts acquired during Cenozoic east-vergence thrusting that juxtaposed the basement rocks with both Ordovician and Upper Paleozoic rocks (Fig. 2b, c). Deformation and associated low-grade metamorphism heterogeneously affected this association, originating discrete belts of gneisses. Caminos (1993) correlated the San Rafael Block Precambrian basement to the Western Pampeanas Ranges. Astini et al. (1996) and Thomas et al. (2012) cited an unpublished U–Pb age that yielded a Grenvillian age for the basement rocks. Davicino and Sabalúa (1990) report geochemistry information on mafic rocks and described mylonite and cataclastic rocks along the El Nihuil mafic unit. First Rb–Sr data were obtained by Cingolani and Varela (1999) from seven samples of granodioritic to tonalitic rocks, exposed along the Seco de los Leones and Ponón Trehué creeks; their whole-rock isochron yielded a Mesoproterozoic age of  $1063 \pm 106$  Ma. For more detailed references see also Sato et al. (2000, 2004), Casquet et al. (2006), Vujovich et al. (2004), Ramos (2004), Rapela et al. (2010), and Cingolani et al. (2000, 2012b, 2014). A comprehensive review of the geological and isotopic features of Grenvillian-age



**Table 1** GPS coordinates of the studied samples at different outcrop sectors

Sample	GPS	Rock type	Methodology
<b>Leones type section</b>			
CV17	35° 12' 26"S–68° 18' 32"W	Tonalite	Pb/Pb; Sm/Nd; geochemistry
CV18	35° 12' 26"S–68° 18' 32"W	Gabbro–diorite	Pb/Pb; Sm/Nd; geochemistry
CV19	35° 12' 26"S–68° 18' 32"W	Gabbro–diorite (Biot.–Qz)	Pb/Pb; Sm/Nd; geochemistry
CV20	35° 12' 23"S–68° 17' 33"W	Deformed tonalite (garnet)	Pb/Pb; Sm/Nd; geochemistry
RL2	35° 12' 39"S–68° 17' 53"W	Granitic composition	Rb/Sr
RL3	35° 12' 40"S–68° 18' 06"W	Granitic composition	Geochemistry; Rb/Sr
RL4	35° 12' 40"S–68° 18' 06"W	Granitic composition	Geochemistry; Rb/Sr
RL5	35° 12' 53"S–68° 18' 19"W	Granitic composition	Rb/Sr
RL6	35° 12' 53"S–68° 18' 19"W	Tonalite	Geochemistry; Rb/Sr
01RL1	35° 12' 36"S–68° 17' 38"W	Gabbro	Geochemistry
01RL2	35° 12' 36"S–68° 17' 48"W	Dioritic composition	U–Pb
01RL3	35° 12' 33"S–68° 18' 14"W	Granitic composition	U–Pb
01RL4	35° 12' 33"S–68° 18' 14"W	Granitic composition	Geochemistry
01RL5	35° 12' 33"S–68° 18' 14"W	Dioritic composition	Geochemistry
PT1	35° 10' 01"S–68° 18' 53"W	Granitic composition	Rb/Sr
<b>El Nihuil mafic unit</b>			
N7	34° 55' 35.6"S–68° 45' 21.6"W	Gabbro	Geochemistry; Rb/Sr
N10B	34° 57' 37.4"S–68° 43' 28.1"W	Gabbro	Geochemistry
N19	34° 56' 07.8"S–68° 44' 33.7"W	Foliated gabbro	Geochemistry; Rb/Sr
N15	34° 56' 39.7"S–68° 43' 18.8"W	Foliated tonalite–granodiorite	Sm/Nd; U–Pb; geochemistry
N16	34° 56' 36.4"S–68° 43' 13.7"W	Granitic composition	Geochemistry
N17B	34° 56' 37.8"S–68° 43' 04.5"W	Granitic composition	U–Pb; geochemistry
99S22	34° 55' 40.8"S–68° 42' 44.0"W	Gabbro	Rb/Sr
99S18	34° 55' 38.5"S–68° 45' 25.6"W	Gabbro	Rb/Sr

rocks attached to the southwest of the Río de la Plata craton in Early Paleozoic times was presented by Varela et al. (2011). In this paper, the Mesoproterozoic basement exposures are clearly extended southward of 34°S in the Cuyania terrane, specifically within de San Rafael and Las Matras blocks (Fig. 1). The main difference is the pervasive foliation and subsequent mylonitization that affect the Cerro La Ventana Formation in the San Rafael Block. In this scenario the shallower crustal level is exposed toward the South (Las Matras) as a Grenvillian-age tonalitic-trondhjemitic pluton.

**Table 2** Analytical results of major (in w/%) and trace elements (in ppm) in the studied samples (ACTLABS, Canada)

Samples	Leones type section						El Nihuil mafic unit									
	RL3	RL4	RL6	01RL1	01RL2	01RL3	01RL4	01RL5	N7	N10B	N19	N15	N16	N17B		
<b>Major elements</b>																
SiO <sub>2</sub>	72.65	71.03	68.57	70.92	53.71	55.76	55.37	56.26	48.63	43.24	51.17	65.94	66.04	65.80		
Al <sub>2</sub> O <sub>3</sub>	14.51	14.05	15.12	14.11	16.31	17.96	16.63	15.70	16.01	19.94	23.4	15.06	15.03	15.13		
Fe <sub>2</sub> O <sub>3</sub>	1.62	2.90	3.10	3.64	8.45	7.62	7.91	8.55	9.93	11.74	5.42	4.45	4.14	4.29		
MnO	0.02	0.042	0.063	0.07	0.15	0.109	0.125	0.12	0.177	0.127	0.064	0.06	0.07	0.07		
MgO	0.50	0.91	1.11	0.79	5.08	3.56	4.11	3.09	6.71	4.34	1.63	2.08	2.11	2.08		
CaO	3.25	2.99	3.50	3.65	8.47	7.40	7.08	5.86	10.1	11.3	10.78	4.62	5.22	4.40		
Na <sub>2</sub> O	4.38	4.18	3.94	3.90	3.61	3.60	3.69	4.02	2.98	2.55	3.76	5.14	3.55	3.68		
K <sub>2</sub> O	0.90	1.09	1.85	0.81	1.39	1.05	1.37	2.23	0.33	0.56	0.86	0.43	1.23	1.92		
TiO <sub>2</sub>	0.186	0.341	0.326	0.25	0.52	0.888	0.94	1.29	1.22	2.03	0.71	0.44	0.44	0.45		
P <sub>2</sub> O <sub>5</sub>	0.06	0.12	0.12	0.06	0.11	0.24	0.34	0.47	0.05	0.82	0.12	0.18	0.17	0.18		
LOI	1.04	1.35	1.28	1.80	2.20	2.28	2.10	2.40	3.73	2.95	2.54	2.08	2.17	2.14		
Total	99.13	99.01	98.98	0.00	0.00	100.46	99.64	99.99	99.86	99.6	100.48	100.49	100.17	100.13		
Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>	0.20	0.20	0.22	0.20	0.30	0.32	0.30	0.28	0.33	0.46	0.46	0.23	0.23	0.23		
K <sub>2</sub> O/Na <sub>2</sub> O	0.21	0.26	0.47	0.21	0.39	0.29	0.37	0.55	0.11	0.22	0.23	0.08	0.35	0.52		
Mg#*100	55	55	59	46	70	65	67	59	73	59	54	65	67	66		
<b>Trace elements</b>																
Sc	2	3	10			16	18									
V	15	33	43			131	128									
Cr	36	23	34			20	86									
Co	37	33	27			31	34									
Ni	-20	-20	-20			30	75									
Cu	-10	14	15			75	47									

(continued)

Table 2 (continued)

Samples	Leones type section						El Nihuil mafic unit							
	RL3	RL4	RL6	01RL1	01RL2	01RL3	01RL4	01RL5	N7	N10B	N19	N15	N16	N17B
Zn	-30	57	49			79	94							
Ga	14	15	17			18	18		17	19	21	16	16	15
Ge	1.1	0.8	0.9			1.0	1.1							
Rb	13	18	34			17	26		3	13	20	10	23	34
Sr	445	461	407	252.00	370.00	666	482	420.00	588	668	747	378	392	460
Y	2.4	5.1	12.4	12.00	14.00	12.3	18.5	28.00	10.50	14.70	8.90	15.50	15.90	14.20
Zr	75	145	99	75.00	36.00	29	104	193.00	14	23	33	114	114	104
Nb	1.8	2.9	4.6	1.00	0.00	2.4	11.0	9.00	1.00	2.20	2.00	7.3	7.5	6.7
Cs	0.2	0.2	1.0			0.4	0.2		0.4	0.9	0.3	0.70	0.70	1.60
Ba	805	863	918			519	517		398	326	323	397	1160	1400
Hf	1.9	3.9	2.7	3.40	3.60	1.0	2.7	3.20	0.50	0.70	1.00	3.40	3.60	3.20
Ta	2.48	2.09	1.66			0.85	3.51		0.20	0.20	0.70	2.1	3	1.6
Tl	0.08	0.08	0.12			0.11	0.14		0.09	0.11	0.09	0.06	0.13	0.08
Pb	11	8	7			5	5		19	9	9	12	19	6
Th	3.15	6.31	3.25			0.63	1.18		0.12	0.47	0.57	27.08	18.6	15.2
U	0.29	0.60	0.63			0.31	0.71		0.10	0.22	0.26	5.25	4.97	4.49

**Table 3** Analytical results obtained by FRX methodology at the University of Río Grande do Sul, Porto Alegre, Brazil

Samples	CV5	CV17	CV18	CV19	CV20
<b>(a)</b>					
SiO <sub>2</sub>	56.67	69.86	52.83	50.98	72.11
Al <sub>2</sub> O <sub>3</sub>	16.27	15.34	17.68	16.72	14.22
Fe <sub>2</sub> O <sub>3</sub>	6.77	3.28	8.06	7.88	3.93
MnO	0.11	0.05	0.12	0.11	0.07
MgO	3.55	1.13	4.64	6.47	0.66
CaO	6.20	4.19	7.62	6.81	3.77
Na <sub>2</sub> O	3.62	3.45	3.09	2.74	3.81
K <sub>2</sub> O	2.14	0.88	1.76	0.81	0.14
TiO <sub>2</sub>	1.00	0.38	1.04	1.27	0.38
P <sub>2</sub> O <sub>5</sub>	0.22	0.11	0.22	0.28	0.09
LOI	2.50	1.01	1.98	4.96	0.46
Σ	99.05	99.70	99.04	99.03	99.64
Al <sub>2</sub> O <sub>3</sub> /SiO <sub>2</sub>	0.29	0.22	0.33	0.33	0.20
K <sub>2</sub> O/Na <sub>2</sub> O	0.59	0.26	0.57	0.30	0.04
Fe <sub>2</sub> O <sub>3</sub> /MgO	1.91	2.90	1.74	1.22	5.95
<b>(b)</b>					
Cr	25	37	52	195	18
Co	50	bdl	47	46	6
Ni	39	3	28	89	10
Ga	30	15	21	22	16
Rb	96	8	39	bdl	bdl
Sr	963	735	647	656	275
Y	43	4	21	19	20
Zr	139	196	82	121	135
Nb	7	1	4	7	5
Ba	1026	718	794	398	369
Pb	11	9	8	8	6

*bdl* below detection limit

## 4 Sampling and Analytical Techniques

The Cerro La Ventana Formation was sampled at the type section (CV17 to CV20, RL2 to RL-6, 01RL1, 01RL4, PT1), along the Ponón Trehué and Leones creeks (simplified as ‘Leones’). Another locality was the El Nihuil mafic unit, ductile-deformed rocks within the Loma del Petiso and Lomas Orientales were sampled (N7, N10B, N19, N15, N16, N17 B). Table 1 summarizes the sampling locations and analytical methodologies applied to each sample.

For petrographic studies we use more than 30 samples from different localities covering the whole type basement rocks. Twelve whole-rock samples were analyzed for major, trace, and REE (Table 2) at ACTLABS Canada, by Fusion-ICP and Fusion-ICP MS, except for major and trace elements of four whole-rock samples (CV17 to CV20) that were analyzed by X-ray fluorescence at the Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil (Table 3). For the **Rb–Sr** systematic, the Rb and Sr concentrations were acquired by XRF and the isotopic composition on natural Sr by mass spectrometry. The sample preparation, chemical attacks, and Sr concentration with cation exchange resin were carried out in the clean laboratory of the Centro de Investigaciones Geológicas (CIG, University of La Plata, Argentina) while FRX and mass spectrometry were done at the Centro de Pesquisas Geocronológicas (CPGeo), São Paulo, Brazil (Cingolani and Varela 1999). Results were plotted on isochron diagram, using the Isoplot model after Ludwig (2001). The technical procedure for **Sm–Nd** methodology performed at the Laboratorio de Geología Isotópica, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil started with rock powders spiked with mixed  $^{149}\text{Sm}$ – $^{150}\text{Nd}$  spike and dissolved using an HF–HNO<sub>3</sub> mixture and 6 N HCl in Teflon vials, warmed in hot plate until complete dissolution. The REE were extracted using HDEHP-coated Teflon powder. Isotopic compositions were measured with a VG Sector multicollector mass spectrometer. Sm was loaded on Ta filament and Nd on external Ta triple filament (Ta–Re–Ta) with 0.25 N H<sub>3</sub>PO<sub>4</sub>. All analyses are adjusted for variations instrumental bias due to periodic adjustment of collector positions as monitored by measurements of the internal standard; on this basis the analyses of La Jolla Nd average are  $0.511859 \pm 0.000010$ . During the course of the analyses Nd and Sm blanks were lesser than 750 and 150 pg, respectively. **Pb–Pb** isotopic analyses were performed at Laboratorio de Geologia Isotópica, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil; whole-rock samples were completely dissolved in Teflon vial using an HF–HNO<sub>3</sub> mixture and 6-N HCl. Ion exchange techniques allowed Pb extraction using AG-1 X 8, 200–400 mesh, anion resin. Each sample was dried to a solid and added a solution of HNO<sub>3</sub> with 50 ppb Tl in order to correct the Pb fractionation during the analyses (Tanimizu and Ishikawa 2006). Pb isotopic compositions were measured with a Neptune MC-ICP-MS in static mode, with collecting of 60 ratios of Pb isotopes. The obtained values of NBS 981 common Pb standard during the analyses were in agreement with the NIST values. **U–Pb (ID-TIMS)** procedure of zircon analyses at Centro de Pesquisas Geocronológicas—IGcUSP, Brazil, is as follows: after 10 kg of sample was crushed and reduced to 140–200-mesh grain sizes the portion rich in heavy minerals was treated with bromoform ( $d = 2.89 \text{ g/cm}^3$ ) and methyl iodide ( $d = 3.3 \text{ g/cm}^3$ ), and the fraction containing the heavy minerals was processed in the Frantz separator at 1.5 A, and split into several zircon-rich no-magnetic fractions. The final purification of each fraction was achieved by hand picking. Each analyzed fraction represents 30 mg of zircon. Dissolution of zircon crystals was carried out with HF and HNO<sub>3</sub> in Teflon micro-bombs in which a mixed  $^{205}\text{Pb}/^{235}\text{U}$  spike was added. A set of 15 micro-bombs arranged in a metal



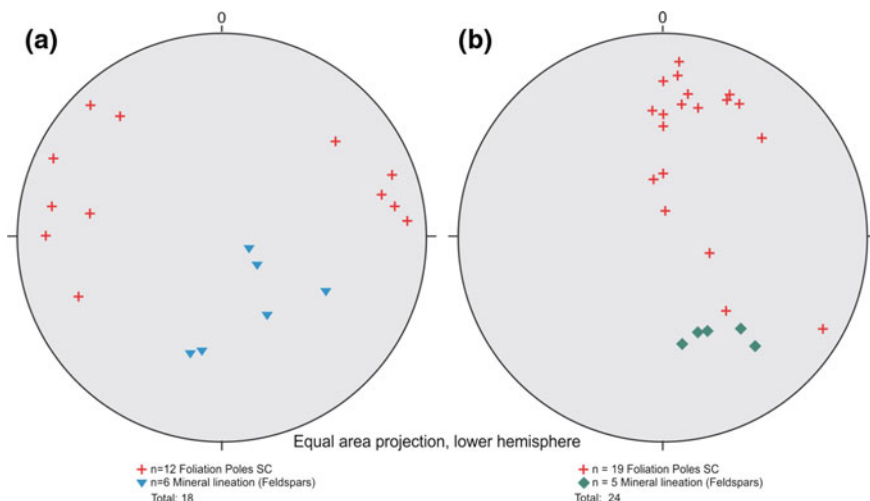
jacket is left for 3 days in a stove at 200 °C. Then, the HF is evaporated and HCl (6N) added to the micro-bombs, replaced in the stove for 24 h. After the evaporation of HCl 6N, the residue is dissolved in HCl (3N). U and Pb are concentrated and purified by passing the solution in an anionic exchange resin column following the technical procedure after Krogh (1973). The solution enriched in U and Pb is, after addition of phosphoric acid, evaporated until the formation of a micro-drop. The sample is deposited in a rhenium filament and the isotopic composition is determined with multicollector Finnigan MAT 262 solid source mass spectrometer (TIMS). After reduction of the data (PBDAT), the results are plotted in appropriate concordia diagrams using the software ISOPLOT/EX (Ludwig 1999, 2001). During the period of analyses the standard  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios were NBS 983  $0.071212 \pm 0.00008$ ; NBS 981  $0.911479 \pm 0.01$ ; and NBS 0.46692  $\pm 0.01$  (Sato and Kawashita 2002). U–Pb ages by LA-ICP-MS were obtained at Centro de Pesquisas Geocronológicas, São Paulo (N15–N17B), and at Laboratório de Geologia Isotópica, Universidade Federal do Rio Grande do Sul, Porto Alegre (N15), both located in Brazil. Crystal zircons were obtained after crushing and sieving about 3–5 kg of each sample. The fractions retained in less than 140  $\mu\text{m}$  mesh were separated using hydraulic processes to obtain heavy mineral pre-concentrates. These were treated with bromoform to obtain the complete heavy mineral spectra. Methylene iodide was used to achieve a fraction enriched in zircons, followed by an electromagnetic separation with Frantz Isodynamic equipment when necessary. The final selection of crystals, mounted in 2-cm-diameter epoxy resin and polished, was examined under a binocular microscope. The grains were photographed in reflected and transmitted light, and cathodoluminescence (CL) images were produced in order to investigate the internal structures of the zircon crystals as well as to characterize different populations. Choice of spot sites was guided by CL imaging. The U–Pb isotope analyses in both laboratories were performed on zircon grains using a Thermo-Fisher Neptune laser-ablation multicollector inductively coupled plasma mass spectrometer equipped with a 193 Photon laser system. For the operating conditions and instrument settings of the NEPTUNE instrument and laser-ablation system during analytical sessions see Sato et al. (2009) and Bühn et al. (2009), for CPGeo-USP and LGI-UFRGS, respectively. The data are portrayed in Concordia or Tera–Wasserburg diagrams generated with Isoplot/Ex (Ludwig 2001, 2003). U–Pb (LA-ICP-MS) zircon isotopic data are shown in Tables 9 and 10 (in Electronic Supplementary Material).

## 5 Petrological and Structural Signatures

The studied samples located at the **Leones** type section (Figs. 2 and 4a–g) are classified as basic to mesosilicic gneisses, foliated gabbros, quartz diorites, and tonalites, partially grading to amphibolites and migmatites. This complex is intruded by diorites with structural lineament N10°E/55°SE which yielded migmatite xenoliths.



**Fig. 4** Field photographs showing the outcrops of Cerro La Ventana Formation at the Leones type section. **a** Thrust fault with east vergence over the Upper Paleozoic unit; **b–d** quartz diorites and tonalites, partially graded to amphibolites; **e** pegmatite veins; **f, g** angular dioritic enclaves with textural similarity to Las Matras pluton (Varela et al. 2011)

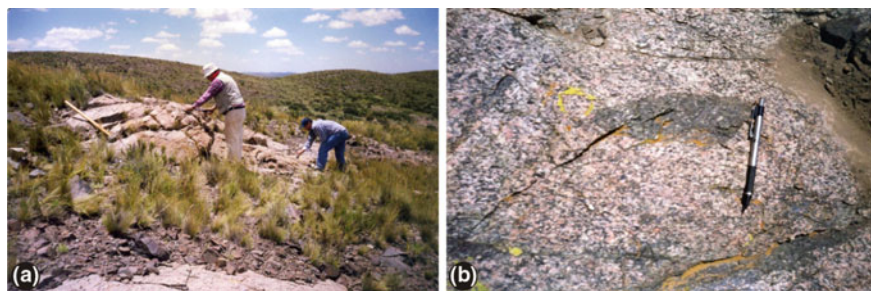


**Fig. 5** Measurements of foliation and mineral lineation. **a** Leones type section; **b** El Nihuil mafic unit (tonalitic orthogneisses)

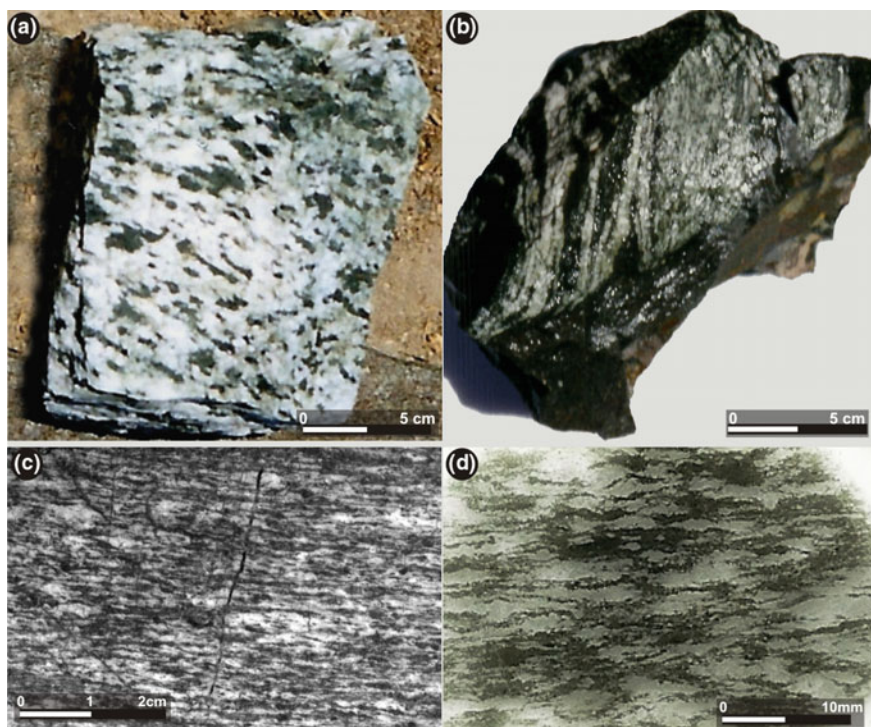
The foliation of some diorites is  $N20^{\circ}E/60^{\circ}NW$  without any evidence of migmatization. In several places the mentioned rocks are cut by less-deformed pink-granitoids and pegmatites (Fig. 4e). Associated to a vertical faulting with  $N80^{\circ}W$  direction an intense epidotization is present. A ductile deformation is developed with *ca.* N-S shear metamorphic foliation, dipping with high angle toward NW or NE. Linked to the foliation stretching feldspar mineral lineation could be observed, dipping to S or SE. In Fig. 5a, b the structural attitudes of the mylonitic foliation and the mineral lineation are shown, with a main concentration toward  $N13^{\circ}W/72^{\circ}SW$ . The location of mineral lineation suggests a main transport associated to a shear zone that generated both structures with an important oblique component.

The basement exposed along the type section (Leones River) corresponds to a metamorphosed volcano-plutonic complex with hardly any sedimentary protolith. Main rocks are tonalites and foliated quartz diorites and gabbros that pass to amphibolites, and minor granodioritic–dioritic orthogneisses, with abundant angular microgranitoid enclaves now deformed and stretched (Fig. 4f, g.) intruded in mafic to felsic metavolcanics with porphyritic relic textures. Tabular mafic to felsic dykes cut the country rocks and intrusives and are metamorphosed along with them. In some places from Leones River section the tonalites are rich in garnets (i.e., sample CV20) suggesting that the volcano-plutonic complex could reach the high greenschist–amphibolite facies. Deformation coeval with the metamorphism record the folding of the complex and generated a penetrative foliation  $S_{x-1}$  NW-SE dipping  $50^{\circ}$  to NE and SW. Fold axes have N-S orientation dipping *ca.*  $60^{\circ}S$ . The foliated quartz-dioritic rocks are composed of less-zoned plagioclase ( $An_{42}$ ), amphibole, and scarce quartz. Apatite and sphene are most common accessory



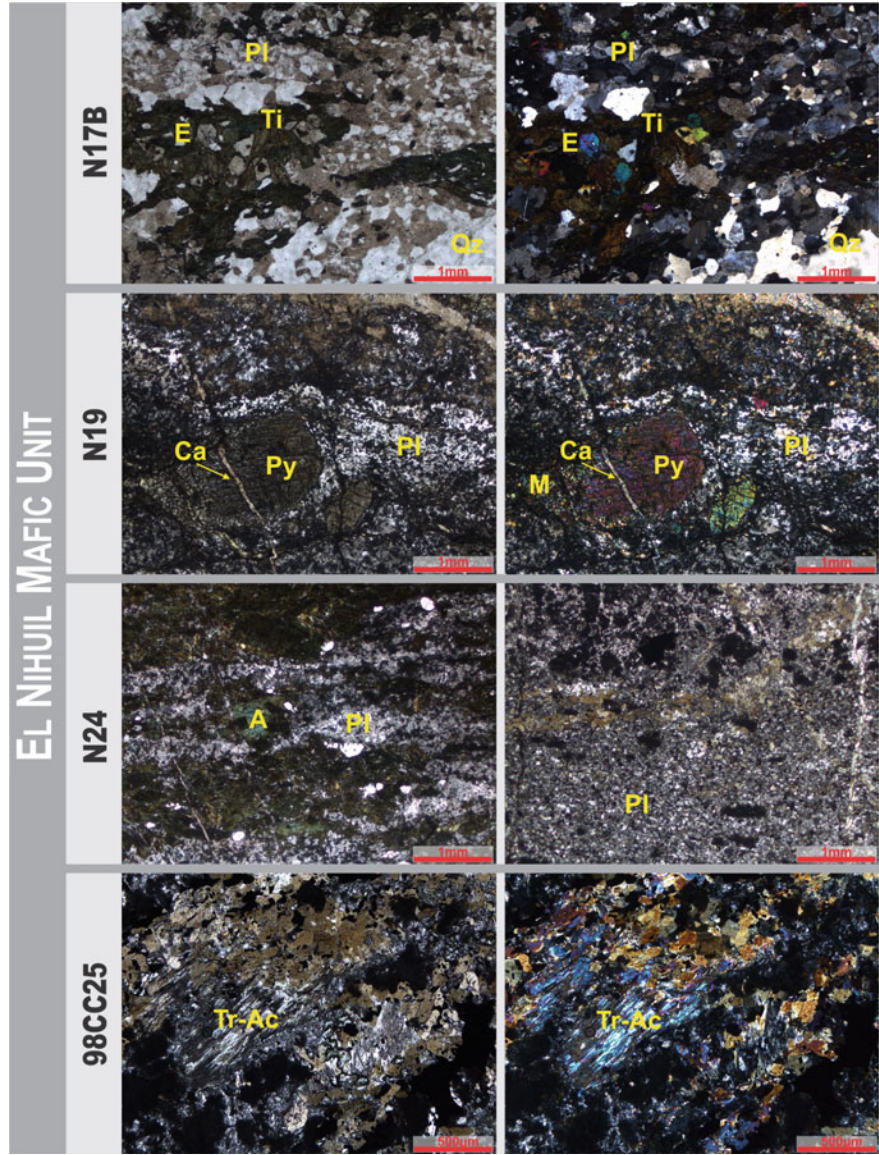


**Fig. 6** **a** Lomas Orientales basement outcrops along the El Nihuil mafic unit; **b** studied samples were taken on tonalitic orthogneisses with mafic enclaves



**Fig. 7** **a, b** Hand samples of ductile-deformed gabbros; **c, d** detail of petrographic sections showing mylonitic texture in gabbros, from El Nihuil mafic unit

minerals. The deformed samples show recrystallized amphibole parallel to the foliation. The plagioclase is strongly altered to sericite and epidote. The tonalites are composed of zoned plagioclase ( $An_{38}$ ), biotite, and quartz. The biotite is mainly





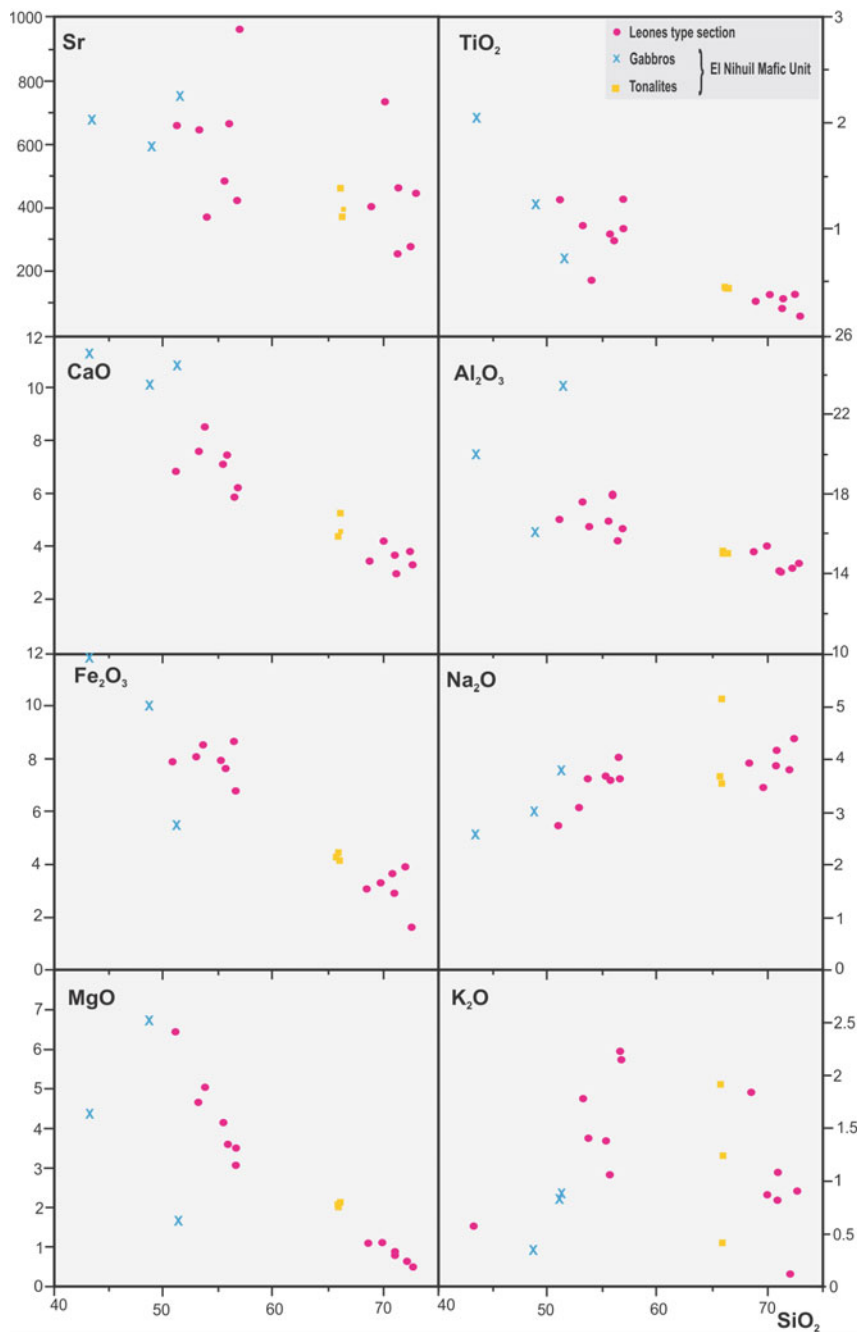
◀**Fig. 8** Photomicrographs (Leica DM 2500P microscope) of samples from the El Nihuil mafic unit ('Loma del Petiso shear zone' and Lomas Orientales). **N17B**: This sample shows well-oriented metamorphic fabric with 8-mm-long hornblende (*A*), with mylonite texture; quartz (*Qz*) and plagioclase (*Pl*) are also present with scarce K-feldspar, showing polygonal mosaic and lensoid texture. The porphyroclasts/porphyroblasts with quartz inclusions lensoidal granoblastic texture within a matrix of plagioclase and quartz. Accessory minerals are sphene (*Ti*) and epidote (*E*). Rock derived from mafic protolith like tonalite, quartz diorite, or quartz amphibolite. (2.5X). **N19**: Sample with pyroxene (*Py*) and plagioclase (*Pl*) as porphyroclasts, partially brecciated, and showing veins of secondary calcite (*Ca*) and with recrystallization of plagioclase. Silicification is also present. Porphyroclasts edges of pyroxene with high-temperature recrystallization forming 'mantle' (2.5X). **N24**: mafic foliated rock with hornblende (*A*), plagioclase (*Pl*) and tremolite—actinolite showing mylonitization in hydrous conditions (2.5X). **98CC25**: Rock sample with granoblastic texture, altered, and brecciated. The amphibole (*A*) was transformed in tremolite—actinolite (*Tr*–*Ac*). Secondary minerals are apatite and opaques. Other recognized minerals are calcite, quartz, and epidote. Equigranular texture, mylonitized. Amphibole in mosaics and mafic phenoclasts are replaced by fibrous minerals (2.5X)

altered to chlorite and medium-grained epidote, probably related to a subsolidus crystallization event. Accessory minerals are apatite, sphene, and allanite.

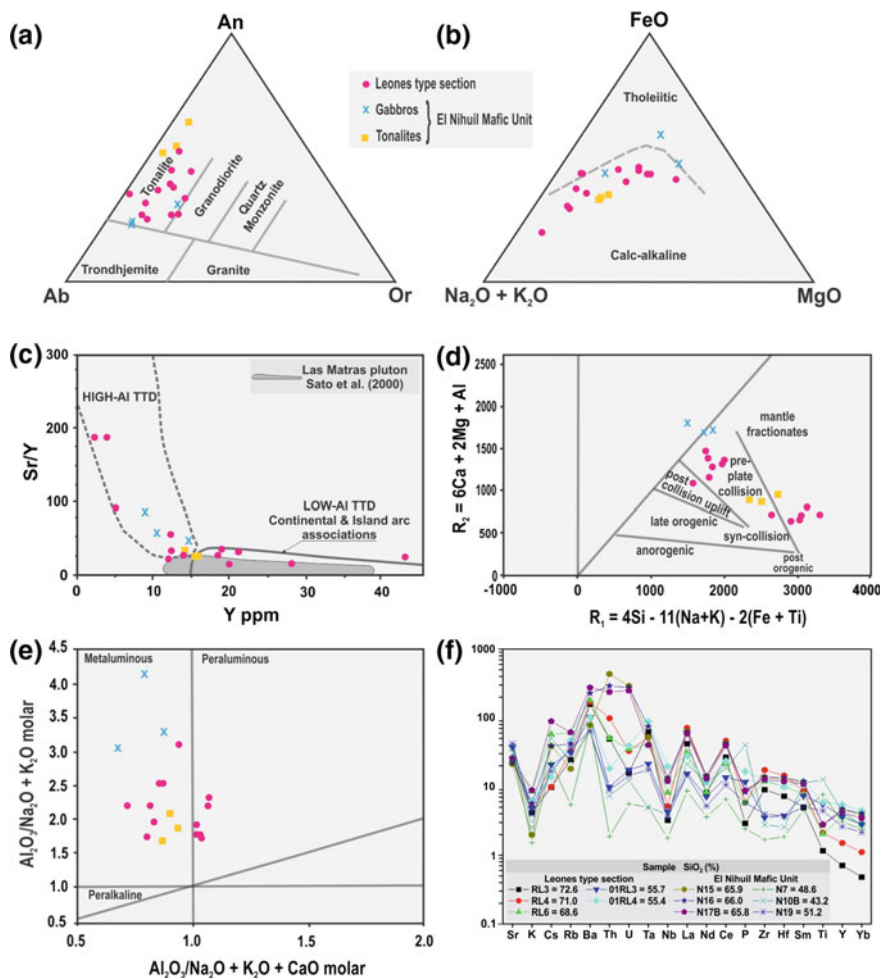
We also include in this chapter, the strongly ductile-deformed gabbros and foliated granodiorite–tonalite orthogneissic samples (Fig. 6a, b) from outcrops preserved at "Loma del Petiso shear zone" and Lomas Orientales within the **El Nihuil Mafic Unit** ca. 45–50 km to the NW of the Ponón Trehué region (Cingolani et al. 2000). The petrological characteristics of gneissic rocks are comparable to the tonalites described at Leones River. They have a metamorphic foliation N83°W/54° SW quite similar in all gneissic outcrops suggesting that they correspond to Cerro La Ventana Formation basement relicts (preserved like enclaves or roof pendants) here intruded by Lower Paleozoic dolerites within the El Nihuil mafic unit (Fig. 3; Cingolani et al., this volume).

The basement relicts that crops out at the El Nihuil mafic unit mentioned before are composed of gabbros and tonalites–granodiorites showing mylonitic and cataclastic textures (Figs. 7a–c, 8 and 9).

The relationships with the Lower Paleozoic Ponón Trehué Fm (Fig. 2) and El Nihuil Dolerites (Fig. 3) suggest that the deformation and metamorphism affecting the Cerro La Ventana Formation should have occurred long before its exhumation during Early Ordovician and probably during the late stages of the Mesoproterozoic Grenville orogeny. During the Cenozoic, the final compressive tectonism juxtaposed through east-vergence thrusting basement rocks with both Ordovician and Upper Paleozoic units, as pointed out by Nuñez (1979; Fig. 4a).



**Fig. 9** Harker diagrams for the studied samples for the elements K, Na, Ti, Ca, Fe, Al, Sr, and Mg. A compositional gap can be seen between tonalites and gabbros



**Fig. 10** **a** Classification of rocks after Barker (1979), based on normative An, Ab, Or; **b** AFM diagram showing that samples plot mainly in the calc-alkaline field after Batchelor and Bowden (1985); **c**  $\text{Sr/Y}$  versus  $\text{Y}$  diagram after Drummond and Defant (1990) showing that a half of total samples are similar to those from the Las Matras block, interpreted as low-Al TTD (Sato et al. 2000). However, samples from our work show dispersion with high  $\text{Sr/Y}$  ratios typical of high-Al TTD; **d** in the  $R_1$  versus  $R_2$  tectonic discrimination diagram the samples plot mainly in the pre-plate collision to syn-collision fields; **e** relation of  $\text{A/CNK}$  (molar) and  $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$  molar, showing the metaluminous/peraluminous signature of studied rocks; **f** expanded diagram of the trace elements normalized to the primitive mantle (Taylor and McLennan 1985)

## 6 Lithogeochemistry

### 6.1 Major Elements

The results of whole-rock samples from the Cerro La Ventana Formation were split into the two groups of outcrops to better describe them (Tables 2 and 3):

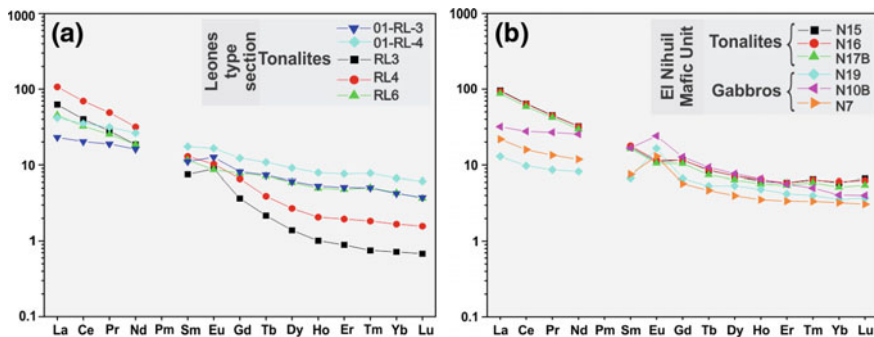
1. **El Nihuil Mafic Unit**, (a) tonalites (N15, N16, N17B) with  $\text{SiO}_2$  around 66%,  $\text{Al}_2\text{O}_3$  of 15% and  $\text{Fe}_2\text{O}_3$  between 4.1 and 4.4%; the concentrations of all major elements are quite similar for the three samples, but a wider spread is found for  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$ ; (b) gabbros (N7, N10B, N19) have a  $\text{SiO}_2$  concentration varying from 43.2 to 51.1%,  $\text{Al}_2\text{O}_3$  is in between 16 and 23.4%,  $\text{Fe}_2\text{O}_3$  ranges from 5.4 to 11.7%, and  $\text{MgO}$  is in between 1.6 and 6.7%.
2. **Leones type section**, (a) gabbros and tonalites (CV17 to CV20, 01 RL2, 01RL4) with  $\text{SiO}_2$  concentrations between 52.8 and 56.6%,  $\text{Al}_2\text{O}_3$  ranges from 15.7 to 17.9%,  $\text{Fe}_2\text{O}_3$  contents vary from 6.7 to 8.5%, while  $\text{MgO}$  is in between 3.1 and 5.1%; (b) the last group here described corresponds to the more acidic component (granodiorites) of the basement and includes samples (RL3, RL4, RL6, 01RL1) showing  $\text{SiO}_2$  concentrations above 68.5 and up to 72.6%,  $\text{Al}_2\text{O}_3$  is in between 14 and 15.3% and  $\text{Fe}_2\text{O}_3$  contents vary from 1.6 to 3.9%.

Harker diagrams (Fig. 9) clearly show the behavior of major elements and Sr for all studied samples from the two groups: a positive correlation can be seen for  $\text{Na}_2\text{O}$ , whereas a negative correlation is observed for  $\text{TiO}_2$ ,  $\text{CaO}$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{MgO}$ . Correlations between Sr and  $\text{K}_2\text{O}$  with  $\text{SiO}_2$  can be roughly described as negative, despite the dispersion shown. These characteristics could be indicating cogenetic rocks.

In the An-Ab-Or diagram (Fig. 10a) the rock samples plot in the field of the tonalites, although a few are close to the field of granodiorites and two tonalite enclaves from El Nihuil mafic unit plot in the field of trondhjemites close to the tonalite field; in the AFM diagram samples follow a calc-alkaline trend (Fig. 10b). Differences between samples from the type section and gabbroic samples from the El Nihuil mafic unit are evident, since the latter follow a more tholeiitic signature. The bulk of samples from the Cerro La Ventana Formation plot within the field of metaluminous rocks; although a few are in the peraluminous field, their  $A/\text{CNK}$  ratios are of 1.1 maximum (Fig. 10e). In the R1 versus R2 tectonic discrimination diagram the samples plot in the field of pre-plate collision to syn-collision (Fig. 10d). In the expanded multielement diagram normalized to primitive mantle, it is shown a coherent evolution of the LIL and HFS elements for the studied samples suggesting cogenetic events. Only the presence of the Th and U positive anomaly in the El Nihuil mafic samples show a difference (Fig. 10f).







**Fig. 11** Chondrite-normalized REE diagrams for, **a** Leones type section; **b** El Nihuil mafic unit. Normalization values from Taylor and McLennan (1985)

## 6.2 Trace and Rare Earth Elements

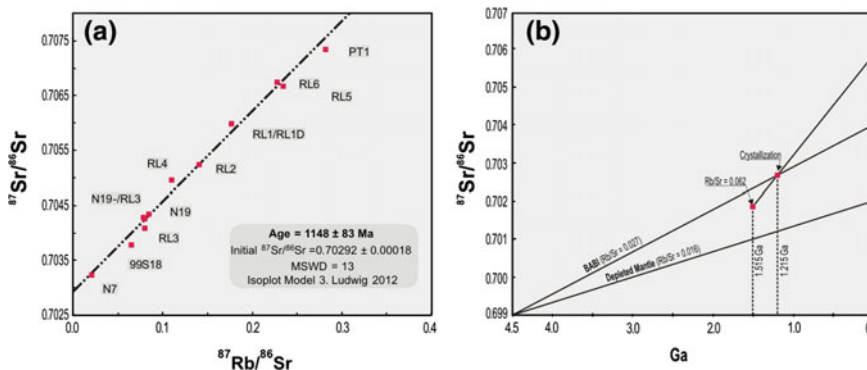
Sr/Y versus Y is a useful diagram (Fig. 10c) to discriminate between high and low-Al tonalite–trondhjemite–dacite (TTD) complexes. Main groups of samples plot accordingly to rocks from the Las Matras block (Sato et al. 2000), as low-Al TTD; however, some samples show high Sr/Y ratios which are typical of high-Al TTD in agreement with the diagram of Drummond and Defant (1990).

Samples from the type section of the Cerro La Ventana Formation as well as those from mafic and felsic deformed relicts included in the El Nihuil mafic unit are characterized by high values of Mg# ( $\text{Mg}/(\text{Mg} + \text{Fe}) \times 100$ ; gabbros: 65–67, tonalites 55–70), with respect to rocks with similar silica contents, including those from the Las Matras TTG (Sato et al. 2000, 2004). Furthermore, the Mg# is higher to that produced by slab melts at 1.4 GPa with a residue of gt + cpx  $\pm$  amph and is superposed with the hybridized slab melts and high magnesia adakites fields, according to Rapp et al. (1999). In order to describe the grade of magnesium enrichment with respect to other differentiated magma, the Mg#/K molar versus silica was plotted. Both the low and high silica rocks studied show similar Mg enrichment respect to K, signature which allows linking both groups of rocks to a same igneous evolution. The Mg#/K ratio is higher for the Cerro La Ventana Formation compared with Las Matras TTG series, suggesting a lower grade of differentiation for the first unit. In the R1 versus R2 diagram the tonalites and diorites from Leones type section plot in two separate groups. The rocks from the crustal enclaves included in El Nihuil mafic unit behave similarly to the tonalites (Fig. 10d). Samples from Leones creek have  $\text{La}/\text{Yb}_N$  ratios in between 5.5 and 86.3 and  $\text{Eu}_N/\text{Eu}^*$  ranges from 0.9 to 1.7; their chondrite-normalized REE diagram (Table 4; Fig. 11a) shows rather positive Eu anomalies. Samples from the El Nihuil

**Table 5** Rb–Sr isotopic data from samples of the Cerro La Ventana type section and El Nihuil mafic unit

	Lab. N °	Field N°	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	Error	$^{87}\text{Sr}/^{86}\text{Sr}$	Error
Leones type section	CIG 1003	RL1	16.1	263.7	0.1767	0.0049	0.70598	0.00007
	CIG 1004	RL2	14	288.2	0.1406	0.0039	0.70524	0.00012
	CIG 1005	RL3	13.3	482.6	0.0798	0.0022	0.70409	0.00008
	CIG 1006	RL4	19.3	508.1	0.1099	0.0031	0.70495	0.00009
	CIG 1007	RL5	36.4	449	0.2347	0.0066	0.70667	0.00009
	CIG 1008	RL6	34.3	436.3	0.2276	0.0064	0.70675	0.00009
	CIG 1009	PT1	25.8	265.1	0.2817	0.0079	0.70734	0.00009
	CIG 1015	RL1 D	16.1	263.7	0.1767	0.0049	0.70598	0.00011
	CIG 1016	RL3 D	13.3	482.6	0.0798	0.0022	0.70426	0.00012
El Nihuil Mafic Unit	CIG 1104	N19	23	787.5	0.0845	0.0017	0.704338	0.000028
	CIG 1105	99S22	28.6	492.5	0.1681	0.0034	0.70633	0.000019
	CIG 1197	99S18	7.8	348.6	0.0648	0.0013	0.703779	0.000035
	CIG 1201	N 7	4.3	603.9	0.0206	0.0004	0.703228	0.000063
	CIG 1203	N 19'	21.2	781.1	0.0786	0.0016	0.704282	0.000049
	CIG 1204	99S22'	25.8	480.7	0.1554	0.0031	0.706366	0.000035

mafic unit shows patterns depleted in HREE (Fig. 11b), with  $\text{La}/\text{Yb}_\text{N}$  ratios in between 15.3 and 16.9. Therefore, they are dissimilar to diorites from the same unit, which develop REE patterns parallel to N-MORB and have  $\text{La}/\text{Yb}_\text{N}$  ratios lower than 1.4. Gabbros display patterns with positive Eu anomalies typical of plagioclase-rich igneous rocks.



**Fig. 12** **a** Rb–Sr isochronic diagram using Isoplot Model 3 by Ludwig (2012) on samples from Leones type section (RL 2, RL 3, RL 5, RL 6, and PT1) and from El Nihuil mafic unit (N7, N19, 99S18). **b** Linear  $^{87}\text{Sr}/^{86}\text{Sr}$  evolution of BABI and of a depleted mantle through time (Faure 1986). The initial  $^{87}\text{Sr}/^{86}\text{Sr}$  found for Cerro La Ventana Fm including samples from El Nihuil mafic unit (0.7029) suggest a derivation from mantle represented by BABI (Rb/Sr = 0.027) considering a 1.2 Ga crystallization age. Another explanation could be refusion of a magma (with Rb/Sr = 0.047) extracted from depleted mantle (Rb/Sr = 0.016) at ca. 1.5 Ga

## 7 Isotopic Data

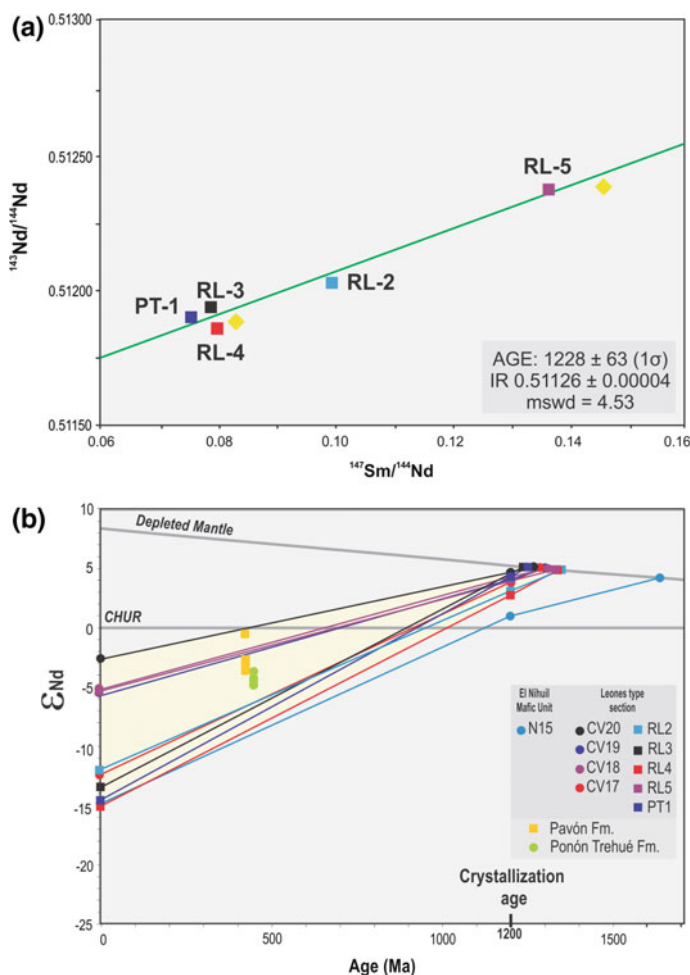
**Rb–Sr:** The Rb–Sr systematic was applied by Cingolani and Varela (1999) on 7 whole-rock samples (RL1, RL2, RL3, RL4, RL5, RL6, and PT1), from the granodioritic–tonalitic facies outcropping at the type section of the Cerro La Ventana Formation along Leones and Ponón-Trehué creeks. The Rb concentrations are rather low and vary between 13.3 and 36.4 ppm, while Sr concentrations are high and range from 263.7 to 508.1 ppm; therefore, the  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios are between 0.0798 and 0.2817. According to the model from Williamson (1968), the isochrone age is  $1063 \pm 106$  Ma, and the initial ratio  $^{87}\text{Sr}/^{86}\text{Sr}$  is of  $0.7032 \pm 0.0003$  with MSWD of 1.06. Data recalculated using the Isoplot Model 3 (Ludwig 2012) show an alignment within a low range of  $^{87}\text{Rb}/^{86}\text{Sr}$  (<0.3); the age obtained is  $1109 \pm 130$  Ma (1sigma), initial ratio  $^{87}\text{Sr}/^{86}\text{Sr}$ :  $0.70304 \pm 0.00032$ , and MSWD of 7.4 (Cingolani and Varela 1999).

Four samples from the El Nihuil mafic unit (N19, 99S22, 99S18 and N7), considered as part of the basement, were recently added (Table 5; Fig. 12a). They show Rb concentrations in between 4.3 and 28.6 ppm, while the Sr concentrations range from 348.6 to 787.5 ppm; the  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios are between 0.0206 and 0.1681. Comparing to data from the type section of the Cerro La Ventana Formation, the El Nihuil mafic unit has lower Rb and higher Sr contents. Using all samples from both regions altogether (excluding 99S22 since it is out of the linear isochrone) following Isoplot Model 3 (Ludwig 2012), an isochron with  $1148 \pm 83$  Ma (1sigma), initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.70292 \pm 0.00018$ , and MSWD = 13 is recorded (Fig. 11a). The low initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is indicative of a

**Table 6** Sm-Nd isotopic data for samples taken at Leones type section and El Nihuil Mafic Unit (N15)

Sample	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	Error	$^{143}\text{Nd}/^{144}\text{Nd}$	Error (2 $\sigma$ )	$\epsilon_{\text{Nd}(0)}$	$f_{\text{Sm}/\text{Nd}}$	$\epsilon_{\text{Nd}}$ ( $t = 1.2 \text{ Ga}$ )	$T_{\text{DM}}^a$ (Ma)	$\epsilon_{\text{NdTDM}}$
CV17	2.092	14.104	0.0897	0.0005	0.511996	0.000010	-12.52	-0.54	3.86	1286.8	5.05
CV18	3.146	14.452	0.1316	0.0008	0.512338	0.000012	-5.86	-0.33	4.10	1308.4	5.00
CV19	3.197	14.240	0.1358	0.0008	0.512381	0.000010	-5.00	-0.31	4.32	1291.9	5.04
CV20	3.497	14.221	0.1487	0.0009	0.512503	0.000006	-2.64	-0.24	4.71	1264.1	5.10
N15	3.29	18.88	0.1052	nd	0.511872	nd	-14.94	-0.46	-0.94	1640.0	4.2
RL2	1.46	8.91	0.099344	nd	0.512031	0.000019	-11.84	-0.50	3.1	1345.3	4.91
RL3	1.63	12.75	0.078509	nd	0.511939	0.000012	-13.63	-0.61	4.64	1234.8	5.17
RL4	3.01	22.85	0.079511	nd	0.511863	0.000016	-15.12	-0.60	2.8	1341.9	4.92
RL5	1.85	8.20	0.136597	nd	0.512370	0.000021	-5.22	-0.31	4.0	1325.1	4.96
PT1	2.01	16.17	0.075173	nd	0.511902	0.000027	-14.36	-0.62	4.25	1256.3	5.12

$T_{\text{DM}}^a$ : based on De Paolo (1981) ( $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ );  $\epsilon_{\text{Nd}(0)} = \{[(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}}/0.512638] - 1\} \times 10^4$ , where  $^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}} = 0.512638$ .  
 $f_{\text{Sm}/\text{Nd}} = \{[(^{147}\text{Sm}/^{144}\text{Nd})_{\text{sample}}/0.1967] - 1\}$ , where  $^{147}\text{Sm}/^{144}\text{Nd}_{\text{CHUR}} = 0.1967$  (Hamilton et al. 1983). *nd* no data



**Fig. 13** **a** Sm-Nd isochron diagram from Cerro La Ventana Formation type section samples. **b**  $\epsilon_{\text{Nd}}$  data for samples from Leones type section and El Nihuil Mafic Unit. Data of Ordovician sequences (Pavón and Ponón Trehué Fms) are also shown (Abre et al. 2011; Abre et al., this volume)

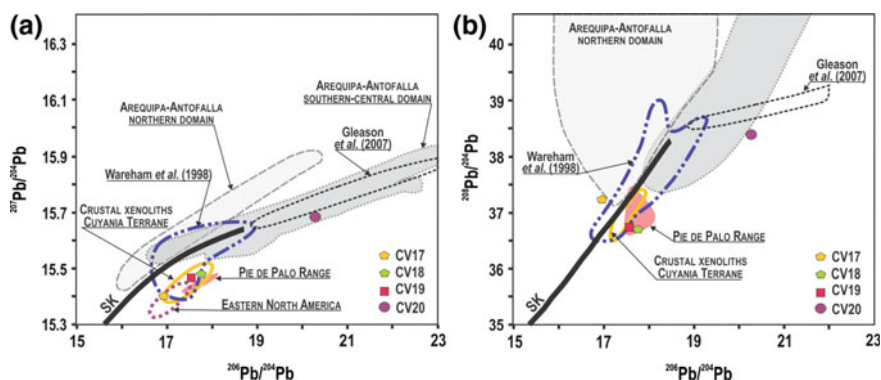
slight evolved Mesoproterozoic source for the tonalitic rocks sampled at Leones and Ponón Trehué creeks as well as for samples from the El Nihuil mafic unit.

If we consider a linear strontium isotopic evolution of BABI through time with  $^{87}\text{Sr}/^{86}\text{Sr}$  from 0.699 to 0.704 ( $\text{Rb}/\text{Sr} = 0.027$ ; Faure 1986) during the 4.5 Ga, the  $^{87}\text{Sr}/^{86}\text{Sr}$  value for *ca.* 1.2 Ga (crystallization age) is close to the value of  $0.70292 \pm 0.00018$  obtained from the Rb–Sr isochronic diagram (Fig. 12b). This could suggest a direct mantle derivation for the magma at this time. The low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios as well as the Potassium contents and high Mg# permit to interpret that the studied samples are juvenile rocks (less evolved), similar to the modern

**Table 7** Pb–Pb analytical isotopic data of samples from the Cerro La Ventana Fm

Sample	$^{206}\text{Pb}/^{204}\text{Pb}$	Error <sup>a</sup>	$^{207}\text{Pb}/^{204}\text{Pb}$	Error <sup>a</sup>	$^{208}\text{Pb}/^{204}\text{Pb}$	Error <sup>a</sup>
CV17	16.965	0.014	15.398	0.017	37.239	0.020
CV18	17.800	0.013	15.473	0.014	36.685	0.015
CV19	17.580	0.009	15.464	0.011	36.749	0.012
CV20	20.319	0.010	15.684	0.010	38.385	0.010

Isotopic ratios corrected for 0.095‰/u.m.a mass fractionation; error<sup>a</sup>: standard relative error (60 measurements in average); total blank during measurements = 119 pg; average isotopic ratios of standard NBS-981 including a deviation of 1sigma (01–08/2010):  $^{206}\text{Pb}/^{204}\text{Pb} = 16.898 \pm 0.003$ ;  $^{207}\text{Pb}/^{204}\text{Pb} = 15.440 \pm 0.003$ ;  $^{208}\text{Pb}/^{204}\text{Pb} = 36.542 \pm 0.010$



**Fig. 14** a, b Pb isotopes of the Cerro La Ventana Fm samples and other basement regions of South America (Ramos 2004). Note that the samples CV17, CV18, and CV19 have distinctive nonradiogenic signature near the field of Pie de Palo complex rocks and crustal xenoliths of Cuyania Terrane; SK = lead isotope curves after Stacey and Kramers (1975)

adakites or Precambrian TTD series. In this sense, are equivalents to the “Grenvillian-age” Las Matras tonalite–trondhjemite pluton (Sato et al. 2000, 2004; Varela et al. 2011).

**Sm–Nd:** Samples selected for whole-rock Sm–Nd isotopic analyses performed at the Laboratorio de Geología Isotópica, Porto Alegre-Brazil, comprise basement rocks from the Leones (type section of Cerro La Ventana Formation: CV17 to CV20, RL2 to RL5 and PT1) as well as one from the El Nihuil mafic unit (sample N15; Table 6). This isotopic work emphasized the crustal residence ( $T_{\text{DM}}$ ) age determinations and allows us to recognition crustal segments to understand the history of tectonic accretion.

An acceptable isochron was obtained using five Sm–Nd analyses and two duplicates (Fig. 13a), indicating an age of  $1228 \pm 63$  Ma (1 sigma), and MSWD 4.53 and initial  $^{143}\text{Nd}/^{144}\text{Nd}$   $0.51126 \pm 0.00004$ . The model ages ( $T_{\text{DM}}$ ) calculated according to DePaolo (1981) for ten samples are in the range 1.23–1.64 Ga. The  $\varepsilon\text{Nd}_{(1200)}$  for these samples (Fig. 13b) is in between  $-0.94$  and  $+4.7$  indicating a ‘depleted’ source, less evolved than CHUR for the time of crystallization, which is

**Table 8** U–Pb analytical data and typology of zircons studied by isotope dilution and TIMS methodology at University of São Paulo, Brazil

SPU	Magnetic fraction	Mineral typology	207/235 <sup>a</sup>	Error (%)	Coef.	238/206	Error (%)	207/206	Error (%)	206/204 <sup>b</sup>	Pb (ppm)	U (ppm)	Weight (m)	206/238 Age (Ma)	207/235 Age (Ma)	207/206 Age (Ma)
02-RL-103 RIO SECO DE LOS LEONES																
2164	D	P(2-4/1), Fr, T, Ambar, cl, Cl, I, F	2.28546	0.49	0.205677	0.484	0.98916	4.86199235	0.484	0.080591	0.0719	385.2	0.037	1206	1208	1212
2165	E	P (2-1.5/1), T, Ot, Pmk, Cl, I, F	2.26035	0.481	0.203087	0.477	0.99332	4.92399809	0.477	0.080722	0.0554	348.1	0.028	1192	1200	1215
2161	A	Py(1.5/1), T, Pmk, Cl	2.29936	0.487	0.206338	0.487	0.99222	4.84641704	0.484	0.080821	0.0607	176.4	0.037	1209	1212	1217
Typology—Zircon																
Shape		Color/Transparency							Internal features							
P(x/y)	Prismatic crystals	T	Transparent crystals						Cl	Crystal with no or few inclusions or fractures						
Py	Prismatic crystals with well-developed pyramidal facets	Ot	Opaque or translucent crystal						I	Crystal with frequent inclusions						
Fr	Crystals fragments								F	Crystal with frequent fractures						

SPU: laboratory number

Magnetic fractions: numbers in parentheses indicated the tilt used on Frantz separator at 1.5 A current

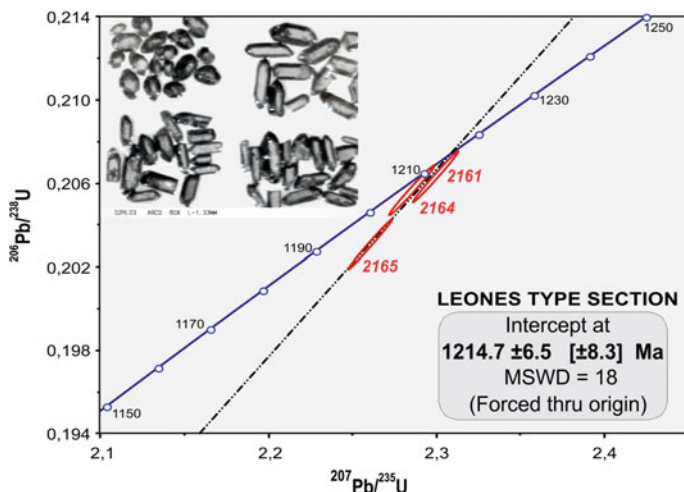
<sup>a</sup>Radiogenic Pb corrected for blank and initial Pb; U corrected for blank;

<sup>b</sup>Not corrected for blank or nonradiogenic Pb

Total U and Pb concentrations corrected for analytical blank

Ages: given in Ma using Ludwig Isoplot/Ex program (1998), decay constants recommended by Steiger and Jäger (1977)





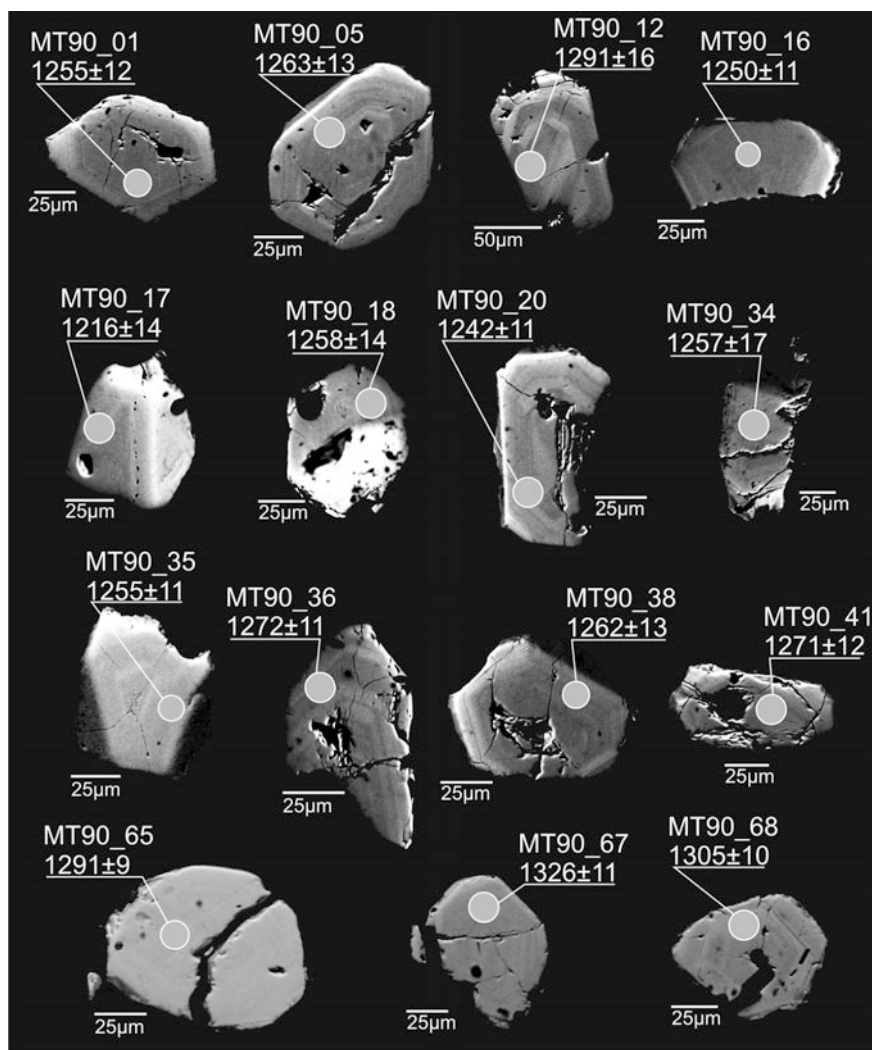
**Fig. 15** Concordia plot of zircons from Leones sample analyzed by isotope dilution and TIMS methodology at University of São Paulo, Brazil. In the inset the microscope image of zircon fractions

rather similar to the immature source for the orthogneisses found in Western Pampean Ranges (Sato et al. 2000; Ramos 2004). Dating obtained from both, Sm–Nd and Rb–Sr methods are roughly coincident within errors, indicating that an average age of 1200 Ma can be reasonably proposed as crystallization age for the Cerro La Ventana Formation with contribution of juvenile material.

**Pb–Pb:** Pb analyses were performed on four whole-rock samples from the Cerro La Ventana Formation (CV17 to CV20);  $^{206}\text{Pb}/^{204}\text{Pb}$  range from 16.965 to 20.319,  $^{208}\text{Pb}/^{204}\text{Pb}$  range from 36.685 to 38.385, whereas the radiogenic lead ( $^{207}\text{Pb}/^{204}\text{Pb}$ ) is in between 15.398 and 15.684 (Table 7). Samples from the Cerro La Ventana Formation plot in a  $^{207}\text{Pb}/^{204}\text{Pb}$  diagram (Fig. 14a) below the Stacey and Kramers (1975) second-stage Pb evolution curve for average crust, similar to rocks from the basement of Cuyania Terrane (Pie de Palo Range and crustal xenoliths). In a  $^{208}\text{Pb}/^{204}\text{Pb}$  diagram (Fig. 14b) most of the samples also plot below the second-stage Pb evolution curve for average crust as basement rocks from the Cuyania Terrane, except for sample CV17 which is above such a curve. Although sample CV20 (garnet it was described on thin section) remains below SK curve, it shows the higher Pb ratios, particularly regarding  $^{206}\text{Pb}/^{204}\text{Pb}$ , and being therefore dissimilar to crustal xenoliths and Pie de Palo rocks from the basement of the Cuyania Terrane.

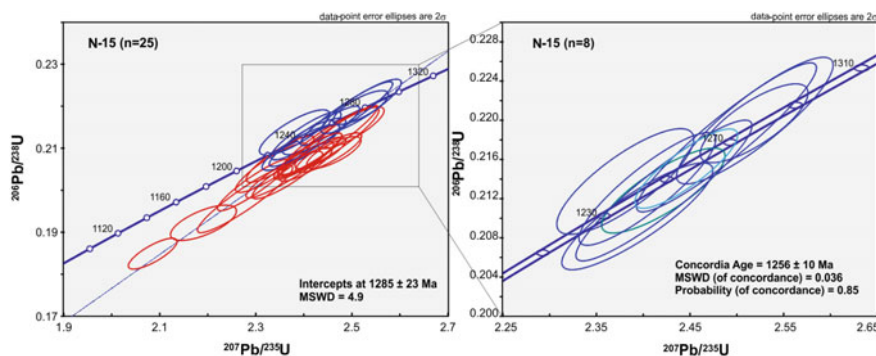
**U–Pb:** Two methods were applied: the isotope dilution (ID) with thermal ionization mass spectrometry (TIMS) and in situ LA-ICP-MS as follow:

- (a) **ID-TIMS:** A sample of the tonalitic facies located at Leones River type section (01RL03) with 55.78% of  $\text{SiO}_2$  was chosen for zircon U–Pb TIMS dating. The analyses were carried out at the Centro de Pesquisas Geocronológicas, São



**Fig. 16** Backscattering images of selected zircon crystals with spot locations by LA-ICP-MS analyses at LGI-UFRGS, Porto Alegre, Brazil laboratory. Ages in Ma

Paulo, Brazil. Four zircon fractions (Table 8; Fig. 15) were analyzed, with prismatic, euhedric and well-developed crystal faces. All were transparent crystals without inclusions or fractures. The obtained age of  $1214.7 \pm 6.5$  Ma was based on main concordant 2161 and 2164 fractions and 2165 fraction with little Pb lost. The 2162 fractions with probable Pb crustal heritage were not considered in the age determination. The Mesoproterozoic obtained value is

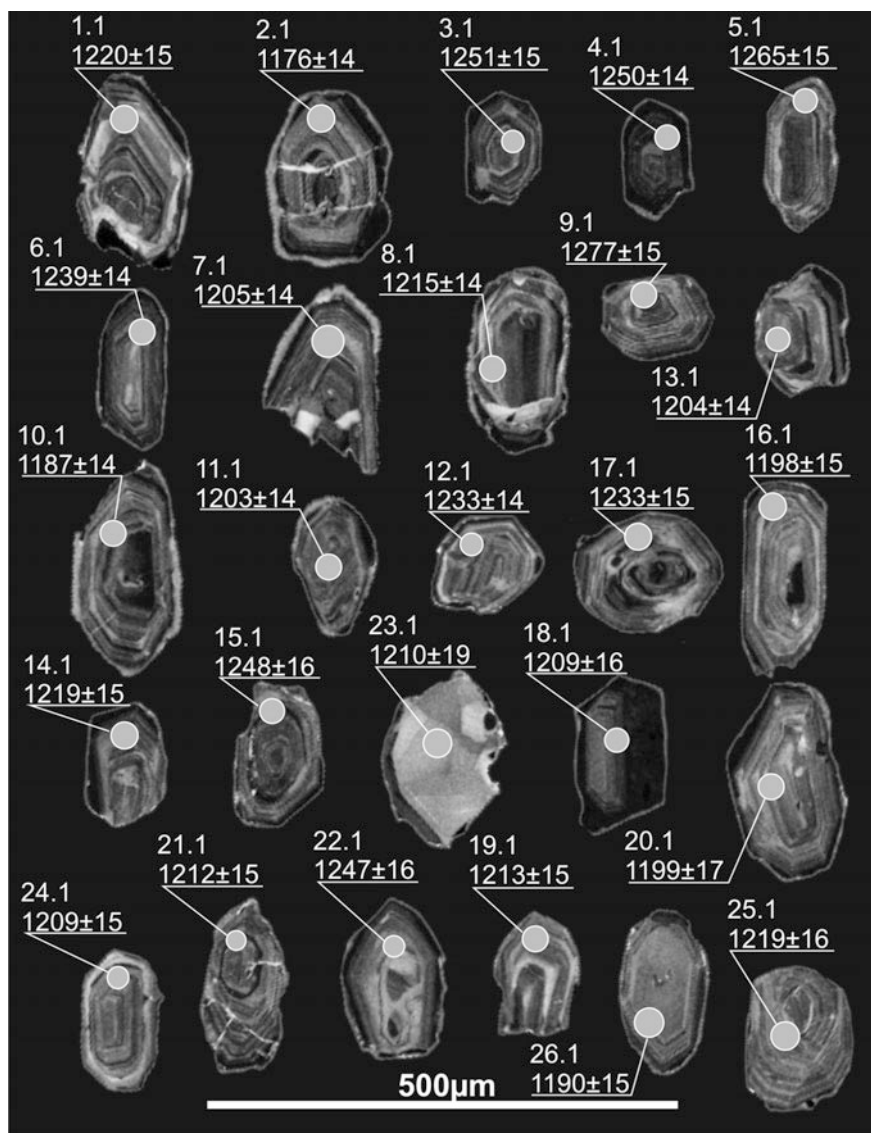


**Fig. 17** Concordia plot of zircons from the sample N15 ( $n = 25$ ) from El Nihuil mafic unit; on the right detail of eight concordant results

interpreted as the zircon crystallization age during the emplacement of the tonalitic magmatic rock.

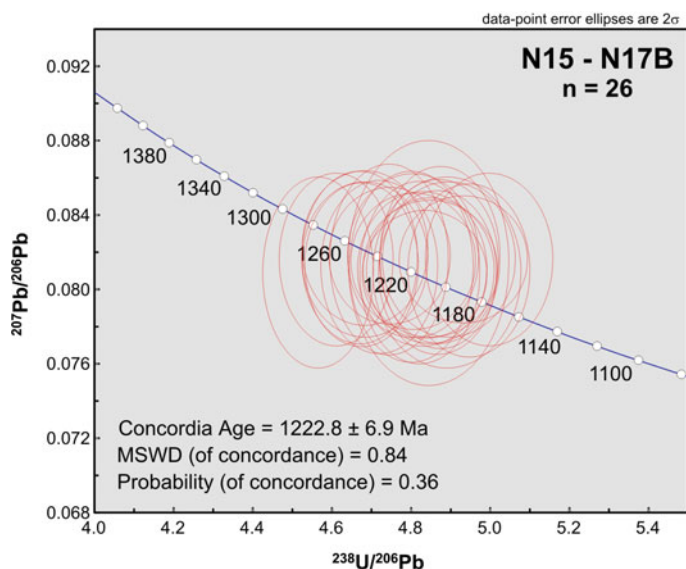
- (b) **LA-ICP-MS:** At the region of Lomas Orientales as part of the El Nihuil mafic unit (Cingolani et al. 2012b) crop out a meter-scale relics of tonalite–orthogneissic rocks with intermediate composition ( $\text{SiO}_2$  around 66%) bearing a foliation with  $\text{N}83^\circ\text{W}/54^\circ\text{SW}$  (Fig. 5). The in situ U–Pb (LA-ICP-MS) zircon data on the sample N15 was obtained at the Laboratorio de Geología Isotópica, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil. The results yielded a  $^{207}\text{Pb}/^{208}\text{Pb}$  weighted mean age of  $1285 \pm 23$  Ma based on 25 spots (Fig. 16; Table 9). The zircon grains vary from colorless to brown, and are prismatic and subhedral with few inclusions. Some grains show rounded terminations. Backscattering images reveal that most grains display oscillatory zoning (Fig. 16). Some grains exhibit metamictization in their central part. Cracks are relatively common. The data point out a Mesoproterozoic crystallization age when all 25 results are plotted despite some scatter illustrated by the relatively high MSWD (Fig. 17a). Nevertheless, seven concordant results yielded a  $1256 \pm 10$  Ma Concordia age (Fig. 17b) that can be considered the crystallization time.

The sample N15–N17B (tonalitic orthogneiss) taken at the same locality of Lomas Orientales along the El Nihuil mafic unit was analyzed by the in situ U–Pb (LA-ICP-MS) zircon data at the Centro de Pesquisas Geocronológicas, São Paulo, Brazil (Fig. 18). The obtained age plotted in a Tera–Wasserburg diagram is  $1222.8 \pm 6.9$  Ma ( $n = 26$ ) and record MSWD (concord.) = 0.8 (Fig. 19; Table 10) with 2 sigma errors. With these U–Pb isotopic data we confirm Rb–Sr and Sm–Nd age showing the Mesoproterozoic (boundary of Ectasian–Stenian Periods, after the IUGS International Chronostratigraphic Chart 2015) basement rocks of the San Rafael Block. The obtained age *ca.* 1.2 Ga is interpreted as a Grenvillian (Mesoproterozoic) zircon crystallization age for the Cerro La Ventana Formation and it is quite similar to those belonging to the basement of other regions from the



**Fig. 18** Cathodoluminescence (CL) images of selected zircon crystals with spot locations by LA-ICP-MS analyses at CPGeo-USP, São Paulo, Brazil laboratory. Ages in Ma

Cuyania allochthonous terrane (Ramos 2004; Sato et al. 2004; Morata et al. 2010; Varela et al. 2011 and references). Rapela et al. (2010) recognized in Western Pampean Ranges and Precordilleran xenoliths that the Mesoproterozoic geodynamic history evolved during 300 Ma, with a complex orogenic evolution dominated by convergent tectonics and accretion of juvenile oceanic arcs to the continent



**Fig. 19** Tera–Wasserburg diagram showing the plot of zircons from the sample N15-N17B from El Nihuil mafic unit

and intraplate magmatism. On the other hand Kumar et al. (2007) proposed a global thermal event at 1.1 Ga as responsible for the development of widespread global magmatic activity during this time.

## 8 Final Remarks

In summary, having interpreted all data presented the following statements can be drawn,

- (a) The San Rafael Block crustal basement called Cerro La Ventana Formation crops out in two localities, at the Leones (type section) and within El Nihuil mafic unit, both areas showing ductile deformation.
- (b) The outcrops at the type section record the primary contact between the basement and Ordovician platform sedimentary rocks, which is unique within the Cuyania terrane.
- (c) The Cerro La Ventana Formation corresponds to a metamorphosed volcano-plutonic complex with hardly any sedimentary protolith that reached the high greenschist–amphibolite facies.
- (d) The ductile deformation coeval with the metamorphism resulted in the folding of the complex and developed a penetrative foliation, which should have occurred long before its exhumation during Early Ordovician and probably

during the late stages of the Mesoproterozoic Grenville orogeny. This is a clear difference with Las Matras pluton from which no thermal overprint has been reported.

- (e) Geochemical data indicate that the Cerro La Ventana Formation comprises cogenetic rocks with a main calc-alkaline and metaluminous character. The bulk of samples have Sr/Y ratios typical of low-Al TTD, although some can be described as high-Al TTD. The Mg# /K ratio is higher in the Cerro La Ventana Formation compared with Las Matras TTG series suggesting less differentiation for the first one. The chondrite-normalized REE diagrams for Leones samples have Eu anomalies rather positive and gabbros from El Nihuil region display patterns with positive Eu anomalies typical of plagioclase-rich igneous rocks.
- (f) The Rb–Sr data defined an isochron with  $1148 \pm 83$  Ma, initial  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70292 \pm 0.00018$ . The low initial ratio is indicative of a slight evolved Mesoproterozoic source. An acceptable isochron was obtained using Sm–Nd methodology indicating an age of  $1228 \pm 63$  Ma. The model ages ( $T_{\text{DM}}$ ) are in the range 1.23–1.64 Ga with Epsilon Nd<sub>(1200)</sub> in between –0.94 and +4.7 recording a ‘depleted’ source, less evolved than CHUR for the time of crystallization.
- (g) In Pb–Pb diagrams studied samples from the Cerro La Ventana plot similar to the rocks from the basement of Cuyania Terrane (Pie de Palo Range and crustal xenoliths) showing a distinctive nonradiogenic signature such as the Grenvillian belt of eastern Laurentia.
- (h) The tonalitic facies located at the Leones River type section was chosen for zircon U–Pb TIMS dating and the obtained crystallization age is  $1214.7 \pm 6.5$  Ma. The in situ U–Pb (LA-ICP-MS) zircon data from El Nihuil Mafic Unit (orthogneisses), analyzed in two different laboratories, plotted in a Concordia diagram record an intercept at  $1256 \pm 10$  Ma, and the second age plotted in a Tera–Wasserburg diagram is  $1222.8 \pm 6.9$  Ma.
- (i) The isotopic data confirm the Mesoproterozoic age for the basement of the San Rafael Block; this age can also be found in basement rocks of other regions considered as part of the Laurentia derived Cuyania terrane in the proto-Andean margin of Gondwana.

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