PERGAMON

Journal of South American Earth Sciences 13 (2000) 587–610

Journal of
South American
Earth Sciences

www.elsevier.nl/locate/jsames

The Las Matras tonalitic–trondhjemitic pluton, central Argentina: Grenvillian-age constraints, geochemical characteristics, and regional implications

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Received 1 March 1999; received revised form 1 December 1999; accepted 1 April 2000

Abstract

The N–S trending belt with Grenvillian-age rocks developed in central western Argentina represents the basement of an allochthonous terrane derived from Laurentia during the Early Paleozoic. The Las Matras pluton (36°46′S, 67°07′W) is located at the southern extension of this belt in the Las Matras Block. It consists of a low-Al tonalitic to trondhjemitic facies characteristic of an arc magmatism. Isotopic studies yielded Grenvillian Rb–Sr (1212 ± 47 Ma) and Sm–Nd (1188 ± 47 Ma) ages which, due to the undeformed and non-metamorphosed character of the pluton, are interpreted to represent a crystallization age of around 1200 Ma. Although this age is slightly older than available dates from other exposures of the same belt, and the undeformed feature is also distinctive for Las Matras, the depleted Sr and Nd isotopic signatures of the pluton agree with those from other magmatic rocks involved in that belt. The differences found between Las Matras and the northern exposures indicate that this belt with Grenvillian-age rocks comprises regions of non-homogeneous evolution. Although the correlation of the Lower Paleozoic platform carbonates from the sedimentary cover of the Grenvillian-age basement rocks suggests the surroundings of the Southern Grenville Province (Texas and northern Mexico) as the probable detachment site for the Argentine belt, comparison of magmatic and tectonic processes involved in these basement rocks does not indicate similar evolutions. This fact can suggest an independent evolution of the Argentine belt prior to amalgamation to the Laurentian Grenville orogen. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Grenville orogeny; Central and western Argentina; Trondhjemites; Terrane accretion

1. Introduction

The main orogenic activities in the crystalline basement of central and western Argentina (Fig. 1) took place during latest Proterozoic to Early Paleozoic times (Pampean and Famatinian orogenic cycles of the Proto–Andean southwestern margin of Gondwana). However, older rocks of Mesoproterozoic Grenvillian ages have also been identified within this orogen. These older rocks were first documented by Varela and Dalla Salda (1992; Rb–Sr data) at Sierra de Pie de Palo, Western Sierras Pampeanas. After that, metamorphic rocks of similar ages (U–Pb, Sm–Nd, Rb–Sr) were successively found in a N–S belt comprising the Precordillera (Abruzzi et al., 1993; Mahlburg Kay et al., 1996), Western Sierras Pampeanas (McDonough et al., 1993; Ramos et al., 1996; Varela et al., 1996; Pankhurst and Rapela, 1998), Cordillera Frontal (Ramos and Basei, 1997; Basei et al., 1998), and San Rafael Block (Astini et al., 1996; Cingolani and Varela, 1999). Recently, the first results of Rb–Sr and Sm–Nd Mesoproterozoic ages were reported by Sato et al. (1998, 1999) for a tonalitic to trondhjemitic pluton at Las Matras in the La Pampa Province of central Argentina. This pluton is located just at the southern extension of this N–S belt. It seems to belong to the same tectonic unit, although some geological features are different, like those concerning the visible lack of ductile deformation. To the east of this almost 900-km-long belt with Grenvillian-age rocks, a parallel belt comprises the Eastern Sierras Pampeanas and the Chadileuvú Block, in which the Lower Paleozoic Famatinian tectonic, metamorphic, and igneous activities are the most important features.

The Grenvillian-age rocks of central and western Argentina have been involved in the basement of Laurentian-derived exotic terrane proposals. These terranes should have docked to the southwestern margin of Gondwana during the Early Paleozoic Famatinian orogeny; they have

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PII: S0895-9811(00)00053-5

been called “Occidentalia” (Dalla Salda et al., 1992a,b, 1998; Dalziel et al., 1994), “Precordillera” (Astini et al., 1995, 1996; Astini, 1998; Rapela et al., 1998a), “Cuyania” (Ramos, 1995; Ramos et al., 1996, 1998), “Texas plateau” (Dalziel, 1997), and “Chilenia” (Ramos et al., 1984). These various proposals do not coincide in their terrane extensions, and they are based on the following tectonic hypothesis: a large part of Laurentia was left behind after a continent–continent collision (Occidentalia), an independant smaller block separated from Laurentia and collided with Gondwana (Precordillera and Cuyania), and a part of a continental plateau located adjacent to Laurentia was left after a collision against Gondwana (Texas plateau). Chilenia has been proposed as another smaller block docked later during the Early Paleozoic. The most characteristic rocks of these terranes, especially those of the Precordillera and Cuyania terrane, are Grenvillian-age basement rocks and a sedimentary cover. The similarity in isotopic signatures of these basement rocks and those of the North American Grenville Province was pointed out by Mahlburg Kay et al. (1996). Among the cover rocks, the most characteristic are the Lower Paleozoic platform carbonate deposits of the Precordillera, whose fossiliferous content, stratigraphy, and paleomagnetic data are comparable to those of the Appalachian equivalent strata (Bond et al., 1984; Astini et al., 1995; Thomas and Astini, 1996; 1999; Astini, 1998; Benedetto, 1998; Keller et al., 1998; Rapalini and Astini, 1998). These comparisons include the possibilities that the North American Appalachian orogeny and the South American Famatinian orogeny initiated as a single complex mountain system (Dalla Salda et al., 1992b; Dalziel et al., 1994) or developed in close proximity (Dalziel, 1997).

It is beyond the scope of this paper to discuss the validity of the different tectonic hypotheses and the precise limits of each proposed terrane. Here, we compare our data on the Las Matras area with all the Grenvillian-age rocks of central and western Argentina and include all of them within the term “belt with Grenvillian-age rocks.”

The Rb–Sr, Sm–Nd, and K–Ar ages obtained from the Las Matras pluton as well as their geological and geochemical features are reported in this paper. They are the first indications that the belt with Grenvillian-age rocks of central and western Argentina extends up to latitudes close to 37°S. Hence, they contribute to our knowledge of the geology of this Mesoproterozoic basement belt and to the geotectonic framework related to the Laurentia–Gondwana interaction.

2. Geological setting

The Las Matras pluton (36°46′S, 67°07′W) is located in the northwestern part of La Pampa Province (Fig. 1). After a brief reference in accord with an unpublished report of Ortiz (1967), Llambías (1975) and Linares et al. (1980) described a dioritic pluton of Late Proterozoic age, intruded by a Paleozoic granite. The dates obtained by the latter authors were in the range 810–690 Ma (K–Ar in amphiboles and whole-rock) for the basic facies and 392–382 Ma (K–Ar whole-rock) for the acidic facies.

Younger rock units include Upper Cambrian–Lower Ordovician (Melchor et al., 1999a,c) limestones and marbles (San Jorge Formation: Criado Roqué, 1972) (?)Upper Carboniferous quartzites (Agua Escondida Formation: González Díaz and García, 1968) and Permo-Triassic volcanic rocks (Linares et al., 1980). The rock association of this region of La Pampa Province is similar to that of the San Rafael Block to the northwest (Fig. 1), and for this reason we propose the new name “Las Matras Block” (Fig. 1). This block is in contrast with southeastern La Pampa Province where the (?)Upper Cambrian to Ordovician metamorphic rocks and Upper Cambrian to Devonian granitoids are the most important units underlying the Permo-Triassic volcanics (Linares et al., 1980; Sato et al., 1996; Tickyj et al., 1999b). Based on this latter rock association, the southeastern region of La Pampa Province was termed the Chadileuvú Block (Fig. 1) by Llambías and Caminos (1987) and Llambías et al. (1996).

The limestones of the San Jorge Formation and the quartzites of the Agua Escondida Formation crop out in close spatial association within the Las Matras Block, although the stratigraphic relationship between them is not yet clear. The recently obtained deposition age of the San Jorge Formation (Melchor et al., 1999a) indicates it is coeval with the Cambro–Ordovician carbonates of the Precordillera and San Rafael Block, which have Laurentian affinities. The possibility remains open that the quartzites exposed in the area of Las Matras — although assigned to the Late Carboniferous Agua Escondida Formation by Linares et al. (1980) — can also be correlated with the clastic facies of those carbonate shelf deposits extending from the Precordillera.

The Las Matras pluton appears without exposed country rock relationship. The nearest metamorphic rocks recognized are those in a well 280 m in the underground of the “Subcuenca de Alvear,” 70 km north of Las Matras. They are garnet–hornblende–biotite–schists, with one K–Ar determination of 605 Ma (Criado Roqué, 1979). Based on their lithology and age, Criado Roqué (1979) correlated these rocks with the Cerro Ventana Formation (Criado Roqué, 1972), the metamorphic basement of the San Rafael Block. Criado Roqué (1979) also mentioned the possibility of correlation with the Las Matras pluton, based on preliminary K–Ar ages of this pluton published later by Linares et al. (1980). The Grenvillian age of the Cerro Ventana Formation was later confirmed by U–Pb and Rb–Sr methods (Astini et al., 1996; Cingolani and Varela, 1999).

Metamorphic rocks are found in the Chadileuvú Block, 150 km southeast of Las Matras (Linares et al., 1980; Tickyj, 1999). There, the metamorphism took place during (?) latest Precambrian to Early Paleozoic times. Within the Chadileuvú Block, metamorphic rocks are described,

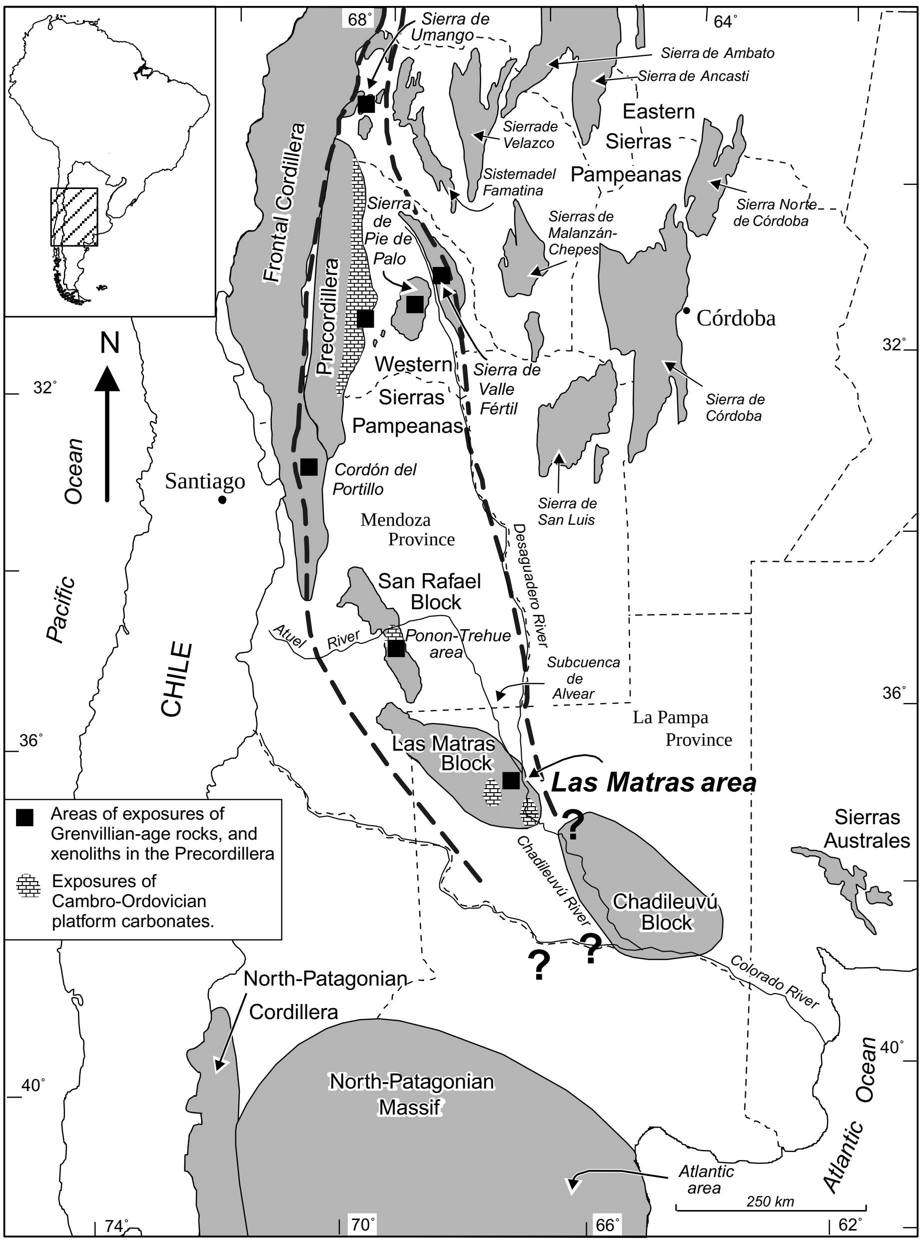

Fig. 1. The Proterozoic and Paleozoic geological units of central and western Argentina. The areas with Grenvillian-age rock exposures (Western Sierras Pampeanas, Precordillera, Frontal Cordillera, San Rafael Block, and Las Matras Block) are arranged in a N–S belt, defining a "belt with Grenvillian-age rocks." This belt does not mean a new terrane proposal, although the following proposed terranes are involved, with different areal extensions and paleotectonic hypotheses referring to a terrane of Laurentian origin: Occidentalia (Dalla Salda et al., 1992a), Precordillera (Astini et al., 1995), Cuyania (Ramos, 1995), Texas Plateau (Dalziel, 1997) and Chilenia (Ramos et al., 1984). Las Matras is located in the southern region of this belt (Las Matras Block). The Eastern Sierras Pampeanas and the Chadileuvú Block are located to the east of this belt, where the most important orogenic activities took place during the latest Proterozoic to Early Paleozoic times.

among others, in the area of Valle Daza, where a mafic granoblastic rock containing clinopyroxene, amphibole, quartz, plagioclase, and K-felspar was dated at 884 Ma (K–Ar amphibole) by Linares et al. (1980).

In the area of Las Matras (Fig. 2) the poor exposures of the pluton are found in an area of 4×4 km^2 on very low and gentle slopes, covered by unconsolidated sediments and vegetation. The outcrops are mainly concentrated in the eastern part of the area depicted in Fig. 2. To the west, there are exposures of quartzite beds (Cerro El Poleo), where the general bedding trend is N45°W and subvertical. The exposed sequence was characterized by Melchor (1996) as consisting of light gray fine quartz arenites, partially stained by reddish oxides, and scarce layers of conglomeradic arenites and fine-grained conglomerates. Tabular beds with parallel lamination predominate; occasional layers with cross-bedding were also found. Although very small outcrops of the Las Matras pluton are

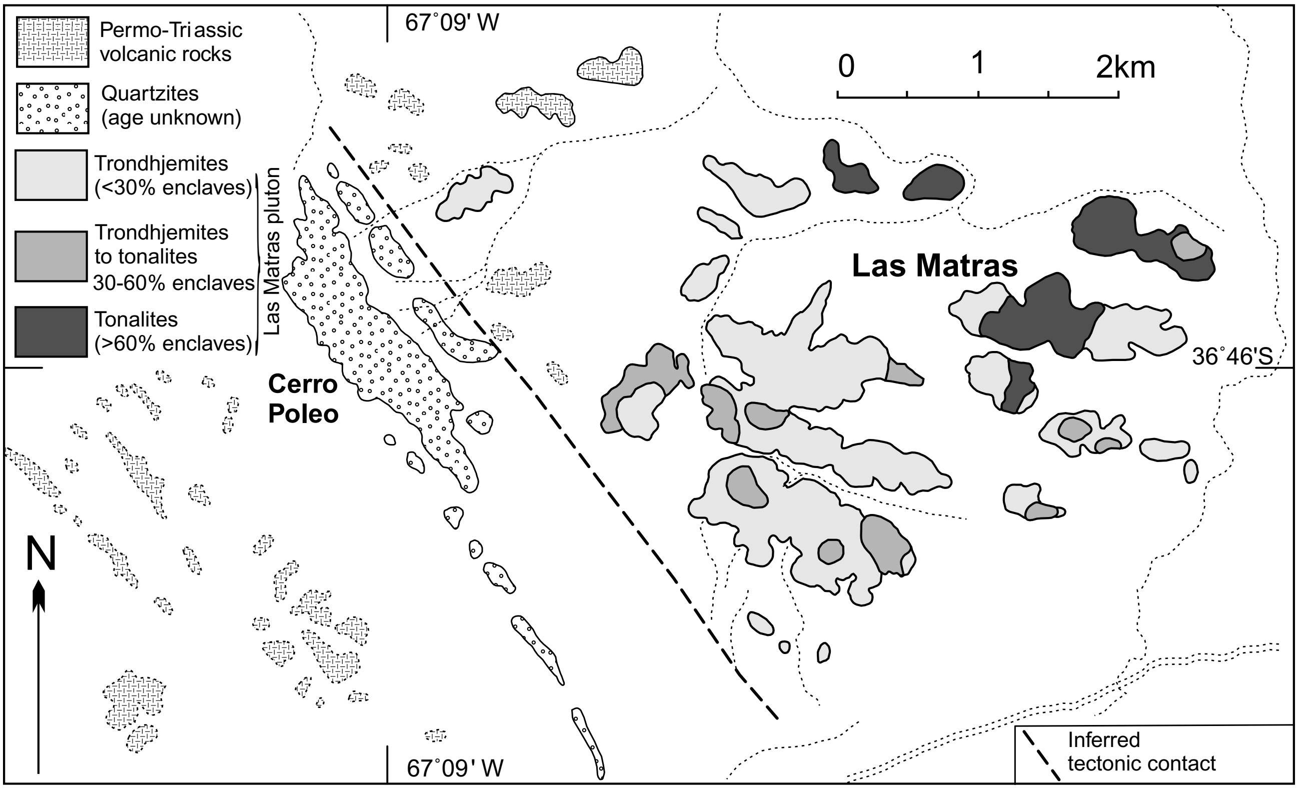

Fig. 2. Geological sketch map of the Las Matras pluton; for location see Fig. 1. The pluton is poorly exposed, without country rock relationship, and covered by modern sediments. The contacts between the internal facies (areas of different proportions of tonalitic enclaves) of the pluton are transitional.

found as close as 200 m from the quartzites, no contact could be found between them. The lack of metamorphism in the quartzites, plus the very sharp NW-trending borders of their outcrops parallel to bedding, are suggestive of a possible tectonic contact between these units.

On the other hand, this contact area is covered by regoliths of Permo-Triassic volcanic rocks of mainly dacitic to rhyolitic compositions. A NW-trending rhyolitic dike cuts across the trondhjemitic facies of the pluton. In one of the Permian dacitic exposures, a brittle shear deformation, causing a penetrative fracture cleavage, could be observed in a NW–SE trending belt that is a few hundred meters wide. Such a NW-striking structure is widespread in the La Pampa Province, controlling many large-scale structures throughout the Paleozoic era, like the orientation of the metamorphic rocks, elongation of the Permian sedimentary basin, and distribution of the Upper Paleozoic volcanic rocks. West of the quartzite beds there are also other very small outcrops and regoliths of similar porphyritic volcanic rocks and tuffs, following a similar NW trend of the exposures.

3. The Las Matras pluton

The Las Matras pluton is an undeformed microgranitoid enclave pluton that is composed of a medium-grained leucocratic facies containing various proportions of dark, fine-grained equigranular to porphyritic microgranitoid enclaves. The leucocratic facies is of trondhjemitic composition (as determined chemically), and the mafic facies is tonalitic. Due to the irregular distribution of the enclaves and their swarms (areas that range from meters in width up to hundreds of meters wide; see Fig. 2), the various rock types were distinguished as trondhjemites (<30% of tonalitic enclaves; see Fig. 3a), trondhjemites to tonalites (30–60%), and tonalites (<60% or areas of more homogeneous tonalitic facies; see Fig. 3d). Rocks of trondhjemitic composition cover the major area of exposures.

The enclaves show different sizes and morphologies (Fig. 3b and c). Some are homogeneously globular, with subcircular plan view, up to 2 m in diameter. The contacts are sharp, without chilled margins. Others have irregular shapes, but generally with lobated or crenulated contacts, coexisting with those of different sizes. Discrete felsic halos less than 1 cm thick could also be observed. Within the areas more homogeneously trondhjemitic, the enclaves are scarce, less than 5 cm wide, and have diffuse contacts. Within areas more homogeneously tonalitic, the trondhjemitic magmas appear as straight veins, with matching walls, filling narrow sectors between angulose enclaves. In some cases, they fill lobate interstices between enclaves, having coarser grain sizes than those of the enclaves.

The texture of the rocks is granular, with minerals in

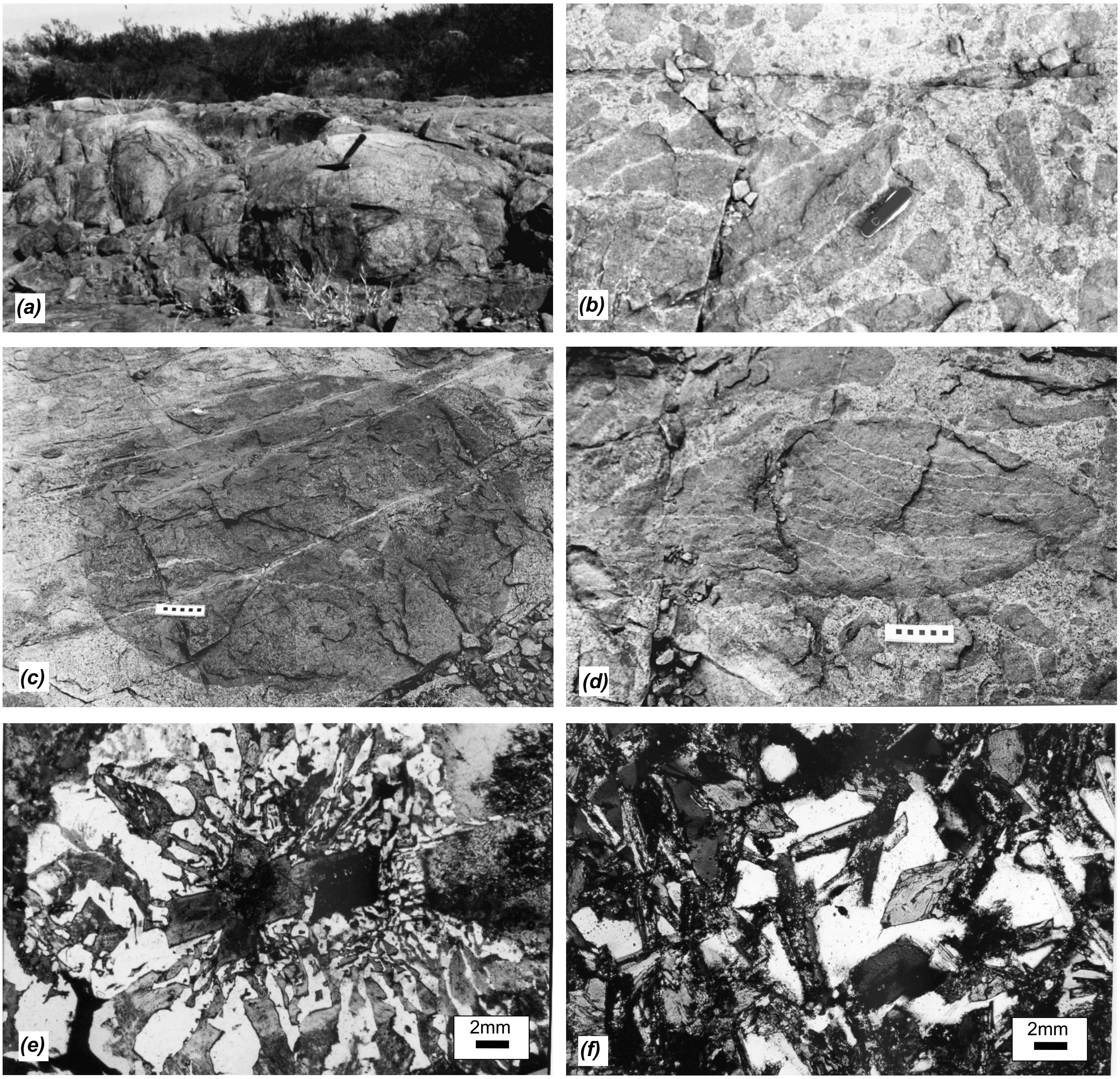

Fig. 3. (a) Las Matras pluton, a general field view of the homogeneous trondhjemitic facies in the central area of the pluton, almost without microgranitoid enclaves. (b, c, d) Different sizes and proportions of tonalitic enclaves in the eastern area of the pluton: (b) some have angular to lobular contours; (c) others have subcircular sections about 1 m in diameter (scale has 1 cm divisions); (d) tonalitic facies with abundant enclaves (scale has 1 cm divisions). Photomicrographs show unmodified magmatic textures; crossed polarizers: (e) trondhjemite with euhedral plagioclase surrounded by graphic intergrowth; (f) tonalite with quartz surrounding euhedral amphibole (central right), biotite, and plagioclase.

random orientations. Although 3D observations are difficult because of the poor exposures, mineral or enclave orientations due to magmatic flow or deformation processes, like those described by Vernon et al. (1988), could not be observed.

Geochemical and isotopic features (see below) suggest that the enclave facies is of cogenetic origin with the host rock. It was not possible to make geochemical or isotopic distinction between the two facies, like the case reported by Elburg and Nicolls (1995) and Elburg (1996) for the granitoids and volcanic rocks from the Lachlan Fold Belt.

There are occasional dikes, with different composition, cutting the pluton in different orientations. Their widths are less than 1 m and lengths less than 20 m. The basic ones are dark, with afanitic texture, while the acidic ones are aplitic, pink-coloured, with diffuse and small enclaves.

The tonalitic rocks are composed of plagioclase, quartz, amphibole, biotite, and alkali feldspar, with opaque minerals, apatite, zircon, allanite, and sphene as accessory minerals, and scarce alteration to epidote and clorite. In the trondhjemitic facies, the alkali feldspar is more abundant, while amphibole is scarce or absent. The original magmatic

Table 1
Major, trace and REE analyses from the Las Matras pluton and dikes
(Major oxides analyzed by fusion-ICP and trace and RE elements analyzed by fusion-ICP MS, at the Activation Laboratories (Canada). Standards used: STM1, MAG1, BIR1, DNC1, W2, MRG1, SY3, GXR1)

	Trondhjemites							
	LMT-7	LMT-8	LMT-9	LMT-11	LMT-14	LMT-15	LMT-22	LMT-31
SiO_2	70.67	71.54	73.32	72.09	71.74	75.09	75.51	71.59
Al_2O_3	13.41	14.25	13.67	13.05	13.27	13.21	12.59	13.75
$Fe_2O_3^*$	3.07	3.62	2.85	2.87	2.91	2.44	2.41	3.07
MnO	0.08	0.07	0.04	0.06	0.05	0.05	0.06	0.04
MgO	0.65	0.68	0.43	0.44	0.57	0.39	0.23	0.46
CaO	2.17	2.30	2.38	2.00	2.15	1.62	1.38	2.07
Na_2O	4.03	4.16	4.11	4.22	4.02	4.00	4.52	4.02
K_2O	2.61	2.69	2.40	2.58	2.61	2.96	2.36	2.85
TiO_2	0.33	0.36	0.31	0.29	0.32	0.25	0.23	0.30
P_2O_5	0.06	0.10	0.08	0.14	0.06	0.06	0.05	0.10
LOI	0.92	0.95	0.77	0.83	1.00	0.89	0.70	0.95
Total	98.00	100.72	100.34	98.57	98.70	100.96	100.03	99.17
Rb	67	84	44	47	56	78	51	53
Sr	210	237	256	197	215	171	152	213
Y	33	32	19	33	28	32	37	33
Zr	189	177	165	194	191	169	209	212
Nb	9	9	6	8	8	9	4	7
Ba	820	817	941	799	922	849	846	944
Cs	1.9	3.4		0.7	1.6	1.7		0.8
Hf	5.1	6		5.3	5.1	5.8		5.5
Ta	2.58	2.47		2.77	2.63	2.65		2.5
Tl	0.42	0.49		0.17	0.21	0.48		0.37
Th	5.3	4.8		5.2	5.3	5.3		4.0
U	1.5	1.7		1.6	1.8	1.8		1.4
La	23.4	26.5		27.8	22.6	27.4		23.5
Ce	51.5	56.4		56.9	48.9	58.1		51.4
Pr	5.702	6.633		5.946	5.332	6.724		5.95
Nd	24.2	30.4		25.6	22.5	30.4		24.1
Sm	5.15	6.74		5.43	4.77	6.44		4.97
Eu	0.978	1.405		1.012	0.979	1.113		0.961
Gd	4.69	5.84		4.62	4.17	5.73		4.65
Tb	0.89	1.02		0.88	0.74	0.99		0.88
Dy	5.04	6.13		5.14	4.27	6.16		5.19
Ho	1.04	1.3		1.00	0.88	1.31		1.11
Er	3.33	4.09		3.06	2.66	4.15		3.56
Tm	0.553	0.587		0.538	0.434	0.609		0.543
Tb	3.5	3.91		3.53	2.79	4.02		3.53
Lu	0.559	0.583		0.56	0.451	0.613		0.540

	Tonalites						Dikes	
	LMT-10	LMT-12	LMT-17	LMT-21	LMT-27	LMT-40	LMT-25	LMT26
SiO_2	64.05	60.10	64.76	64.49	65.34	65.61	75.65	56.65
Al_2O_3	15.20	16.02	15.59	15.56	15.48	15.99	12.85	14.59
$Fe_2O_3^*$	6.52	8.30	6.23	5.38	5.81	5.56	1.96	7.25
MnO	0.13	0.17	0.12	0.11	0.11	0.09	0.04	0.12
MgO	1.77	2.50	1.60	1.61	1.33	1.48	0.30	7.05
CaO	4.57	5.62	4.36	4.82	3.63	3.27	1.40	7.88
Na_2O	4.05	3.49	4.16	4.35	4.92	4.09	4.22	2.19
K_2O	1.86	1.78	1.96	1.90	1.67	2.22	3.10	1.83
TiO_2	0.75	0.93	0.66	0.70	0.68	0.717	0.26	0.59
P_2O_5	0.29	0.23	0.26	0.23	0.51	0.30	0.06	0.16
LOI	1.60	1.26	1.23	1.16	0.94	1.34	0.83	1.37
Total	100.79	100.41	100.93	100.30	100.40	100.67	100.66	99.69
Rb	47	100	64	47	39	68	61	53
Sr	312	338	363	382	334	329	160	266
Y	27	32	38	27	32	27	17	12
Zr	110	117	127	131	144	171	185	106

Table 1 (*continued*)

	Tonalites						Dikes	
	LMT-10	LMT-12	LMT-17	LMT-21	LMT-27	LMT-40	LMT-25	LMT26
Nb	4	7	7	7	9	7	7	5
Ba	474	346	558	600	573	732	1439	537
Cs	1.5	3.7			3.5	4.5	0.6	1.8
Hf	3.1	4.1			4.8	4.6	6.4	3.6
Ta	1.11	1.29			1.69	1.4	3.14	0.98
Tl	0.12	0.65			0.19	0.52	0.32	0.36
Th	2.8	3.2			2.9	3.1	4.5	11.0
U	1.0	1.0			1.0	1.2	1.6	3.8
La	13.5	21.4			21.1	19.3	56.7	24.1
Ce	33.9	48.1			48.7	42.4	99.5	51.1
Pr	4.072	6.006			6.190	5.11	9.798	5.544
Nd	18.3	28.8			30.6	21.8	38.1	23.9
Sm	4.4	6.74			7.29	4.83	5.49	4.4
Eu	1.136	1.534			1.923	1.39	1.515	1.053
Gd	3.89	6.03			6.39	4.57	3.73	3.12
Tb	0.72	1.06			1.11	0.81	0.54	0.46
Dy	4.07	6.44			6.54	4.66	3.01	2.55
Ho	0.84	1.35			1.37	0.98	0.66	0.51
Er	2.5	4.18			4.2	2.95	2.36	1.6
Tm	0.389	0.581			0.567	0.433	0.335	0.197
Tb	2.45	3.84			3.72	2.95	2.49	1.31
Lu	0.402	0.568			0.554	0.432	0.424	0.198

textures have not been modified by metamorphic overprints (Fig. 3e and f). According to preliminary electron probe microanalysis data of amphibole and feldspars, the emplacement level of the pluton should have been shallow, at least in the late stages. This shallow emplacement level is also evidenced by graphic textures (Fig. 3e) detected in some trondhjemites.

3.1. Geochemistry

Major, trace-, and RE elements were analyzed for 8 whole-rock samples of the leucocratic facies, 6 samples of the melanocratic facies, 1 basic dike, and 1 acidic dike (Table 1). The analyses were performed at the Activation Laboratories (Canada), by Fusion-ICP for major oxides and by Fusion-ICP MS for trace and RE elements.

The major element composition characterizes the rocks as tonalites–trondhjemites (Fig. 4a), of low-Al and medium-K contents. The classification of trondhjemites is in accordance with the definition of Barker (1979), with SiO_2 in the range 70.7–75.5%, $FeO^* + MgO = 2.3$–3.9%, $CaO = 1.4$–2.4%, $Na_2O = 4.0$–4.5%, and relatively high values K_2O, $= 2.4$–3.0%. The SiO_2 range of the tonalites is low, 60.1–65.6%. However, the general chemical features are quite similar to those of the trondhjemites, hence they are considered as cogenetic. The sodic character dominates over potassic ($Na_2O/K_2O = 1.8$–3 for the tonalites and 1.3–2.0 for the trondhjemites), and all the rocks are metaluminous (Fig. 4b). The two samples of dikes ($SiO_2 = 56.7$ and 75.7%) do not show behaviour similar to that of the pluton.

Despite the compositional gap recognized between the tonalitic and trondhjemitic rocks, the Harker diagrams (Fig. 5) show good negative trends for MgO, FeO, CaO, TiO_2, and Al_2O_3. For Na_2O, no trend can be delineated, while K_2O increases for the trondhjemites. This different behaviour for the alkalies is observed in the more sodic character of the tonalites compared to the trondhjemites (Fig. 4b). In the AFM diagram (Irvine and Baragar, 1971) both the tonalites and trondhjemites show a calc-alkaline signature.

Rb (<100 ppm) and Sr (<382 ppm) are low, Y (generally 27–38 ppm) and Ba (346–600 ppm for tonalites and 817–941 ppm for trondhjemites) are moderate. The low Sr/Y and moderate contents of Y (Fig. 6) are characteristic of low-Al TTD (tonalites, trondhjemites and dacites), which also characterize the calc-alkaline andesite–dacite–rhyolite suites from continental and island arcs. Concentrations of Zr are low to moderate, 110–171 ppm for tonalites and 165–212 ppm for trondhjemites.

Tonalites and trondhjemites have very coherent REE patterns and show little variation in both overall abundance and profile shape (Fig. 7). Total REE analyzed are low (121–154 ppm for trondhjemites, 91–140 ppm for tonalites), and very little increase of total REE accompanies the increase in SiO_2. The patterns show slight LREE enrichment and flat HREE behaviour ($La/Sm_N = 1.8$–3.2 and $La/Yb_N = 3.7$–5.5). The Eu negative anomaly is slight to moderate ($Eu/Eu^* = 0.74$–0.90 for tonalites and 0.56–0.68 for trondhjemites) and, together with the clear decrease of Sr with increasing SiO_2 content, suggests progressive removal of plagioclase from the magma. The low $(La/Yb)_N$ and relatively high $(Yb)_N$ values are also characteristics of the

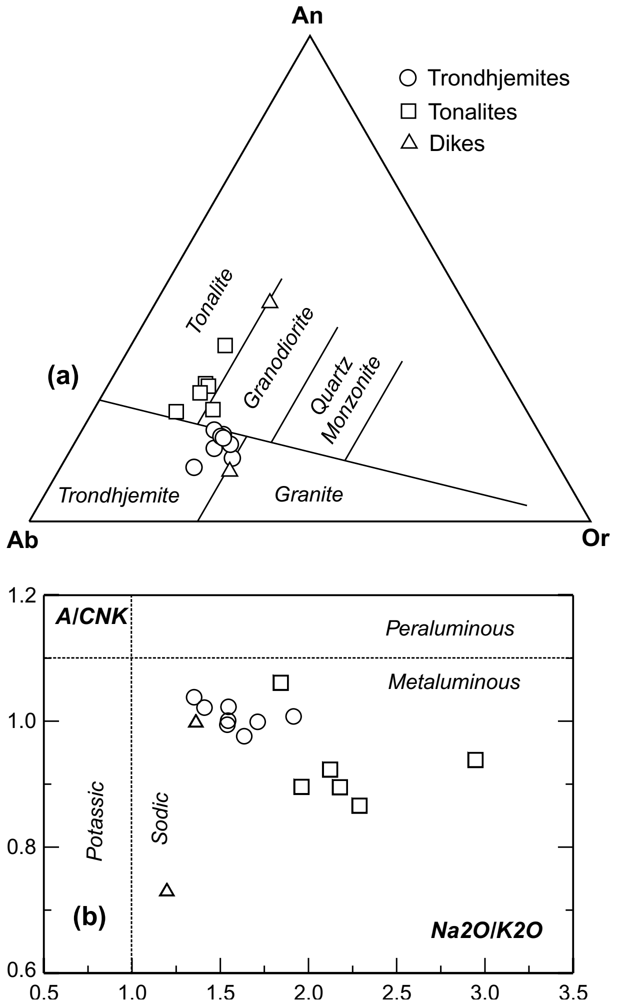

Fig. 4. (a) Classification of trondhjemites and tonalites, after O'Connor (1965), based on normative Ab, An, and Or. (b) Relation between A/CNK (molar) and Na_2O/K_2O, showing the sodic and metaluminous character of these rocks. The tonalites are more sodic and metaluminous than the trondhjemites.

low-Al (or high-Yb) TTD (Martin, 1986; Drummond and Defant, 1990). In contrast, the basic and acidic dikes show quite different patterns, indicating a different magmatic origin.

Both the tonalites and trondhjemites have all the major, trace, and REE chemical characteristics of low-Al TTD. The partial melting models of Drummond and Defant (1990) and Drummond et al. (1996) depicted for these rocks indicate derivation from a plagioclase-bearing basaltic source or, alternatively, plagioclase fractionation from mantle-derived magmas. The slight enrichment in the LIL elements like Sr, Rb, K, Th, and U observed at Las Matras is indicative of a slight crustal signature component; this can be achieved through either melting of basaltic material derived from a depleted mantle or direct derivation from an enriched mantle. The fact that no other mafic magma is found associated with the pluton complicates these interpretations. In any case, the Rb vs. Y + Nb discrimination (Pearce et al., 1984) as well as the La/Yb values (>2.3) agree with an environment of continental magmatic arc.

In contrast, the high-Al subtype TTD has quite different trace and REE patterns because of the involvement of garnet in petrogenesis. These rocks, which are quite abundant in the Archean gneissic terranes, are explained as a much higher pressure melting product of hot slab basalts transformed to amphibolite and eclogite at a deeper and more oceanward position than the calc-alkaline arc (Martin, 1986, 1987; Drummond and Defant, 1990). They have also been related to mantle delamination processes (Kay and Mahlburg Kay, 1993).

3.2. Age

To constrain the age of the Las Matras pluton, one Rb–Sr errorchron, one Sm–Nd isochron, and a new K–Ar date have been obtained in addition to the K–Ar dates reported by Linares et al. (1980). A U–Pb zircon dating is presently in process.

The Rb–Sr method was applied using 14 whole-rock samples from the tonalitic as well as the trondhjemitic facies, including the 2 dikes. For the Sm–Nd method, 1 trondhjemitic and 2 tonalitic whole-rock samples, together with 2 amphibole separates from the tonalites were used. Rb and Sr XRF analyses, the isotope dilution technique for Sm–Nd analyses (using a combined ^{149}Sm–^{150}Nd spike according to the technique described by Sato et al., 1995), as well as the mass spectrometry for Sm, Nd, and Sr, were carried out at the Centro de Pesquisas Geocronologicas, São Paulo. The isotopic ratios were measured using the VG 354 mass spectrometer with multiple and single collector systems. Only the extraction of natural Sr through cation exchange columns was performed at the Centro de Investigaciones Geológicas, La Plata. K–Ar amphibole dating from the tonalite was also carried out at the Centro de Pesquisas Geocronológicas.

Rb–Sr whole-rock dating (Fig. 8a, Table 2) show an acceptable alignment of 10 samples within a low range of $^{87}Rb/^{86}Sr$ (<1.2). The age obtained was 1212 ± 47 Ma (2σ), initial $^{87}Sr/^{86}Sr$ 0.7030 ± 0.0004, and MSWD 3.7. It was not possible to separate the tonalitic facies from the trondhjemitic within the errorchron. The two samples of dikes did not align with the pluton. Two other trondhjemitic samples (LMT-8 and LMT-14) were also excluded because of their scattered positions. Taking into account that the pluton does not show any textural evidence of ductile deformation and metamorphism, this date is considered to be related to the crystallization age. The low initial Sr ratio is indicative of an only slightly evolved common source for both the tonalitic and trondhjemitic rocks.

The five samples analyzed by the Sm–Nd method define an acceptable isochron (Fig. 8b, Table 2) of 1188 ± 47 Ma, and MSWD 0.3. The model ages (T_{DM}) calculated according to DePaolo (1981) for the whole-rock samples are in the range 1551–1604 Ma. The $\epsilon Nd_{(1200)}$ for these samples is

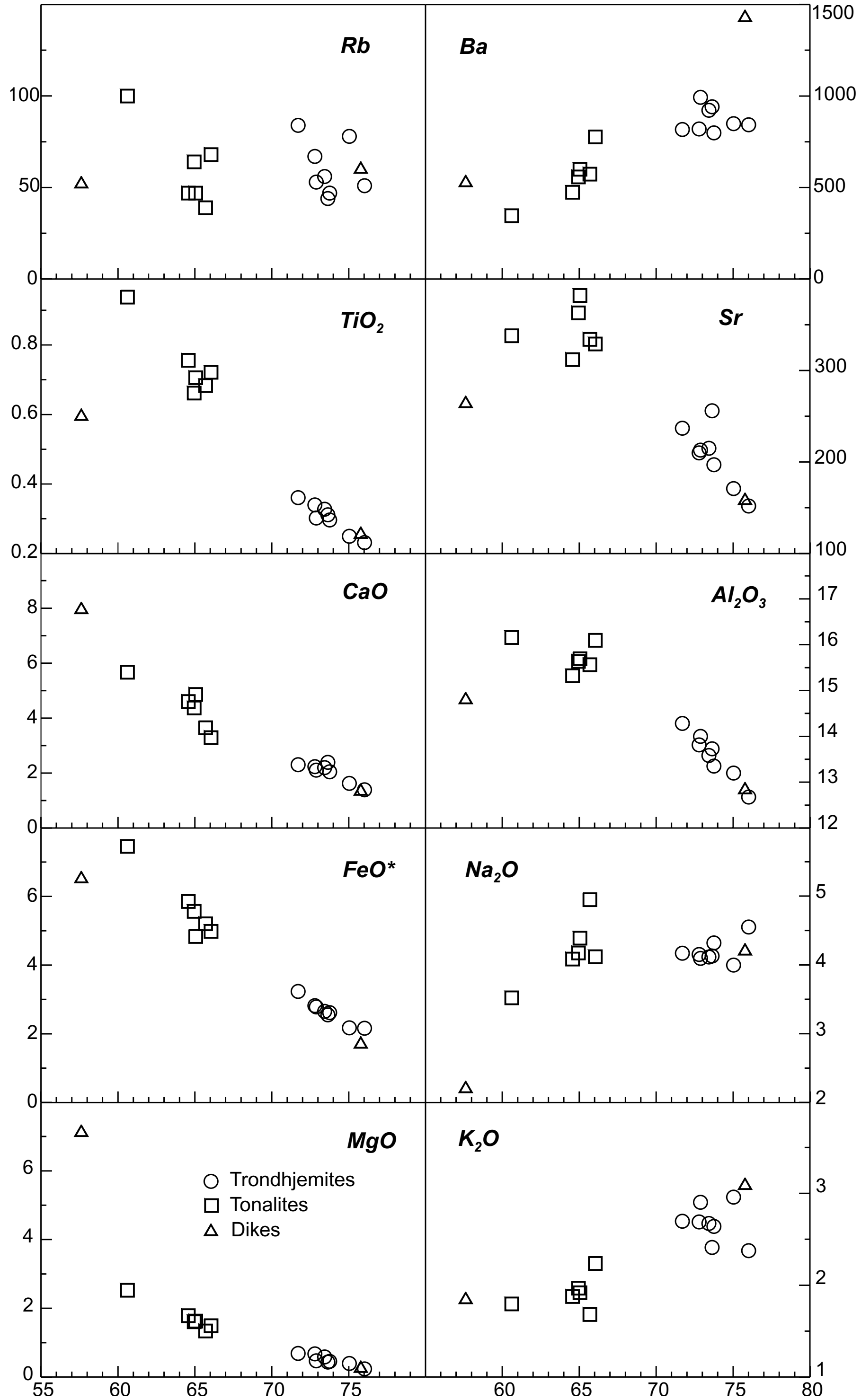

Fig. 5. Harker diagrams (dry bases) for the rocks of the Las Matras pluton, for major elements, Rb, Sr and Ba. SiO_2 ranges are 60.1–65.6% for tonalites, and 70.7–75.5% for trondhjemites (see Table 1). A compositional gap can be seen between the tonalites and trondhjemites.

very close, between +1.6 and +1.8, indicating a "depleted" source, less evolved than CHUR for the time of crystallization. The low values of $\epsilon Sr_{(1200)}$ (−4.5 to +4.8) are also indications of their depleted character. The rough coincidence within error ranges of the Sm–Nd and the Rb–Sr dates indicates that an average of 1200 Ma can be reasonably proposed as the crystallization age for the Las Matras pluton.

If we consider a linear strontium isotopic evolution of BABI through time (Fig. 9a), with $^{87}Sr/^{86}Sr$ from 0.699 to 0.704 (Rb/Sr 0.027; Faure, 1986) during the 4.5 Ga, the $^{87}Sr/^{86}Sr$ value for 1.2 Ga (crystallization age of the Las

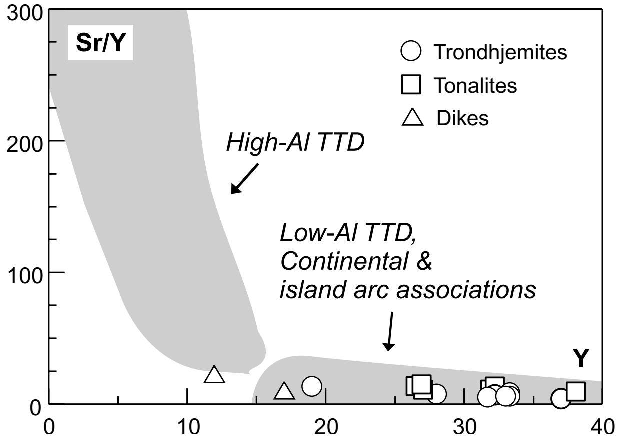

Fig. 6. Sr/Y vs Y diagram (Drummond and Defant, 1990). The rocks of the Las Matras pluton plot in the low-Al TTD field, which also characterizes the calc-alkaline andesite–dacite–rhyolite suites from continental and island arcs.

Matras pluton) is 0.7028, which is very close to the value of 0.7030 ± 0.0003 obtained from the Rb–Sr errorchron. This could explain a direct mantle derivation for the magma at this time. However, if we consider the linear evolution of a depleted mantle (Rb/Sr 0.016; Faure, 1986), the ^{87}Sr/^{86}Sr of 0.7030 obtained for the Las Matras pluton can also be explained as a result of fusion of crustal material extracted from that depleted mantle at 1.6 Ga (Fig. 9a). A crustal residence time of ~400 million years (up to 1.2 Ga) can be calculated in a closed system having a Rb/Sr ratio of approximately 0.12. After this, partial fusion and complete homogenization of the Rb–Sr system could have occurred, yielding a 1.2 Ga pluton with ^{87}Sr/^{86}Sr = 0.7030. The low values of Rb/Sr (0.11–0.39) found in the rocks can support this evolution from a depleted mantle model rather than from a normal mantle one.

The above Sr depleted-mantle model age of 1.6 Ga agrees well with the Nd T_{DM} model ages (1551–1604 Ma) calculated after DePaolo (1981; Fig. 9b). This coincidence favors this refusion hypothesis of material derived from a depleted mantle. Nevertheless, the possibility of derivation from a depleted mantle contaminated by recycled sediments (or an enriched mantle) in a subduction zone cannot be discarded, as can be seen by the poorly defined epsilon values (ϵNd +1.8 to +1.7, and ϵSr −4.5 to +4.8).

The K–Ar date, obtained for amphibole separated from a tonalite, was 869 ± 17 Ma (Table 2). This value is closer to the published data in the range of 690–810 Ma (Linares et al., 1980). These dates, together with the 392–382 Ma K–Ar whole-rock dates (Linares et al., 1980) can suggest different degrees of resetting during the Early Paleozoic Famatinian orogeny that affected the central western Argentine region. Alternatively, they can represent two different thermal events, one in the Neoproterozoic and another during Early Paleozoic times (Linares et al., 1980; Sato et al., 1996; Tickyj, 1999). Up to now, we have not had evidence to support any of these alternative interpretations.

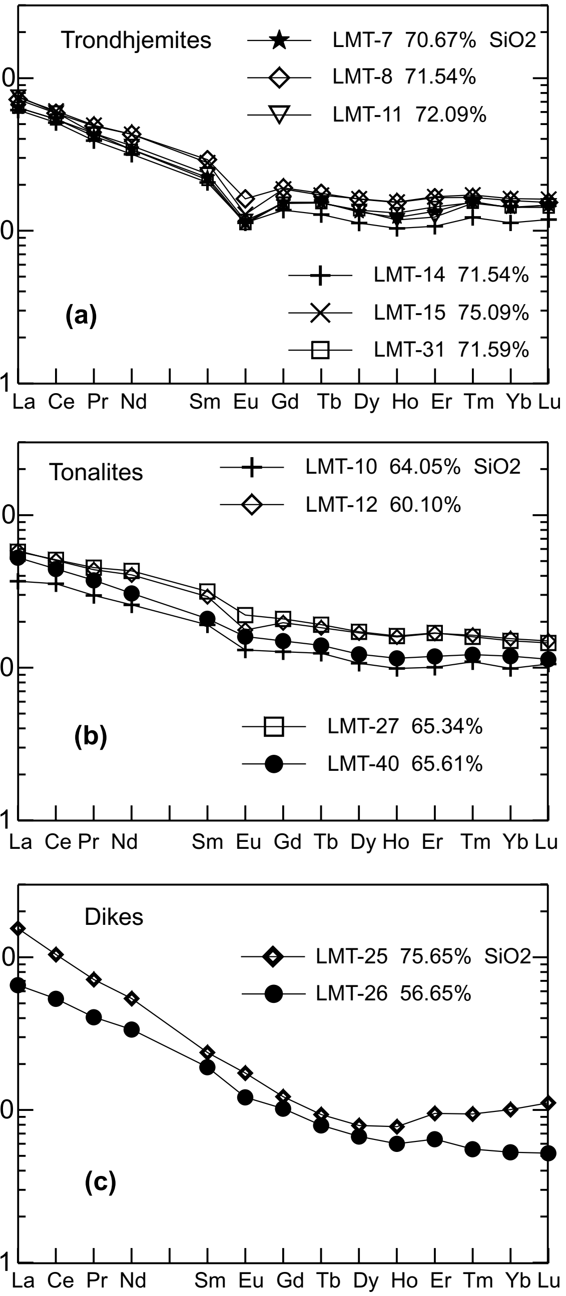

Fig. 7. Chondrite-normalized REE patterns for the (a) trondhjemites; (b) tonalites; and (c) dikes. The trondhjemites and tonalites show consistent patterns, with low $(\mathrm{La/Yb})_{\mathrm{N}}$ and small negative Eu anomalies, typical of low-Al TTD. The two dikes show quite different patterns.

3.3. Comparable Grenvillian basement rocks in Argentina

To the north of Las Matras, Grenvillian-age basement rocks involved in the Early Paleozoic Famatinian orogeny of the southwestern margin of Gondwana are exposed at the following morphostructural units (cf. Fig. 10, Table 3).

Western Sierras Pampeanas. The northernmost exposure in the Western Sierras Pampeanas corresponds to the area of Sierra de Umango (Varela et al., 1996) where biotite schists, amphibolites, acidic gneisses, mafic gneisses, and marbles

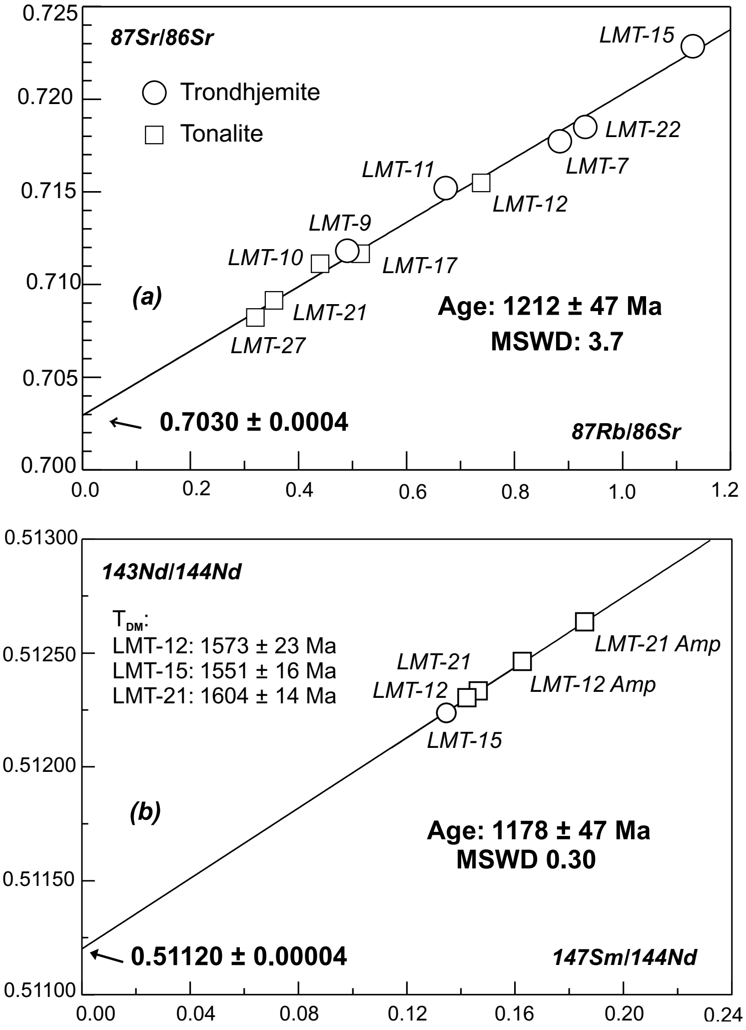

Fig. 8. (a) Rb–Sr whole rock errorchron; and (b) Sm–Nd whole rock-amphibole isochron for the Las Matras pluton. Both the trondhjemitic and tonalitic facies are aligned on the same isochrons, indicating that they are comagmatic.

occur. Metamorphic grades range from greenschist to granulite facies. The acidic gneisses yielded a whole rock Rb–Sr isochron age of 1030 ± 30 Ma, probably corresponding to the metamorphic process. The geochemistry of amphibolites has been interpreted as compatible with a magmatic arc or back arc environment (Vujovich and Kay, 1996).

To the southeast, at Sierra de Valle Fértil, an association of paragneisses, orthogneisses, and amphibolites of granulite facies have been described (Mirré, 1971); Cingolani (unpublished data) obtained a Rb–Sr preliminary isochron of 963 ± 86 Ma (see Varela et al., 1996). The intermediate to basic rocks that intruded this basement in the southern continuation of the mountain chain (Sierra de la Huerta) have been interpreted as representing the root of a magmatic arc (Vujovich et al., 1996; Castro de Machuca et al., 1996a), probably of island type (Castro de Machuca et al., 1996b).

In the Sierra de Pie de Palo, greenschist to granulite facies rocks (see synthesis in Vujovich and Kay, 1998) comprise ortho- and paragneisses and schists, migmatites, as well as mafic–ultramafic associations (peridotites, serpentinites, metagabbros, metadiorites, amphibolites, mafic schists) and marbles. These rocks yielded a crystallization U–Pb age of 1105 ± 79 Ma and a ^{207}Pb/^{206}Pb metamorphism date of 1060–1080 Ma (McDonough et al., 1993; recalculated values in Ramos et al., 1998). Rb–Sr metamorphism ages have been reported by Varela and Dalla Salda (1992) — 1027 ± 57 Ma, reference isochron, and Pankhurst and Rapela (1998) — 1021 ± 12 Ma. The geochemical study of these rocks allowed Vujovich and Kay (1996, 1998) to postulate a tectonic setting within an oceanic arc/back arc environment.

At the western rim of Sierra de Pie de Palo, there are carbonate and clastic shelf sediments affected by low-grade metamorphism (Vujovich and Ramos, 1994; Dalla Salda and Varela, 1984; Ramos et al., 1998). These rocks show some lithological similarities with the Cambro–Ordovician carbonate shelf deposits associated with the belt with

Table 2
Analytical results of Rb–Sr, Sm–Nd, and K–Ar datings from the Las Matras pluton and dikes
(Values obtained for standards: NBS-987, $^{87}Sr/^{86}Sr$ 0.71026; La Jolla, $^{143}Nd/^{144}Nd$ 0.511847. T_{DM} model ages calculated according to the single-stage method of DePaolo (1981))

Sample	Material	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$				
Rb–Sr analytical results									
LMT-7	Trondhjemite	68.1	223.2	0.88387 ± 0.001767	0.71772 ± 0.00009				
LMT-8	Trondhjemite	76.5	231.2	0.95875 ± 0.01918	0.71733 ± 0.00009				
LMT-9	Trondhjemite	43.9	259.6	0.48989 ± 0.00979	0.71182 ± 0.00008				
LMT-10	Tonalite	55.4	365.5	0.43913 ± 0.00878	0.71109 ± 0.00012				
LMT-11	Trondhjemite	48.7	209.7	0.67236 ± 0.01345	0.71519 ± 0.00007				
LMT-12	Tonalite	87.8	345.2	0.73715 ± 0.01474	0.71545 ± 0.00007				
LMT-14	Trondhjemite	56.2	232.2	0.66418 ± 0.01328	0.71591 ± 0.00008				
LMT-15	Trondhjemite	65.8	168.8	1.12967 ± 0.02259	0.72285 ± 0.00012				
LMT-17	Tonalite	64.1	361.2	0.51383 ± 0.01027	0.71165 ± 0.00008				
LMT-21	Tonalite	47.3	387.0	0.35375 ± 0.00707	0.70912 ± 0.00011				
LMT-22	Trondhjemite	47.3	151.2	0.93064 ± 0.01861	0.71849 ± 0.00010				
LMT-25	Dike	54.8	159.8	0.99269 ± 0.01985	0.71634 ± 0.00009				
LMT-26	Dike	49.5	266.8	0.53716 ± 0.01074	0.71346 ± 0.00008				
LMT-27	Tonalite	37.2	336.8	0.31957 ± 0.00639	0.70819 ± 0.00009				
Sm–Nd analytical results									
Sample	Material	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	T_{DM} (Ma)	$\epsilon Nd_{(0)}$	$\epsilon Nd_{(1200)}$	$\epsilon Sr_{(1200)}$
LMT-12	Tonalite	5.4	23.0	0.1422 ± 0.0005	0.512303 ± 0.000011	1572	−6.53	+1.81	−4.51
LMT-12Amp	Amphibole	10.3	38.5	0.1626 ± 0.0005	0.512462 ± 0.000006				
LMT-15	Trondhjemite	5.4	24.1	0.1347 ± 0.0005	0.512237 ± 0.000008	1551	−7.82	+1.67	+4.80
LMT-21	Tonalite	4.9	20.4	0.1464 ± 0.0005	0.512332 ± 0.000005	1605	−5.97	+1.73	−0.80
LMT-21Amp	Amphibole	22.6	73.5	0.1857 ± 0.0006	0.512634 ± 0.000004				
K–Ar analytical results									
Sample	Material	% K	^{40}Ar Rad 10^6 (ccSTP/g)	% ^{40}Ar atm	Age (Ma)				
LMT-21Amp	Amphibole	0.6774 ± 0.0049	29.39	8.61	869.3 ± 17.0				

Table 3
Summary of ages, lithologies, metamorphic grades, and tectonic environments for exposures comprising the belt with Grenvillian-age rocks in central western Argentina. At Las Matras, a non-deformed ca. 1200 Ma magmatic arc is registered. To the north the ages represent igneous crystallization (1118 ± 54–1069 ±36 Ma) and metamorphism (less than 1083–1021 ± 12 Ma). These data are suggestive of a non-homogeneous tectonic evolution for the entire Argentine belt, although the depleted Sr and Nd isotopic signatures are similar

(Numbers in square brackets refer to: [1] Varela et al., 1996; [2] Vujovich and Kay, 1996; [3] Mirré, 1971; [4] Vujovich et al., 1996; [5] Castro de Muchuca et al., 1996a,b; [6] Pontoriero and Castro de Machuca, 1999; [7] McDonough et al., 1993; [8] Ramos et al., 1998; [9] Varela and Dalla Salda, 1992; [10] Pankhurst and Rapela, 1998; [11] Ramos et al., 1996; [12] Vujovich and Kay, 1998; [13] Abruzzi et al., 1993; [14] Mahlburg Kay et al., 1996; [15] Ramos and Basei, 1997; [16] Basei et al., 1998; [17] Caminos, 1993; [18] Vujovich, 1998; [19] Astini et al., 1996; [20] Cingolani and Varela, 1999; [21] Núñez, 1979; [22] this study; [23] Linares et al., 1980)

Locality	Date — method[a] — material [References]	Dated rock type	Dated process	General lithology, metamorphism, tectonics [References]
Western sierras pampeanas				
Sierra de Umango	1030 ± 30 Ma — Rb/Sr — wr isochron ($\mathrm{Sr_i}$ 0.7026 ± 0.0003) [1]	Acidic orthogneiss	Metamorphism?	Biotite-schists, acidic gneisses, amphibolites, mafic gneiss, marbles. Green-schist to granulite facies. Magmatic arc or back arc environment. [1,2]
Sierra de Valle Fértil–Sierra de la Huerta	963 ± 86 Ma — Rb/Sr — wr isochron [in 1]	Orthogneiss	Metamorphism?	Orthogneiss, paragneiss, amphibolites. Intruded by tonalites, quartz diorites, mafic to ultramafic rocks. Amphibolite to granulite facies. Root of magmatic arc. [3–6]
Sierra de Pie de Palo	1060–1080 Ma $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$-zircon	Orthogneiss	Metamorphism	Peridotites, meta-gabbros, serpentinites, amphibolites, fls–bio–grn–plg–schists and gneisses, marbles. Oceanic arc–back arc complex. [4,12]
	1105 ± 79 Ma — U/Pb — zircon [7,8]		Ign. crystallization	
	1027 ± 59 Ma — Rb/Sr — wr reference isochron ($\mathrm{Sr_i}$ 0.7043 ± 0.0002) [9]	Schists, gneisses, migmatites	Metamorphism	
	1021 ± 12 Ma — Rb/Sr — wr isochron ($\mathrm{Sr_i}$ 0.7045 ± 0.0003) [10]	Orthogneiss	Metamorphism	
	606.1 ± 0.7 Ma — Ar/Ar — amph			
	777.8 ± 3.1 Ma — Ar/Ar — amph [8,11]			
Precordillera	1102 ± 6 Ma — U/Pb — zircon	Mafic amphibolite	Ign. crystallization	Plagioclase-bearing amphibolite, biotite-bearing acidic gneiss, pyroxene–garnet granulite gneisses. Protoliths formed in an oceanic arc–back arc environment near a continental margin. [13,14]
	1118 ± 54 Ma — U/Pb — zircon	Acidic gneiss	Ign. crystallization	
	ca.1083 Ma $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ — zircon	Mafic amphibolite	Metamorphism	
	T_{DM} 1560–1685 Ma — Sm/Nd — wr ($\epsilon\mathrm{Nd}_{1100}$ +2.0 to +2.7)	Mafic granulite		
	T_{DM} 1340–1470 Ma — Sm/Nd — wr ($\epsilon\mathrm{Nd}_{1100}$ +2.1 to +3.5)	Mafic amphibolite		
	T_{DM} 800–1000 Ma — Sm/Nd — wr ($\epsilon\mathrm{Nd}_{1100} > +7.0$)	Acidic orthogneiss		
	$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ 17.1–17.8 $^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$ 15.42–15.49 $^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$ 36.6–37.4 [13,14]			

Table 3 (*continued*)

Locality	Date — method[a] — material [References]	Dated rock type	Dated process	General lithology, metamorphism, tectonics [References]
Frontal Cordillera				
Cordón del Portillo	1069 ± 36 Ma — U/Pb — zircon [15]	Quartz–plg–gneiss	Ign. crystallization	Greenschist facies gneisses and schists, amphibolites, marbles. [16–18]
	T_{DM} 1427–1734 Ma — Sm/Nd — wr [16]	Schists and gneisses		
San Rafael Block				
Ponon Trehue area	Preliminary Grenvillian U–Pb age [in 19]	Granodiorites to tonalites	Metamorphism?	Mylonitized acidic orthogneisses, micaschists and migmatites. Acidic to intermediate granitoids (with ductile deformation), and pegmatitic and aplitic veins. [21]
	1063 ± 106 Ma — Rb/Sr — wr isochron ($\mathrm{Sr_i}$ 0.7032 ± 0.0004) [20]			
Las Matras Block				
Las Matras area	1212 ± 47 Ma — Rb/Sr — wr errochron ($\mathrm{Sr_i}$ 0.7030 ± 0.0004)	Tonalites–trondhjemites	Ign. crystallization	Undeformed tonalitic to trondhjemitic (micro-granitoid enclave) pluton. No country rock exposed. Continental magmatic arc. [22]
	1188 ± 47 Ma — Sm/Nd — wr–amph isochron	Tonalites–trondhjemites	Ign. crystallization	
	T_{DM} 1551–1604 Ma — Sm/Nd — wr ($\epsilon\mathrm{Nd}_{1200}$ +1.6 to +1.8)			
	869 ± 17 Ma — K/Ar — amph [22]	Tonalite	?	
	810 ± 5, 763 ± 25, 740 ± 30 Ma, K/Ar — amph	Tonalite		
	690 ± 20 Ma — K/Ar — wr	Tonalite		
	392 ± 15, 382 ± 15 Ma — K/Ar — wr [23]	Trondhjemite		

[a] Method: wr = whole rock; amph = amphibole.

Grenvillian-age rocks, but do not have clear age constraints yet.

The Precordillera. The Precordillera is a morphostructural unit mainly composed of Paleozoic sedimentary rocks involved in a fold-and-thrust belt during the Tertiary Andean orogeny. Within this unit, the Cambro–Ordovician carbonate rocks are exposed through all the eastern part (Fig. 1). The basement rocks appear only as xenoliths within Tertiary volcanics (Leveratto, 1968), comprising mafic amphibolitic schists and biotite-bearing acidic gneisses, mafic pyroxene granulite, and pyroxene–garnet granulite gneisses. The studies of Abruzzi et al. (1993) and Mahlburg Kay et al. (1996) allowed the recognition of igneous crystallization U–Pb ages of amphibolites and gneisses at 1118 ± 54 Ma and 1102 ± 6 Ma, as well as a $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ metamorphism ages younger than about 1083 Ma for a mafic granulite. Meso-Proterozoic Sm–Nd T_{DM} ages as well as the depleted signatures of Pb isotopic ratios are comparable to those of the North American Grenville Province (Mahlburg Kay et al., 1996). The proposed tectonic environment based on geochemical data is an oceanic arc/back arc setting near a continental margin.

Frontal Cordillera. In the Cordón del Portillo, the basement rocks crop out in the southern part, around 33°S. These low- to medium-grade metamorphic rocks (Caminos, 1993; Vujovich, 1998) comprise para- and orthogneisses, amphibolites, and marbles. The U–Pb age of 1069 ± 36 Ma (Ramos and Basei, 1997) determined in prismatic igneous zircons would represent a crystallization age for the protolith of the gneisses. Sm–Nd T_{DM} ages calculated for other schists and gneisses are between 1427 and 1734 Ma (Basei et al., 1998; Basei et al., unpublished data), which are similar to those obtained from the Precordillera by Mahlburg Kay et al. (1996).

San Rafael Block. The basement rocks of the Cerro La Ventana Formation (Criado Roqué, 1972), or La Ventana

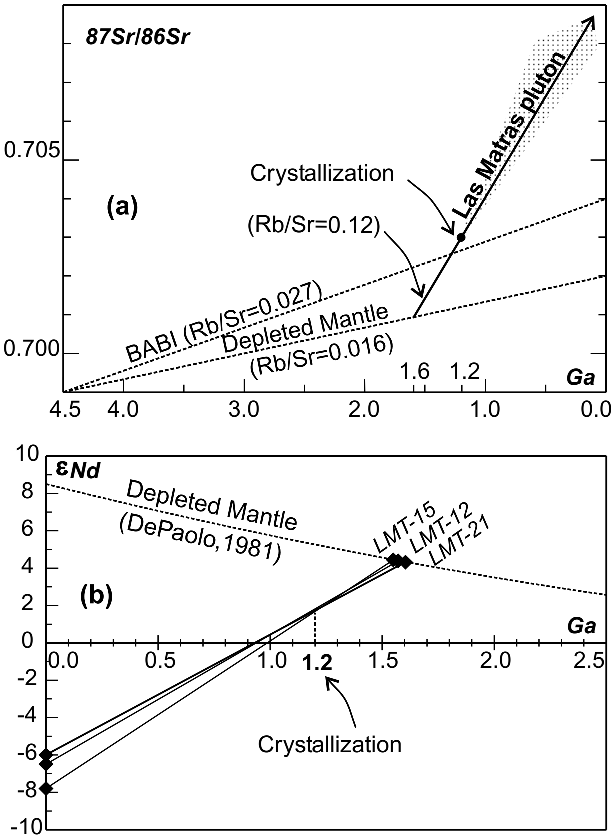

Fig. 9. (a) Linear ^{87}Sr/^{86}Sr evolutions of BABI and a depleted mantle through time; Rb/Sr data taken from Faure (1986). Although the initial ^{87}Sr/^{86}Sr found for Las Matras (0.7030) could be explained as a direct derivation from a normal mantle represented by BABI (Rb/Sr = 0.027) at 1.2 Ga (^{87}Sr/^{86}Sr 0.7028), it also can be explained as a refusion of a magma (having Rb/Sr = 0.12) extracted from a depleted mantle (Rb/Sr = 0.016) at 1.6 Ga. The range of Rb/Sr found in the pluton (0.11–0.39) is represented by the dotted area. This Sr-depleted mantle model age of 1.6 Ga coincides well with the Nd T_{DM} model ages calculated after DePaolo (1981), which are between 1.57 and 1.61 Ga (b). The ϵNd $_{(1200)}$ values for the moment of crystallization are between +1.67 and +1.81, indicating a source less evolved than CHUR.

Formation (Núñez, 1979), crop out in the area of Ponon Trehue in a NNW–SSE trending belt 10 km long by 2 km wide. They consist of amphibolites and mylonitized acidic orthogneisses, micaschists, and migmatites as well as acidic to intermediate granitoids and pegmatitic and aplitic veins (Núñez, 1979; Criado Roqué and Ibáñez, 1979). According to the petrographic description of Núñez (1979), all these rocks show evidence of ductile deformation. Similar rocks were also localized in some wells (Criado Roqué and Ibáñez, 1979) to the southeast. Astini et al. (1996) cited an unpublished U–Pb date by Bowring et al. that yielded a Grenvillian age for these rocks. Furthermore, a Rb–Sr whole-rock isochron constructed from 7 samples of granodioritic to tonalitic rocks, which are exposed as 5 m long lenses parallel to the foliation of the metamorphic rocks, also yielded a Grenvillian age of 1063 ± 106 Ma (Cingolani and Varela, 1999). These basement rocks of the Ponon Trehue area are overlain by Ordovician fossiliferous sandstones, slates, and limestones (Lindero Formation of Núñez, 1979; Ponon Trehue Formation of Criado Roqué and Ibáñez, 1979). These were initially correlated with the limestones mentioned from the Las Matras Block (Wichmann, 1928) and also with the Ordovician carbonate platform of the Precordillera (Bordonaro et al., 1996).

A summary of the Grenvillian ages, isotopic signatures, and Neoproterozoic dates from this belt with Grenvillian-age rocks is shown in Fig. 10.

Within the above context, the low-Al tonalitic–trondhjemitic pluton at Las Matras, characterizing a magmatic arc with an age of ~1200 Ma, allows its inclusion at the southern extension of the belt with Grenvillian-age rocks of central western Argentina. Along its length of almost 900 km (see Fig. 1), it comprises tectonic environments of continental magmatic arcs, backarcs, or oceanic arcs/back arcs near a continental margin. However, the undeformed Las Matras pluton contrasts with the medium- to high-grade metamorphic units to the north (orthogneises, amphibolites, granulites, schists, gneises, migmatites, etc). This difference is even more remarkable if we consider that the age of the pluton (1200 Ma) is older than those U–Pb, Pb–Pb, and Rb–Sr dates reported from the Western Sierras Pampeanas, Precordillera, Cordillera Frontal, and San Rafael Block. There, as summarized in Table 3, the U–Pb igneous crystallization ages are between 1118 ± 54 Ma and 1069 ± 36 Ma, and the U–Pb, Pb–Pb, and Rb–Sr metamorphism ages are between <1083 Ma and up to 1021 ± 12 Ma.

The apparent lack of overprints by regional metamorphism and ductile deformation at Las Matras should imply that this area remained unaffected or, alternatively, protected from further orogenic processes. The geological relationship with respect to the garnet-bearing schist dated at 605 Ma (Criado Roqué, 1979), and located only 70 km to the north of Las Matras, is not yet clear.

On the other hand, the Sm–Nd model ages obtained from Las Matras (1551–1604 Ma) are partially consistent with the data obtained from the Cordillera Frontal (Basei et al., 1998) and Precordillera (Mahlburg Kay et al., 1996). The low initial ^{87}Sr/^{86}Sr ratio of the Las Matras pluton (0.7030) is also a characteristic feature of the deformed granodioritic to tonalitic rocks of the San Rafael Block (0.7032, Cingolani and Varela, 1999) and of the orthogneiss of Sierra de Umango (0.7026, Varela et al., 1996). These are in agreement with the depleted character of the magmas involved.

With respect to the K–Ar date of 690–869 Ma obtained from the Las Matras pluton, no geological evidence can explain an isotopic resetting during Neoproterozoic times. However, other similar K–Ar dates were mentioned from the Sierra de Valle Fértil by Toubes Spinelli (1983) for pegmatites (587–750 Ma), tonalitic gneisses (603 and 660 Ma), and an amphibolite (800 ± 50 Ma) whose geological meanings are difficult to appraise. Other examples are the K–Ar date of 635 ± 95 Ma (amphibole of amphibolite, Linares and Aparicio, 1976), and the Ar/Ar total gas age of

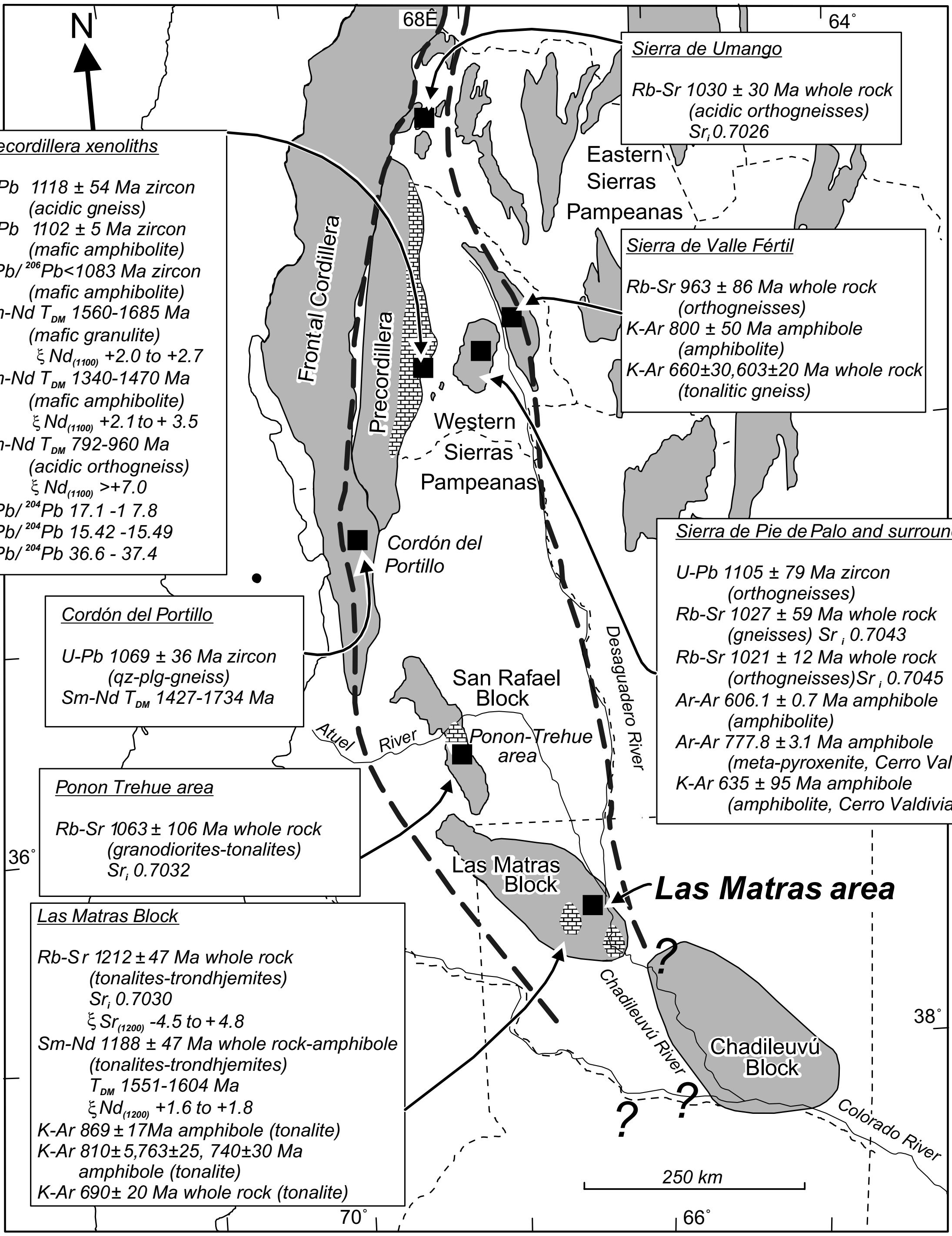

Fig. 10. Summary of the Grenvillian age constraints, isotopic signatures, and Neoproterozoic dates from the "belt with Grenvillian-age rocks" in central western Argentina, based on the general map shown in Fig. 1 and data given in Table 3. The igneous crystallization age obtained for the Las Matras pluton (ca. 1200 Ma) and its non-deformed character contrasts with the crystallization ages (1118 ± 54–1069 ± 36 Ma) and metamorphism ages (<1083–1021 ± 12 Ma) found for rocks to the north. This can suggest a non-homogeneous tectonic evolution for the entire belt. The low initial ^{87}Sr/^{86}Sr values and the available Sm–Nd model ages are consistent throughout the belt.

777.8, approaching 1050 Ma (hornblende of meta-pyroxenite, Ramos et al., 1998) at Cerro Valdivia south of Sierra de Pie de Palo. The main deformational ages at Sierra de Pie de Palo, Cerro Barbosa, and Valdivia, and also the Sierra de Valle Fértil-Sierra de la Huerta, are within Early Paleozoic times (Linares and Aparicio, 1976; Toubes Spinelli, 1983; Ramos et al., 1998; Pontoriero and Castro de Machuca, 1999). These Early Paleozoic ages are considered to represent the cooling and uplift after the complex deformational events associated with the docking of the Cuyania

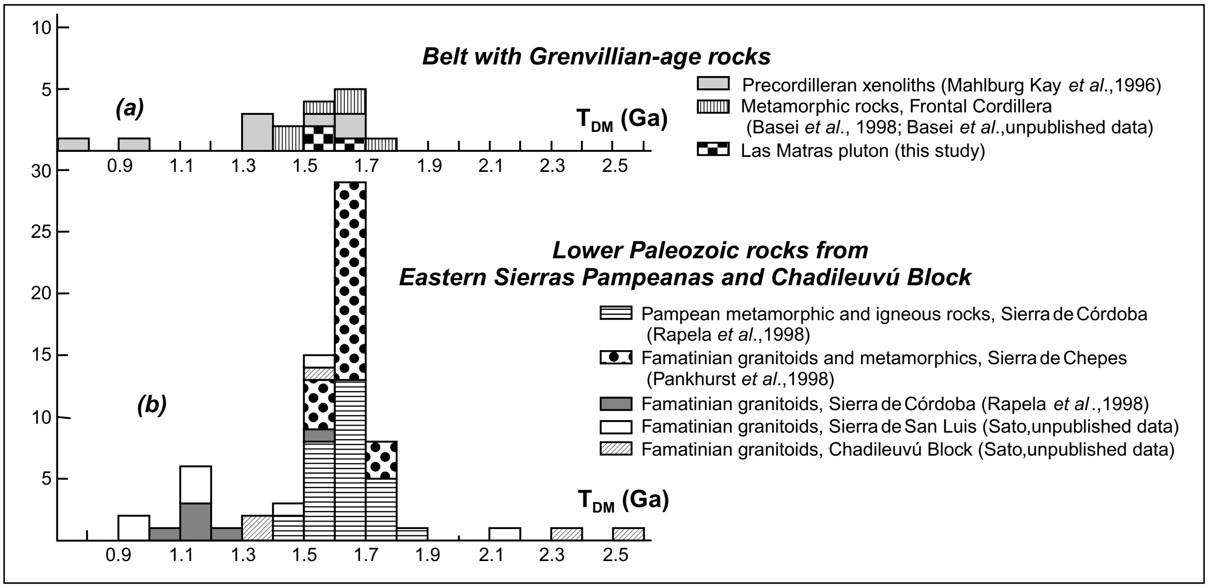

Fig. 11. T_{DM} model age histograms for: (a) the Grenvillian-age basement rocks (17 samples); and (b) the Early Paleozoic basement rocks from the Eastern Sierras Pampeanas and the Chadileuvú Block (70 samples). Although the orogenic cycles involved in these two parallel belts are different, the compiled T_{DM} data do not suggest, up to now, a clear separation of the lower crustal compositions of both belts. Only some few Paleoproterozoic data are remarkable in the Eastern Sierras Pampeanas and the Chadileuvú Block, which are not seen in the Grenvillian-age rocks.

(mid-Ordovician to Silurian) and Chilenia (Devonian) terranes at the proto-margin of Gondwana (Ramos et al., 1998). Other examples of Neoproterozoic K–Ar dates have been reported by Linares et al. (1980) and Criado Roqué (1979) within the La Pampa Province. For all the Neoproterozoic dates, no geological explanation could be found up to now.

4. Regional implications

The association of Grenvillian-age rocks with Cambro–Ordovician platform carbonates is the most characteristic feature of the Laurentian-derived Precordillera or Cuyania terrane. This rock association is clearly observed in the Precordillera (29–33°S) and the San Rafael Block (35°S). In the Las Matras Block, the Grenvillian-age basement rocks are also spatially associated with the recently dated Cambro–Ordovician carbonates of the San Jorge Formation. Consequently, we confirm the southern extension of the Precordillera or Cuyania terrane up to the latitudes of exposures of the San Jorge Formation (37°15′S), as also stated by Melchor et al. (1999b) and originally suggested by Ramos (1995) and Astini et al. (1995).

To the east of and parallel to this belt of the Laurentia-derived terrane are located the Eastern Sierras Pampeanas (Sistema de Famatina, Sierras de los Llanos-Malanzán-Chepes, Sierra de San Luis, Sierra de Córdoba) and the Chadileuvú Block (Fig. 1). This belt of basement rocks is characterized by major orogenies of Late Proterozoic to Early Paleozoic times, successively developed during the Pampean (Late Proterozoic–Early Cambrian) and Famatinian (Late Cambrian–Devonian) cycles. Particularly, the Famatinian orogeny is considered to be the result of the collision of the Grenvillian basement terrane to the southwestern margin of Gondwana (e.g., Dalla Salda et al., 1998; Ramos et al., 1998). Igneous rocks emplaced during these times and the associated metamorphic rocks (Linares et al., 1980; Sato et al., 1996; Llambías et al., 1998; Pankhurst and Rapela, 1998; Pankhurst et al., 1998; Rapela et al., 1998b; Saavedra et al., 1998; Sims et al., 1998; von Gosen and Prozzi, 1998; Tickyj, 1999; Tickyj et al., 1999a, among others) indicate the location of the magmatic arc. The available Sm–Nd data indicate a very consistent Mesoproterozoic lower crust (T_{DM} 1541–1725 Ma, 21 samples) for the Ordovician granitoids of Sierras de los Llanos-Malanzán and Chepes (Pankhurst et al., 1998). The Early Cambrian to Ordovician metamorphic rocks and granitoids of the Sierras de Córdoba also yielded a consistent group of T_{DM} between 1477 and 1822 Ma, with the exception of the late high-Na suite with 1069–1573 Ma (Rapela et al., 1998b). The sparse data from the Early Paleozoic granitoids of Sierra de San Luis (8 samples: Sato, unpublished data) show scattered Paleoproterozoic (~2200 Ma) and Meso- to Neoproterozoic (1525–958 Ma) model ages. In the Chadileuvú Block, the Upper Cambrian to Ordovician granitoids (5 samples analyzed: Sato, unpublished data) are grouped in the Paleoproterozoic (2524 and 2358 Ma) and Mesoproterozoic (1517–1371 Ma). All these model ages, most frequently within the Mesoproterozoic, cannot be clearly distinguished from those found in the belt with Grenvillian-age rocks. In the Eastern Sierras Pampeanas and Chcadileuvú Block, only a few older (Paleoproterozoic) components are identified within the lower crust (Fig. 11).

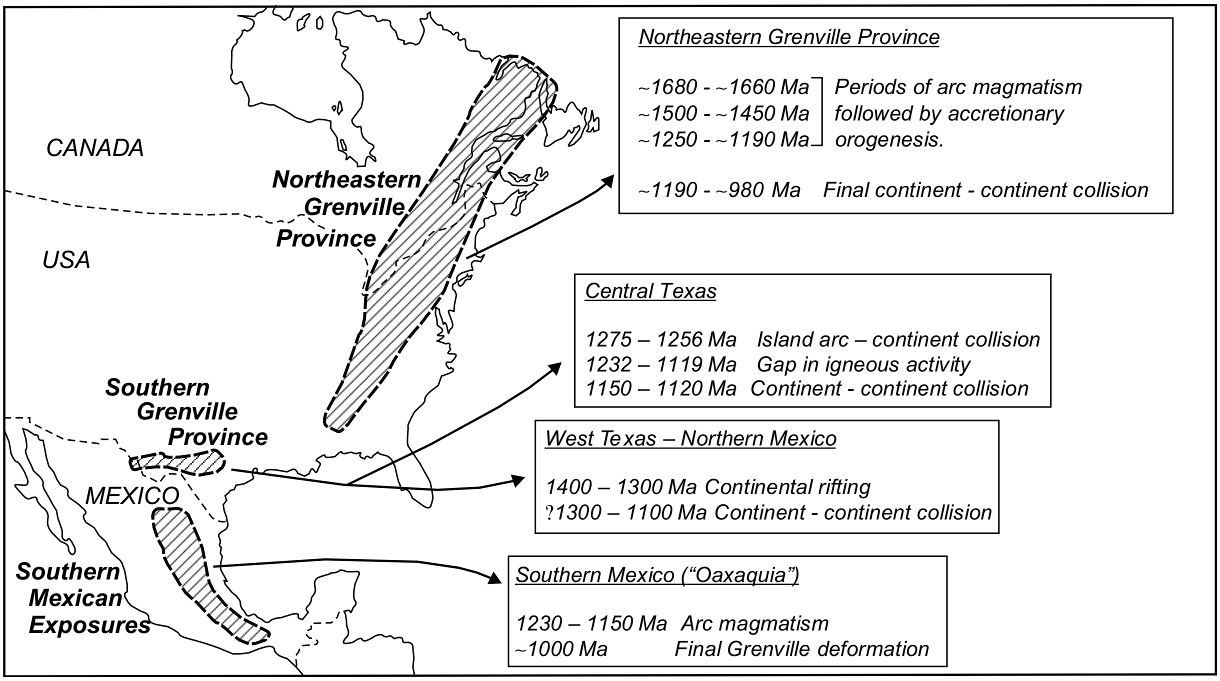

Fig. 12. Location map of the North American Grenville Provinces, compiled after Ruiz et al. (1988) and Mosher (1998). Data used for the summaries shown in each region are from the references given here. Northeastern Grenville Province: Rivers (1997), Martignole and Friedman (1998) and Corrigan et al. (2000). Southern Grenville Province (central and west Texas into northern Mexico): Mosher (1998) and Rougvie et al. (1999). Southern Mexico: Patchett and Ruiz (1987), Ruiz et al. (1988), Lawlor et al. (1999) and Weber and Köhler (1999). The "belt with Grenvillian-age rocks" of Argentina does not fit with any of these regions; however, the Early Paleozoic sedimentary cover correlation suggests the Southern Grenville Province as detachment site for the basement of the Precordillera or Cuyania terrane. Therefore, a possible independent evolution of the Argentine belt can be inferred, prior to the final amalgamation of the Laurentian Grenville orogen.

Within the belt with Grenvillian-age rocks, the effects of the Famatinian orogeny are traced through very scarce intrusive rocks of Early Paleozoic up to earliest Carboniferous ages (Western Sierras Pampeanas), and tectonic and metamorphic overprints resulting in isotopic resettings (Linares and Aparicio, 1976; Toubes Spinelli, 1983; Varela and Dalla Salda, 1992; Cingolani et al., 1993; Ramos et al., 1996; 1998; Varela et al., 1996; Pontoriero and Castro de Machuca, 1999). This influence of the Famatinian tectonics seems to diminish toward the south, as can be seen at the San Rafael Block and the Las Matras Block where no thermal overprint of these ages has been reported up to now. Perhaps only the low-grade metamorphism and ductile deformation associated partially with the limestones of the San Jorge Formation (Melchor et al., 1999c; Tickyj, 1999) could have occurred during this period, although the timing is not yet precisely constrained.

The continuity of the western allochthonous Precordillera or Cuyania terrane and the eastern autochthonous Famatinian magmatic arc south of the Colorado River within Patagonia is not yet well known. As a first approach, the existence of metamorphic rocks of variable grades, with dates between the Neoproterozoic and Cambrian and intruded by Ordovician granitoids (Ramos, 1975; Giacosa, 1997; Varela et al., 1997; 1998), indicate the possibility that the Atlantic area of the North Patagonian Massif represents the southern extension of the Eastern Sierras Pampeanas and Chadileuvú Block (Tickyj, 1999). Nevertheless, these correlations are not yet well documented. On the other hand, the southern continuity of the Grenvillian-age rocks has not been proved up to now. The preliminary Rb–Sr date of 850 ± 50 Ma reported from the Mina Gonzalito gneiss in the North Patagonian Massif (Linares et al., 1990) was later invalidated by another U–Pb date of 526 Ma (Varela et al., 1998). In the western region of the North Patagonian Massif, preliminary ages, Rb–Sr isochrons and errorchrons of up to 860 Ma (Parica, 1986; Dalla Salda et al., 1991a,b), or even the Rb–Sr reference isochron of 1190 ± 16 Ma (Linares et al., 1988) could not be confirmed by other methods like U–Pb, which yielded Late Paleozoic dates (Basei et al., 1999; Varela et al., 1999).

As a result, the possible alternatives to the continuity of the Grenvillian-age rocks south of the Colorado River are: (1) that the Las Matras pluton is the southernmost outcrop of this belt and the basement does not continue southwards; (2) that the basement does continue to the south but is now displaced along a transcurrent fault zone. For the latter alternative, the Colorado River itself can represent the location. The area of Las Matras, however, should have remained protected from deformation events through the entire Proterozoic to Phanerozoic period.

5. Comparisons with the North American Grenville Provinces

The Laurentian derivation of the Precordillera or Cuyania terrane was proposed based on the correlations of the Early Paleozoic lithology, biostratigraphy, paleogeography, and paleomagnetism. Within the North American Appalachian orogen, the southern area of the Ouachita embayment was pointed out as the probable detachment site for the Argentine Precordillera (Dalla Salda et al., 1992b; 1998; Astini et al., 1995; Keller and Dickerson, 1996; Dickerson and Keller, 1998; Rapalini and Astini, 1998; Thomas and Astini, 1999).

The possible source areas for the Argentine belt with Grenvillian-age rocks are then restricted to the surroundings of the Southern Grenville Province (Texas and northern Mexico), according to the source area for the Precordilleran Lower Paleozoic rocks. This rules out the Northeastern Grenville Province as a source (Fig. 12).

For this Southern Grenville Province, Mosher (1998) summarized the tectonic evolution of the Grenville orogenic belt. According to that study, the >300 Ma orogenic activity in central Texas comprises island arc–continent collision (1275–1256 Ma), followed by a gap in igneous activity (1232–1119 Ma), and a continent–continent collision (1150–1120 Ma), causing polyphase deformation and high-P metamorphism. In western Texas (and northern Mexico), after a continental rifting (1400–1300 Ma), similar continent–continent collision that caused polyphase deformation was unconstrained between 1300 and 1100 Ma. Within these evolutions, all the involved rocks are deformed except the northernmost foreland regions of the orogen (north of the Llano or Grenville Front: Soegaard and Callahan, 1994) and the post-tectonic, high-K anorogenic granitoids (e.g. Red Bluff and Enchanted Rock granites: Smith et al., 1997) younger than 1120 Ma. The post-metamorphic cooling history was traced between 1100 and 1000 Ma based on U–Pb, Rb–Sr, and Ar–Ar determinations (Rougvie et al., 1999).

Comparing the above evolution of the Southern Grenville Province with the Argentine exposures, the time for crystallization of the Las Matras pluton (around 1200 Ma) corresponds to a time with no record of magmatism in the Southern Grenville Province. In addition, the ranges of igneous crystallization (1118 ± 54–1069 ± 36 Ma) and metamorphism ages (1083–1021 ± 12 Ma) obtained from the Argentine rocks other than Las Matras pluton also correspond to a post-collisional, not deformational time of the Southern Grenville Province. These differences suggest that, up to now, a direct correlation of the Grenvillian rocks of the Southern Grenville Province with the Argentine belt has not been possible. Only a general correlation of tectonic environments, comprising oceanic arc/back arc complexes near a continental margin (Vujovich and Kay, 1996; 1998) or a continental or island magmatic arc (Castro de Machuca et al., 1996a,b; Vujovich and Kay, 1996; Vujovich et al., 1996; this study), and the depleted Pb/Pb or Sm/Nd signatures (Mahlburg Kay et al., 1996; Basei et al., 1998; Patchett and Ruiz, 1989; additional data in Mosher, 1998) can be established. On the other hand, few examples of trondhjemitic rocks found within the evolution of the Grenville orogeny are of high-Al character; apparently, these are younger than the Las Matras pluton, as in Cerro del Carrizarillo and Sierra del Cuervo, México (1080 ± 5 Ma: in Mosher, 1998) or also in the Northeastern Grenville Province of the Adirondack Highlands (~1060 Ma: Daly and McLelland, 1991).

The general tectonic evolution of the Northeastern Grenville Province (reviewed by Rivers, 1997; additional data from Corrigan et al., 2000), which developed upon the Archean to Paleoproterozoic crust, is characterized by more than 400 million years of active margin tectonism, comprising subduction/accretion and arc/back arc settings. Major juvenile crustal additions and substantial growth of the Laurentian margin occurred during different periods, which comprise arc magmatism followed by accretionary orogenesis (~1680 to ~1660 Ma, ~1500 to ~1450 Ma, and ~1250 to ~1190 Ma). The final continent–continent collision associated with the Grenvillian Orogeny is registered between ~1190 to ~980 Ma, including three distinct pulses of crustal shortening separated by periods of extension and emplacement of mafic magmas and anorthosite complexes. The last stages of terrane assembly (major shear zone movements) were constrained at around 1000 Ma (Martignole and Friedman, 1998), and the subsequent extensional regime lasted until ~900 Ma (Busch et al., 1997).

For this Northeastern Grenville Province, again it is noticeable that the period of 1230–1190 Ma (coinciding with the timing of crystallization of the Las Matras pluton) was a time of cessation of subduction-related magmatism that culminated with a back arc closure (Rivers, 1997). The general juvenile character of magmas (Daly and McLelland, 1991; McLelland et al., 1993; Rivers, 1997) is a constant feature of the entire province.

Another alternative for the source area of the Argentine belt with Grenvillian age rocks is the southwesternmost region of the Grenville Provinces in southern Mexico. There, the different rock exposures have been included in the “Oaxaquia” microcontinent (Ortega-Gutiérrez et al., 1995). The rocks comprise metagranites, amphibolites, mafic and intermediate orthogneisses, paragneisses, marbles, and metaquartzites, that underwent granulite facies metamorphism associated with minor magmatism during the final Grenville deformation at around 1000 Ma (Ruiz et al., 1988; Lawlor et al., 1999; Weber and Köhler, 1999). Among these exposures, a felsic orthogneiss of the Guichicovi Complex yielded a crystallization age for the granitic protolith of 1231 ± 43 Ma and a peak granulite metamorphism age of 975 ± 35 Ma (U–Pb zircon: Weber and Köhler, 1999) from the Maya terrane. In the area of Novillo, the Huiznopala gneiss records an arc magmatism extending from ~1200 to 1150 Ma (various U–Pb dates). A later granulite facies metamorphism was probably associated with the emplacement of an anorthosite–gabbro complex at ~1000 Ma (Lawlor et al., 1999; Weber and Köhler, 1999). Post-metamorphic, Sm–Nd garnet ages of ~933 to ~911 Ma and Rb–Sr biotite ages of ~882 to ~866 Ma (Weber and Köhler, 1999), as well as Rb–Sr biotite ages of 876 and 827 Ma (Patchett and Ruiz, 1987), are reported. The Sm–Nd isotopic features indicate depleted-mantle model ages of 1.4–1.6 Ga for the meta-igneous rocks of all the southern Mexico exposures (Patchett and Ruiz, 1987; Ruiz et al., 1988; Lawlor et al., 1999; Weber and Köhler, 1999). The Pb/Pb isotopic signatures are also depleted ones, similar to those reported from the Northeastern Grenville Province (Lawlor et al., 1999, and references therein).

The recognition of an arc magmatism at ~1200 Ma in the southern Mexico Grenville exposures appears to be a distinctive feature within the North American Grenville Provinces, and this age is similar to that found in the Las Matras pluton. Although this magmatic arc registers a later granulite facies deformation, it seems to be the only region with comparable ~1200 Ma magmatism like in Las Matras. The final Grenville metamorphism and deformation at around 1000 Ma in southern Mexico is younger than in the Texas–northern Mexico region where the latest metamorphism took place at around 1150–1120 Ma. The metamorphism ages recorded from the Argentine belt with Grenvillian age rocks (1083–1021 Ma) are intermediate between those two regions. The abundant Sm–Nd and Rb–Sr cooling dates up to ~827 Ma reported from southern Mexico cannot be directly compared with the K–Ar dates (869–690 Ma) of the Las Matras area, because the latter area did not record a deformation and metamorphic history.

Based on the above comparisons of magmatic and metamorphic events, the Argentine belt with Grenvillian-age rocks does not fit completely with any of the North American Grenville Provinces, showing little more similarity with the southern Mexican exposures (the ~1200 Ma magmatic arc) than with the northern Mexico–Texas region (Southern Grenville Province). However, as mentioned above, correlation of the sedimentary cover favors the derivation from the southern area of the Ouachita embayment for the Argentine Lower Paleozoic units. Therefore, the slightly different history detected in the Argentine belt with Grenvillian-age rocks can be explained by taking into account that the North American Grenville orogeny itself is a result of accretions of various Mesoproterozoic micro-blocks and arcs separated by closed oceans (Ortega-Gutiérrez et al., 1995; Ruiz et al., 1988; Rivers, 1997; Mosher, 1998). In other words, it may not be necessary to expect a completely coinciding magmatic and metamorphic history of the basement to explain a derivation from a specific site. The fact that the Mesoproterozoic history found in the Argentine belt does not fit that of the Southern Grenville Province (Texas and northern Mexico) could be due to an independent evolution of the Argentine belt before its final amalgamation to the North American Grenville orogen, and would not constitute a problem in accepting that derivation site. Furthermore, within the Argentine belt itself, the evolution seems not to be homogeneous — having the area of Las Matras an older magmatic arc that has not been deformed by later metamorphic or tectonic processes.

6. Conclusions

As a result of the present study, the following statements can be made:

The Las Matras pluton is a microgranitoid enclave pluton of tonalitic to trondhjemitic composition, with low-Al and medium-K characteristics, possibly associated with a magmatic arc. It is noticeable that the pluton is apparently non-metamorphosed, undeformed, with the magmatic crystallization textures being not modified.

Rb–Sr whole-rock and Sm–Nd whole-rock mineral isochrons are interpreted to represent the crystallization age of the pluton, at around 1200 Ma. Sr, and Nd isotopic signatures indicate that the magma was of depleted character, with $\epsilon \mathrm{Nd}_{(1200)} = +1.7$ to $+1.8$ and $\epsilon \mathrm{Sr}_{(1200)} = -5$ to $+5$. Together with the geochemical data, they suggest a derivation from either a basaltic magma extracted from a depleted mantle or directly from an enriched mantle.

The Grenvillian age obtained from the Las Matras pluton allows for its inclusion within the southern extension of the belt with Grenvillian-age basement rocks that developed in central western Argentina, where the magmas show similar Sr and Nd depleted signatures.

Compared to the rocks of this belt, the most remarkable features of the Las Matras pluton are: (1) an older age of 1200 Ma; (2) the high crustal level emplacement (shallow final emplacement level of the pluton, according to preliminary data); and (3) the apparent lack of overprints of further regional metamorphic or orogenic processes.

The ages obtained from the Las Matras pluton (this study), and from the spatially associated platform carbonate deposits of the San Jorge Formation (Cambro–Ordovician: Melchor et al., 1999a) confirm that, up to now, the Las Matras Block represents the southernmost extension of the Precordillera or Cuyania terrane of Laurentian origin.

To the east of this Precordillera or Cuyania terrane, the well-known parallel belt of the Eastern Sierras Pampeanas and Chadileuvú Block is characterized by the metamorphic and magmatic processes of the Pampean to Famatinian orogenies (latest Proterozoic to Early Paleozoic).

Although the above-mentioned two parallel belts of terranes differ in the timing of their basement evolution, the available Sm–Nd model ages (most frequently in the Mesoproterozoic) do not clearly distinguish their lower crustal compositions. Only some few older (Paleoproterozoic) and also younger (Meso- to Neoproterozoic) data characterize the Eastern Sierras Pampeanas and Chadileuvú

Block. The continuation of these two belts of terranes farther south of the Colorado River is not yet well constrained geologically and geochronologically.

Within the North American Laurentian continent, the recognition of the source area for the Precordilleran Lower Paleozoic rocks as the southern Appalachians also restricts the possible source areas for the Argentine belt with Grenvillian-age rocks to the surroundings of the Southern Grenville Province (Texas and northern Mexico). However, comparisons of magmatic and tectonic processes involved do not suggest a direct correlation of the Argentine belt with any of the North American Grenville Provinces. This difference suggests an independent evolution for the Argentine belt (which, in addition, also comprises non-homogeneous evolutions) prior to the final Grenville amalgamation to Laurentia. The fact that the Grenville orogeny itself is the result of accretion of various microterranes and arcs support this interpretations. This, in turn, does not constitute a problem with accepting the area of the Ouachita embayment as the detachment site for the Precordillera or Cuyania terrane.

The possibilities of correlations with the coeval terranes of the Islas Malvinas (Falkland Islands: Cingolani and Varela, 1976; Thomas et al., 1998; Wareham et al., 1998; Jacobs et al., 1999), the Mesoproterozoic belt of Uruguay (Preciozzi et al., 1999), as well as the Sunsas belt of the South American Amazon Craton (Sadowski and Bettencourt, 1996; Sato and Tassinari, 1997) or the Brazilian coastal and southern regions (Sato, 1998) have not yet been clarified.

Acknowledgements

Field and laboratory work were financially supported by CONICET (grant PIP 4329/96), ANPCyT (grant PICT 0743), and UNLP. We thank S.M. Kay for helpful comments on an earlier version of the manuscript. W. von Gosen is gratefully acknowledged for discussions and constructive review of the manuscript. Discussions with V. Ramos, R. Varela, and I. Mc Reath, and the observations and suggestions of the reviewers (R. Kay and S. Poma) contributed greatly to improving the interpretations. L. Petronilho is also acknowledged for her assistance with laboratory work. We appreciate very much the unpublished T_{DM} data on the Frontal Cordillera provided by M. Basei and coworkers.

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