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Magmatism along the high Paraguay River at the border of Brazil and Paraguay: A review and new constraints on emplacement ages

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ABSTRACT

The magmatic rocks from Alto Paraguay (High Paraguay River extensional lineament), western Apa craton, mainly consist of several major circular alkaline complexes and some rhyolitic domes and ignimbrites. The former are characterized by intrusive Na–alkaline rock-types (nepheline syenites and syenites and effusive equivalents) topped by lava flows and ignimbrites. Two main evolved suites were defined using petrochemical and Sr– isotope data: an agpaitic suite in the north and a miaskitic suite in the south. The domes of subalkaline rhyolitic lavas and ignimbrites occur to the north of the alkaline complexes, along the Paraguay River, near the town of Fuerte Olimpo.

The emplacement ages of the alkaline complexes were constrained using the K–Ar, Ar–Ar, Rb–Sr and Sm–Nd dating methods on whole rocks and/or mineral separates (amphibole, alkali feldspar and biotite). Ages are quite variable (Upper Permian to Middle Triassic), with average K–Ar and Ar–Ar ages of 248.8 ± 4.8 and 241.8 ± 1.1 Ma, respectively, and Rb–Sr and Sm–Nd age data giving best values from 248 ± 4 to 244 ± 27 Ma and from 256 ± 3 to 257 ± 3 Ma, respectively. In contrast, the Fuerte Olimpo volcanics show a Mesoproterozoic age (1.3 Ga, K–Ar and Ar–Ar radiometric methods; and 1.42 ± 0.24 to 1.30 ± 0.03 Ga, Rb–Sr and Sm–Nd methods, respectively).

Rb–Sr systematics ($^{87}Sr/^{86}Sr$ initial ratios ≤ 0.7038) highlight a relatively "primitive" character of the Na–alkaline magmatic source(s), in contrast with the "crustal" values ($^{87}Sr/^{86}Sr$ initial ratio ~ 0.7105) of the Fuerte Olimpo rhyolites. Thus, magmatism in the Alto Paraguay area is related to two extensional events: a younger event corresponding to the Permian–Triassic alkaline rocks, and an older event connected to the Precambrian volcanic acidic rocks.

1. Introduction

The magmatic rocks from the Alto Paraguay (High Paraguay) River at the border between Brazil (Mato Grosso do Sul State) and Paraguay (Comin-Chiaramonti and Gomes, 1996, 2005; Gomes et al., 1996a,b) consist of a few major circular complexes with alkaline affinity, namely Cerro Boggiani, Pão de Açúcar, Fecho dos Morros (Cerrito) and Cerro Siete Cabezas, minor alkaline stocks (Fig. 1 and 1A), and some rhyolitic domes near the village of Fuerte Olimpo (Fig. 1B). The latter rocks are considered to be a local remnant of the Mesoproterozoic magmatism in the western tectonic block of the Rio Apa craton (Cordani et al., 2010).

All the outcrops are restricted to a very narrow N–S trending lineament parallel to the Paraguay River and characterized by extensional earthquakes with hypocentres shallower than or equal to 70 km (Asunción Arch of Berrocal and Fernandes, 1996).

According to paleomagnetic data reported in Ernesto et al. (2014), the main susceptibility K1 axes for the intrusive alkaline complexes delineate planes in approximately NW (northern area) and NE (southern area) directions, confirming the extensional character of the whole area.

The country rocks consist of alluvial sediments of the Paraguay River that probably cover the Precambrian basement. Granitic/gneissic rocks and rhyolitic flows are widespread and belong to the Amoguijá Group (e.g., Alumiador granite) and to the Rio Apa

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crystalline complex, with ages ranging from about 1.7 to 1.2 Ga (Paleo- to Mesoproterozoic; see Araújo et al., 1982; Amaral, 1984).

A significant amount of geochemical and mineralogical data have been reported in previous studies, particularly on the alkaline rocks (e.g., Comin-Chiaramonti et al., 2007a,b and references therein). The main aim of this article is to compare the timing of magmatic events affecting the northwestern fringe of the Paraná Basin using different dating methods (K–Ar, Ar–Ar, Rb–Sr and Sm–Nd), and to discuss the tectonic significance of this magmatic activity.

2. Petrography, classification and nomenclature

The Na–alkaline complexes from Alto Paraguay consist of intrusions with mainly nepheline syenitic and syenitic composition, topped by lava flows and ignimbrites with phonolitic affinity (Fig. 2). The syenitic rocks occur commonly as stocks of different size and dikes.

From a petrochemical point of view, two main suites can be defined within the group of alkaline rock-types (Fig. 3). An agpaitic, strongly undersaturated suite is dominant in the North (Cerro

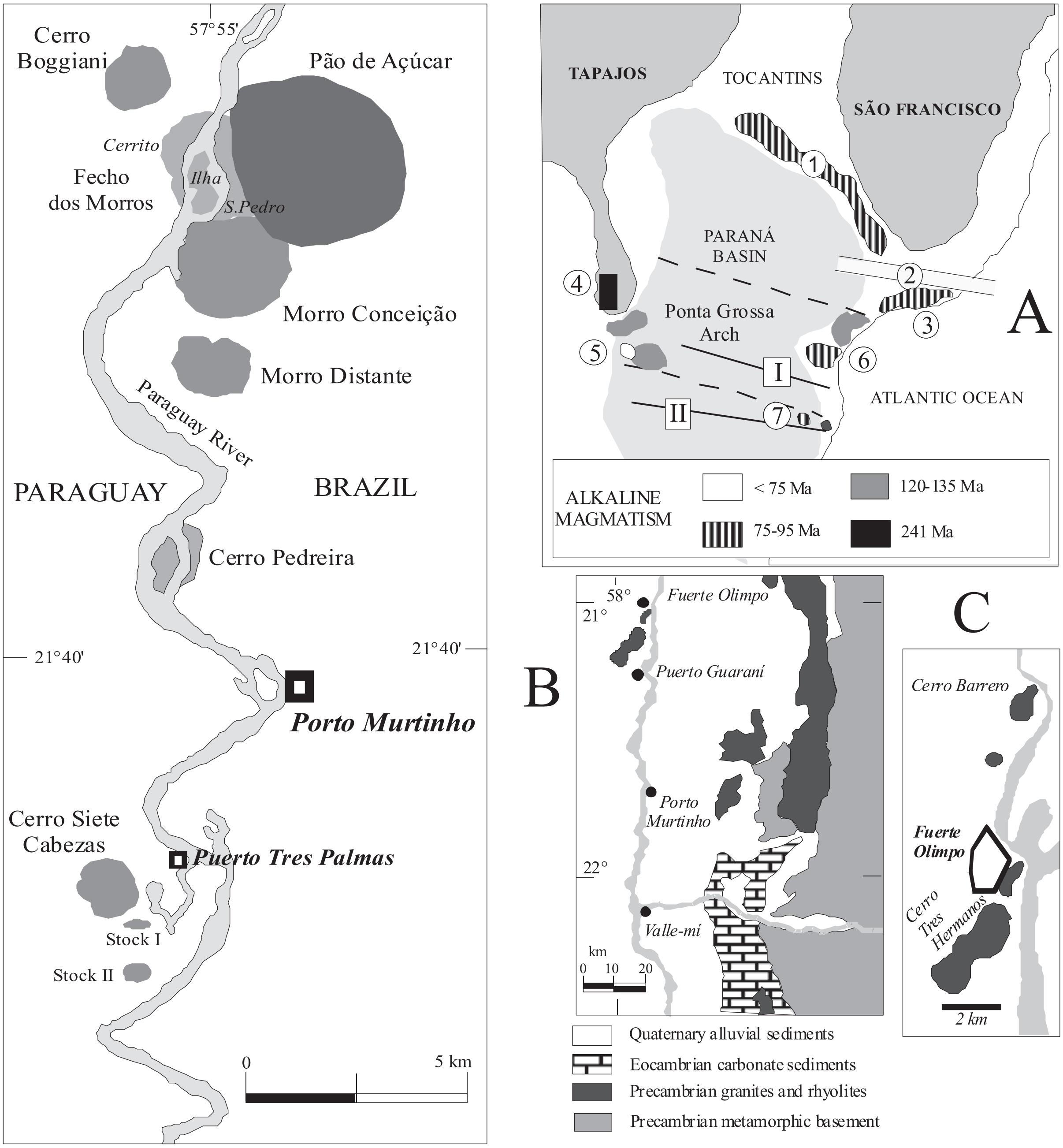

Fig. 1. Sketch map showing the main alkaline occurrences of northern Paraguay (after Velázquez et al., 1996). Note that Cerrito, Ilha and Morro de São Pedro correspond to different segments of the same Fecho dos Morros complex. *Insets*: A. schematic structural map indicating the main areas of alkaline outcrops in and around the Paraná Basin (after Comin-Chiaramonti et al., 2005); 1) Alto Paranaíba; 2) Taiúva–Cabo Frio Lineament; 3) Ribeira Belt; 4) Alto Paraguay; 5) Paraguay; 6) Ponta Grossa Arch; 7) Santa Catarina State; I and II, Piquiri and Uruguay lineaments, respectively. B. Geological sketch map of the Alto Paraguay region in the western tectonic block of the Rio Apa craton (after Wiens, 1986; Cordani et al., 2010). C. Outcrops of rhyolitic lava domes along the Paraguay River near the locality of Fuerte Olimpo (after Gomes et al., 2000).

Boggiani, Pão de Açúcar and Cerrito complexes), while a predominantly miaskitic suite, oversaturated in some places (e.g., Stock 1), is found in the South (Cerro Siete Cabezas).

The agpaitic rocks are typically characterized by sodalite, aegirine and arfvedsonite/magnesio–arfvedsonite, with $Fe^{3+}/(Fe^{3+}+Al^{IV})$ and $Mg/(Mg+Fe^{2+})$ a.f.u. ratios in the alkali amphiboles ranging from 0.64 to 0.99 and from 0.48 to 0.70, respectively, for both the whole population and single samples. In contrast, the miaskitic rocks contain aegirine–augite and/or sodic–calcic amphiboles which are represented by katophorite/ferro-richterite/riebeckite, with Si and $Mg/(Mg+Fe^{2+})$ a.f.u. ratios around 7.25–7.75 and 0.07–0.45, respectively. $Fe^{3+}/(Fe^{3+}+Al^{IV})$ and $Mg/(Mg+Fe^{2+})$ a.f.u. ratios in alkaline amphiboles are 0.93–0.99 and 0.07–0.18, respectively. Exsolved anorthoclase, biotite ($R^{3+}=24$–33; $Fe^{2+}+Mn=45$–61; $Mg=8$–25 a.f.u.), opaques, nepheline (undersaturated rock-types) or quartz (oversaturated rock-types) are ubiquitous. Common accessory minerals include apatite, titanite, fluorite, zircon and pyrochlore. Exotic phases, such as astrophyllite and rosembuschite (Carbonin et al., 2005), and unidentified minerals may be present. For the analyses of mineral phases see Comin-Chiaramonti et al. (2005).

In contrast with the alkaline rocks, the volcanic rocks from Fuerte Olimpo occur as lava domes and are represented by subalkaline rhyolites (Fig. 2) aphyric to weakly porphyritic in texture, with quartz, alkali feldspar and plagioclase (An_{25-28}) as the main microphenocrysts. They also contain variable amounts of epidote–chlorite microblasts and micropatches of calcite set in an aphanitic or glassy groundmass. These rocks can be also described as ignimbrites due to the presence of *fiammae* fragments (Gomes et al., 2000).

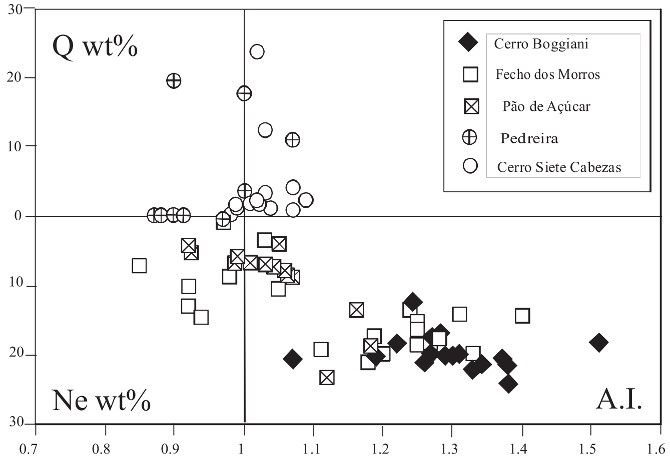

Fig. 3. Agpaitic index [A.I. = $(Na_2O + K_2O)/Al_2O_3$, molar ratio] vs. normative quartz (Q) and nepheline (Ne) of sodic rock-types from the Alto Paraguay complexes. Data from Comin-Chiaramonti et al. (2005).

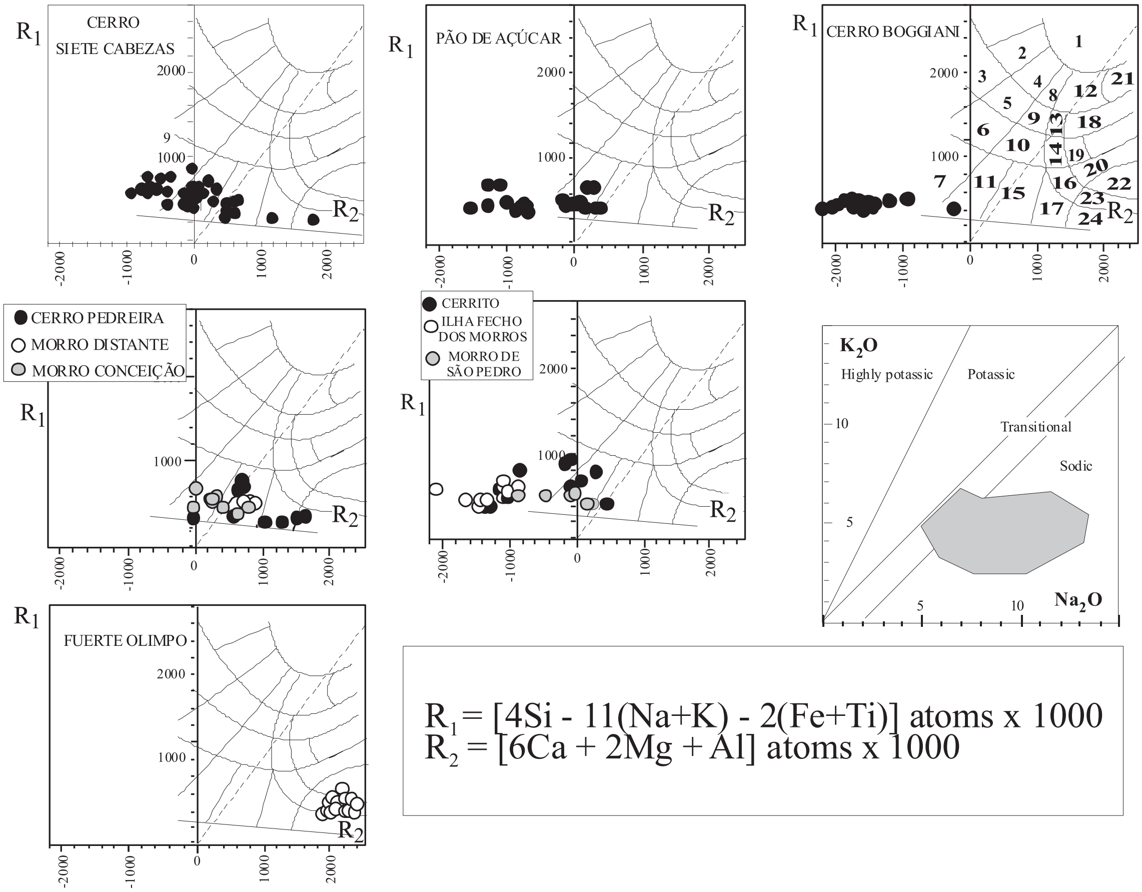

Fig. 2. R_1–R_2 classification diagram (De La Roche et al., 1980) for the alkaline complexes and Fuerte Olimpo lavas. Data from Comin-Chiaramonti et al. (2005). Numbered fields are indicated on the Cerro Boggiani diagram (extrusive equivalents in brackets): 1) Alkali peridotite (picrite); 2) Melteigite (ankaratrite); 3) Ijolite (nephelinite); 4) Theralite (basanite); 5) Essexitic gabbro (tephrite); 6) Essexite (phonotephrite); 7) Nepheline syenite (phonolite); 8) Alkali gabbro (alkali basalt); 9) Syenogabbro (trachybasalt); 10) Syenodiorite (trachyandesite); 11) Nephelinic syenite (trachyphonolite); 12) Olivine gabbro (olivine basalt); 13) Monzogabbro (latibasalt); 14) Monzonite (latite); 15) Syenite (trachyte); 16) Quartz monzonite (quartz latite); 17) Quartz syenite (quartz trachyte); 18) Gabbro–diorite (andesibasalt); 19) Monzodiorite (latiandesite); 20) Granodiorite–tonalite (dacite); 21 Gabbro (tholeiite); 22) Granodiorite (rhyodacite); 23) Granite (rhyolite); 24) Alkali granite (alkali rhyolite). Na_2O–K_2O discrimination diagram (after Le Maitre, 1989) showing the field occupied by the Alto Paraguay alkaline rocks. The complete set of chemical analyses (n = 117, including major and trace elements) is available upon request from the first author.

Table 1
K–Ar data for samples representative of the main Alto Paraguay Na–alkaline complexes and of the Fuerte Olimpo rhyolites.

Locality sample	Rock-type	Material	%K	$^{40}Ar_{rad.}$ (10^{-6}cSPT/g)	Ar atm. (%)	Age (Ma)
Cerro Boggiani						
RP-27	Nephelinic syenite	Amphibole	1.03	10.02	24.42	234.6 ± 13.7
RP-30	Nephelinic syenite	Amphibole	0.27	2.62	31.48	234.0 ± 9.0
RP-43	Peralkal. Phonolite	Whole rock	3.50	34.40	8.44	236.7 ± 10.9
Pão de Açucar						
RP-76	Nepheline syenite	Biotite	6.87	71.06	12.97	248.4 ± 10.7
RP-76[a]	Nepheline syenite	Biotite	7.70	82.49	5	256 ± 3
RP-77	Nepheline syenite	Amphibole	1.42	13.75	28.26	233.2 ± 7.2
RP-114	Nepheline syenite	Biotite	6.90	71.32	7.96	248.3 ± 5.3
RP-114[a]	Nepheline syenite	Biotite	7.38	77.02	4	250 ± 3
SPK-1475[b]	Phonolite	Whole rock	4.72	4.17	7.0	219.1 ± 13.3
SPK-155[c]	Nepheline syenite	Biotite	7.46	75.96	3.1	244.6
SPK-098[c]	Nepheline syenite	Biotite	7.54	75.60	3.8	241.1
SPK-100[c]	Nepheline syenite	Alkali feldspar	5.71	49.75	11.2	211.3
SPK-156[c]	Nepheline syenite	Alkali feldspar	5.68	49.07	12.0	209.6
Ilha Fecho dos Morros						
RP-91	Nephelinic syenite	Amphibole	1.02	8.95	66.39	212.8 ± 14.8
Cerrito						
RP-80	Nephelinic syenite	Biotite	7.45	78.63	10.64	253.2 ± 9.2
RP-80[a]	Nephelinic syenite	Biotite	7.88	85.53	5	254.± 4
Morro Conceição						
RP-9	Syenite	Biotite	6.93	75.71	13.20	263.2 ± 23.1
RP-9[a]	Syenite	Biotite	6.83	71.79	5	254 ± 4
Cerro 7 Cabezas						
RP-61	Nepheline syenite	Amphibole	1.74	16.40	34.44	227.9 ± 7.8
RP-64	Nepheline syenite	Biotite	6.76	71.39	14.24	253.4 ± 12.5
RP-64[a]	Nepheline syenite	Biotite	7.51	77.94	4	249 ± 3
RP-69	Syenite	Amphibole	1.86	17.63	26.70	229.8 ± 8.3
RP-70	Syenite	Biotite	6.10	61.95	19.84	244.4 ± 10.4
Fuerte Olimpo						
FO-19B	Alkali rhyolite	Whole rock	6.45	475.16	1.33	1309 ± 18

Data source for the alkaline rocks: Velázquez et al. (1996).

[a] Istituto di Geocronologia e Geochimica Isotopica del CNR, Pisa.

[b] Compte and Hasui (1971).

[c] Amaral et al. (1967): ages recalculated according to constants recommended by Steiger and Jäger (1977).

3. Radiometric ages

Age data for the Alto Paraguay alkaline rocks have been available for a long time and have defined this activity as the oldest alkaline magmatic event associated with the Paraná Basin. The first report on the geochronology of these rocks was compiled by Amaral et al. (1967) who quoted a "preferred age" of 243 Ma (Middle Triassic) for the Pão de Açúcar complex based on two K–Ar biotite ages, although two additional data on K–feldspars yielded younger ages in the range of 211–209 Ma. Following this work, Compte and Hasui (1971) inferred a K–Ar whole rock age of 214 Ma (Late Triassic) for the same complex, while years later Gomes et al. (1996b) inferred ages (K–Ar and Ar–Ar data for biotite and amphibole separates) ranging from about 250 to 240 Ma (Early to Middle Triassic) for the whole Alto Paraguay sodic magmatism. The main radiometric K–Ar, Ar–Ar and Rb–Sr ages will be discussed in the following sections. In contrast to the alkaline rocks, The Fuerte Olimpo rhyolites have been studied and dated only more recently (Gomes et al., 2000).

Some samples were analyzed both at the Geochronological Research Center (University of São Paulo, Brazil) and the Istituto di Geocronologia e Geochimica Isotopica del CNR (Pisa, Italy). Minerals were separated using conventional and gravimetric techniques. Procedures for K–Ar analyses in São Paulo and Pisa laboratories are described in Amaral et al. (1967) and Del Moro et al. (1983), respectively. Duplicate analyses of biotite were performed for samples from the Pão de Açúcar (RP-76), Cerrito (RP-80), Morro Conceição (RP-9) and Cerro Siete Cabezas (RP-64) complexes in order to assess the reliability of the K–Ar age data. Rubidium and Sr isotopic analyses were performed at the Geochronological Research Center (University of São Paulo, Brazil) using a VG 354 mass multicollector spectrometer. The Sr isotopic compositions were calibrated using NBS987 $^{87}Sr/^{86}Sr = 0.71026$. Samarium and Nd isotopic ratios were determined at the Department of Mathematics and Geosciences, University of Trieste using a VG 54E mass spectrometer, following the procedures of Ludwig (1988) and D'Orazio and Petrini (1989). The La Jolla standard ($^{143}Nd/^{144}Nd = 0.51187$; $2\sigma = 0.00002$; $n = 21$) was used for calibration.

3.1. K–Ar ages

The available analytical results are listed in Table 1, along with some recalculated data from previous studies by Amaral et al. (1967) and Compte and Hasui (1971).

With the exception of the Fuerte Olimpo rhyolite (K–Ar age of 1309 ± 18 Ma), the whole age data set ranges from 256 to 210 Ma. Notably, the younger ages are from alkali feldspars (211–210 Ma) and from a phonolite whole rock (219 Ma) reported in Compte and Hasui (1971). The amphiboles exhibit characteristic chemical disequilibrium that is responsible for Ar loss, as supported by their younger ages in comparison to those of biotites (see Table 1). Furthermore, considering that the prevailing alkali feldspar is anorthoclase, a mineral usually affected by strong perthitic exsolution and secondary kaolinitization, and that whole rocks (phonolites) show sometimes hyaline texture with clayey glass, the most reliable K–Ar data are those obtained from the biotite samples. Notably, the average K–Ar age ($n = 9$) from six Na–alkaline complexes, considering only the most reliable results for biotite, is 248.8 ± 4.8 Ma.

3.2. Ar–Ar ages

$^{40}Ar/^{39}Ar$ analyses were performed on biotites from Cerro Boggiani (nephelinic syenite), Pão de Açúcar (nepheline syenite), Cerrito (nephelinic syenite), Cerro Siete Cabezas (syenite) and Stock I (syenite). The samples display spectra (Fig. 4) with integrated ages spanning from 242 to 240 Ma (241.8 ± 1.1 Ma as the average value).

The amphibole sample from Cerro Siete Cabezas released a relatively disturbed spectrum, with lower temperature steps showing a low Ca–K ratio and a young age (inset A of Fig. 4), probably due to the exsolution of a K-rich phase (K-richterite or biotite). The middle part of the spectrum has a fairly constant Ca–K ratio, but corresponding ages are variable, and the last part of the spectrum displays very high Ca–K ratio likely due to the presence of a Ca-rich phase as inclusion (Gomes et al., 1996b). The integrated date of 236 ± 1.6 Ma is a minimum age, roughly corresponding to those obtained for amphiboles from Cerro Siete Cabezas using the K–Ar method (235–228 Ma, see Table 1), and younger than those obtained for the biotites from the same locality (249–242 Ma), which we consider to be more representative of the emplacement age of the complex. Therefore, the Ar–Ar data confirm that the sodic amphiboles from the Alto Paraguay alkaline rocks cannot be considered as a suitable dating material, and that the biotite must be preferred, as already previously noted by Velázquez et al. (1996).

The Fuerte Olimpo rhyolites data show an integrated age (whole rock) of 1303 ± 3 Ma, corresponding to the Mesoproterozoic (Fig. 4B; Ectasian, according to Gradstein et al., 2012), and remarkably consistent with the K–Ar age (1309 ± 18 Ma; see Table 1).

3.3. *Rb–Sr data*

The Rb–Sr analytical data reported in Table 2 show that Sr contents and ^{87}Sr/^{86}Sr ratios follow three distinct hyperbolas (Fig. 5) relative to 1) Precambrian rhyolites from Fuerte Olimpo (age 1423 Ma, initial ^{87}Sr/^{86}Sr (Sr_i) = 0.71444, see Fig. 6D); 2) Na–alkaline rocks from Cerro Boggiani, Cerrito, Ilha do Fecho dos Morros, Morro de São Pedro and Pão de Açúcar (age 248 Ma, $Sr_i = 0.70347$, see Fig. 6A); and 3) Na–alkaline rocks from Cerro Siete Cabezas and Stocks I and II (age 243–244 Ma, $Sr_i = 0.70375–0.70371$; see Fig. 6B and C).

3.4. *Sm–Nd ages*

The Sm–Nd calculated ages (Table 3 and Fig. 7) are similar to the ages obtained using the Rb–Sr method (Fig. 6): 256 Ma (vs. 248) for Cerro Boggiani + Fecho dos Morros + Cerrito; 257 Ma (vs. 244) for Cerro Siete Cabezas + Stocks; and 1301 Ma (vs. 1423) for Fuerte Olimpo. The initial ^{143}Nd/^{144}Nd ratios are 0.512338, 0.512379 and 0.510620, respectively (see Table 3 and Fig. 7).

4. Discussion

According to Cordani et al. (2010), a regional heating event affected the whole studied region including the Rio Apa craton at about 1.3 Ga, and probably was responsible for 1) regional heating of at least 350–400 °C, as suggested by argon blocking temperatures in biotites; and 2) the local and partial melting of crustal sectors, and the effusion of the rhyolitic lavas in Fuerte Olimpo as well as in Fuerte San Carlos located in the Rio Apa area (cf. Gomes et al., 2000).

Notably, the two groups of Na–alkaline rocks correspond to the agpaitic and miaskitic suites, respectively (see Fig. 3), where the characteristics of the Rb–Sr systematics may be attributed to fractionation processes from two distinct magmatic reservoirs (Velázquez et al., 1996). In addition, the data suggest a single and rapid alkaline magmatic pulse of mantle-derived magmas (initial ^{87}Sr/^{86}Sr ~ 0.703). The tie line relative to the analyzed phases from Cerro Boggiani (alkali feldspar, amphibole and whole rock) straddles the “alkaline” hyperbolas due to very low Sr content and correspondingly low ^{87}Sr/^{86}Sr ratio of the amphibole. These characteristics are consistent with the already mentioned mineralogical–geochemical disequilibrium of the sodic amphiboles in the Alto Paraguay alkaline complexes (Comin-Chiaramonti et al., 2005).

The time integrated ε^tSr–ε^tNd system (Fig. 8) shows that the agpaitic samples (i.e., those in northern Alto Paraguay: Cerro Boggiani, Pão de Açúcar, Fecho dos Morros and Cerrito) plot near the miaskitic ones (i.e., Cerro Siete Cabezas and Stocks) from southern Alto Paraguay. Notably, all samples (excluding Fuerte Olimpo) fit the ε^tSr–ε^tNd data for the nephelinites from southern and central Paraguay (Late Early Cretaceous and Tertiary, respectively, according to Comin-Chiaramonti et al., 2005; see AM samples in Fig. 8 and enlargement). These latter rock-types are believed to represent “primitive” (mg# = 0.675 ± 0.03) mantle-derived material (Comin-Chiaramonti et al., 1997).

The Alto Paraguay nepheline syenites to syenites are more evolved (mg# ranging from 0.19 to 0.52), but are also interpreted as

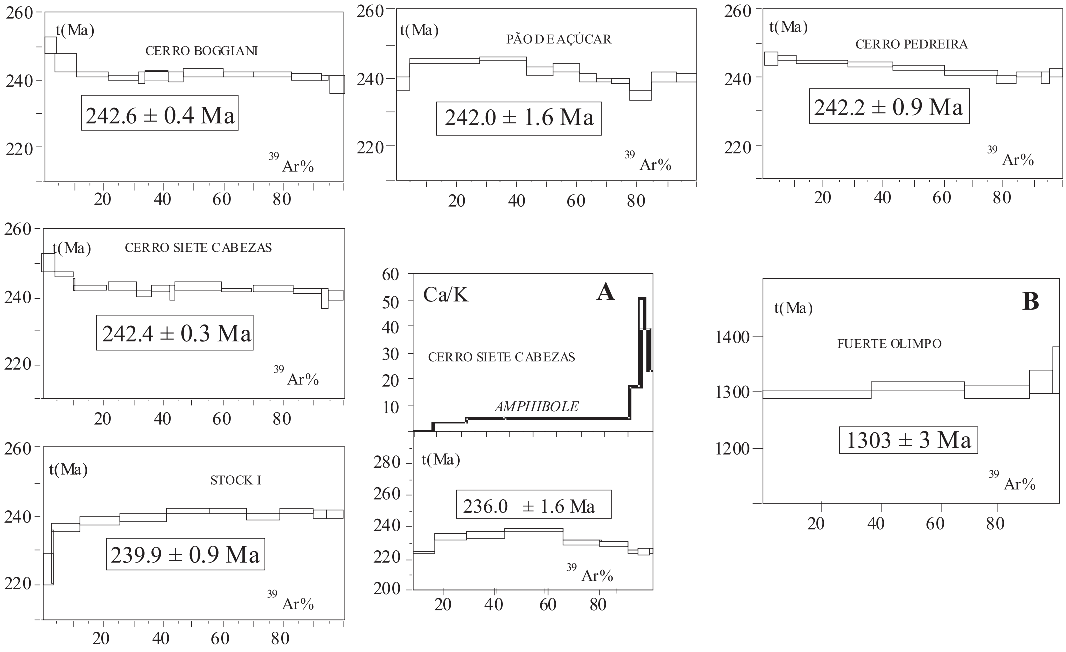

Fig. 4. ^{40}Ar/^{39}Ar spectra for biotite (integrated plateau ages). Insets: A. Cerro Siete Cabezas amphibole (Gomes et al., 1996b); B. Fuerte Olimpo rhyolites (whole rock). The analytical procedures are described in Laurenzi and Villa (1987) and using MMhb-1 as age monitor (520 ± 1.7 Ma, Samson and Alexander, 1987).

Table 2
Rb and Sr contents and isotopic data for Na–alkaline rocks from Alto Paraguay and Precambrian rhyolites from Fuerte Olimpo.

Locality sample	Rock-type	Material	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	$\varepsilon_{\mathrm{Ur}}^{T}$
Cerro Boggiani							
RP-27[b]	Nephelinic syenite	Whole rock	258	76	9.82 (0.30)	0.737916 (8)	−14.9
RP-29[b]	Nephelinic syenite	Whole rock	341.9	242.7	4.08 (0.11)	0.717536 (5)	−15.2
RP-30[b]	Nephelinic syenite	Whole rock	310.1	136.9	6.57 (0.25)	0.726447 (8)	−13.2
RP-30[b]	Nephelinic syenite	Alkali feldspar	365.6	97.6	10.88 (0.31)	0.741701 (6)	−12.4
RP-30[b]	Nephelinic syenite	Amphibole	26.9	68.8	1.13 (0.02)	0.707490 (9)	−10.1
RP-33[a]	Peralkal. Phonolite	Whole rock	344.3	152.9	6.53 (0.18)	0.727061 (7)	−2.5
RP-35[a]	Nephelinic syenite	Whole rock	298.4	120.2	7.20 (0.20)	0.728900 (9)	−10.3
RP-39[a]	Nephelinic syenite	Whole rock	284.7	101.1	8.17 (0.23)	0.732502 (16)	−7.4
RP-40[b]	Peralkal. Phonolite	Whole rock	340.0	180.0	5.47 (0.16)	0.722446 (10)	−15.2
Fecho dos Morros (Cerrito, Ilha Fecho dos Morros, Morro de São Pedro, Pão de Açúcar)							
RP-80[b] Cerrito	Nephelinic syenite	Whole rock	89.5	1481.0	0.18 (0.01)	0.704192 (7)	−9.0
RP-80[a] Cerrito	Nephelinic syenite	Alkali feldspar	84.4	2503.0	0.10 (0.01)	0.704061 (9)	−7.0
RP-80[a] Cerrito	Nephelinic syenite	Biotite	584.4	84.6	20.12 (0.29)	0.77410 (8)	−15.3
RP-87[a] Cerrito	Nepheline syenite	Whole rock	119.7	813.2	0.43 (0.01)	0.705151 (9)	−7.8
RP-89[b] Ilha Fecho dos Morros	Nephelinic syenite	Whole rock	97.8	1126.3	0.25 (0.04)	0.704862 (11)	−3.4
RP-89[a] Ilha Fecho dos Morros	Nephelinic syenite	Biotite	360.7	85.2	12.30 (0.35)	0.746217 (13)	−15.7
RP-89[a] Ilha Fecho dos Morros	Nephelinic syenite	Alkali feldspar	46.5	805.7	0.17 (0.01)	0.704511 (12)	−4.1
RP-91[b] Ilha Fecho dos Morros	Nephelinic syenite	Whole rock	156.0	741.0	0.61 (0.01)	0.705620 (10)	−10.5
RP-95[a] Ilha Fecho dos Morros	Nephelinic syenite	Whole rock	154.5	641.7	0.70 (0.01)	0.705841 (10)	−11.8
RP-253[b] Morro de São Pedro	Nephelinic syenite	Whole rock	145	237	1.77 (0.02)	0.709411 (8)	−14.9
RP-100[b] Pão de Açúcar	Trachyphonolite	Whole rock	107	303	1.02 (0.01)	0.707046 (12)	−10.9
RP-103[b] Pão de Açúcar	Trachyphonolite	Whole rock	114	308	1.07 (0.01)	0.707265 (8)	−10.3
RP-114[b] Pão de Açúcar	Syenite	Whole rock	68	1307	0.15 (0.00)	0.704066 (12)	−9.6
Sr$_i$: 0.70347(28)							
Cerro Siete Cabezas							
RP-61[b]	Nepheline syenite	Whole rock	100	413	0.70 (0.02)	0.706146 (6)	−7.1
RP-63[b]	Nepheline syenite	Whole rock	105	409	0.74 (0.03)	0.706299 (9)	−7.0
RP-66[b]	Nepheline syenite	Whole rock	75	216	1.00 (0.03)	0.707247 (9)	−6.5
RP-70[c]	Nepheline syenite	Whole rock	83.0	335	0.72 (0.02)	0.706060 (6)	−9.2
RP-70[c]	Nepheline syenite	Alkali feldspar	62.1	406.2	0.44 (0.01)	0.705420 (7)	−4.7
RP-74[b]	Nepheline syenite	Whole rock	137.0	266	1.49 (0.05)	0.709005 (11)	−5.5
RP-75[b]	Nepheline syenite	Whole rock	74.0	393	0.54 (0.04)	0.705653 (5)	−6.7
Sr$_i$: 0.70375(37)							
Stock-I, RP-44[b]	Syenite	Whole rock	137.1	92.0	4.32 (0.12)	0.718266 (6)	−13.2
Stock II RP-55[c]	Syenite	Whole rock	154.4	96.9	4.62 (0.13)	0.719347 (6)	−12.6
Stock II RP-212[b]	Nepheline syenite	Whole rock	246	33.0	21.72 (0.16)	0.778595 (18)	−14.2
Stock II RP-214[b]	Nepheline syenite	Whole rock	256	711	1.04 (0.08)	0.707305 (9)	−7.5
Sr$_i$: 0.70349(22)							
Fuerte Olimpo							
RP-10[d]	*Rhyolite*	*Whole rock*	*136*	*141*	*2.81 (0.08)*	*0.76652 (10)*	*90*
RP-16[d]	*Rhyolite*	*Whole rock*	*122*	*134*	*2.65 (0.08)*	*0.76504 (8)*	*116*
RP-18[d]	*Rhyolite*	*Whole rock*	*102*	*198*	*1.50 (0.04)*	*0.74097 (9)*	*108*
RP-19[d]	*Rhyolite*	*Whole rock*	*94*	*238*	*1.15 (0.03)*	*0.73573 (6)*	*135*
RP-20[d]	*Rhyolite*	*Whole rock*	*124*	*208*	*1.73 (0.05)*	*0.74737 (9)*	*131*
RP-22[d]	*Rhyolite*	*Whole rock*	*100*	*265*	*1.09 (0.05)*	*0.73143 (1)*	*89*
Sr$_i$: 0.71052(655)							
Porto Murtinho							
AZ-2[b]	Monzogranite	Whole rock	207	180	3.35 (0.10)	0.78219 (1)	36
Sr$_i$: 0.70517							

Two-σ analytical uncertainties for ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr isotopic ratios are shown in brackets. Initial isotopic (R_i) Sr ratios calculated at 248 Ma (Cerro Boggiani, Fecho dos Morros, Cerrito) and 244 Ma (Cerro Siete Cabezas) for the alkaline rocks (Fig. 6) and at 1423 Ma for the Fuerte Olimpo rhyolites, based on ^{40}Ar/^{39}Ar integrated ages (see Figs. 4 and 6). An age of 1600 Ma was assumed for the monzogranite from Porto Murtinho (Comin-Chiaramonti et al., 2005).

[a] This work.

[b] Comin-Chiaramonti et al. (2005).

[c] Velázquez et al. (1996).

[d] Gomes et al. (2000).

mantle-derived melts because their isotope systematics do not show any evidence of crustal contamination. In contrast, the Alumiador and Porto Murtinho granites and the Fuerte Olimpo rhyolites have a strong crustal component (about 40% and up to 90%, respectively; see Fig. 8).

The model ages (depleted mantle, T_{DM} of Table 3; see DePaolo, 1988) may give a broad indication of the age of the main processes affecting the mantle source(s) of the Alto Paraguay rock-types. T_{DM} relative to the sodic magmatism (Fig. 9 and Comin-Chiaramonti et al., 2007a,b) displays Neoproterozoic ages: Alto Paraguay 0.7–1.0 Ga, Asunción 0.6–0.9 Ga (Central Paraguay) and Misiones 0.8–1.2 (Southern Paraguay).

5. Concluding remarks

The western Rio Apa cratonic outcrops of the northern region of Paraguay consist of Paleo-Mesoproterozoic metamorphic rocks intruded by granitic rocks and covered mainly by Neoproterozoic deposits. Metamorphic medium-grade rocks with an age of

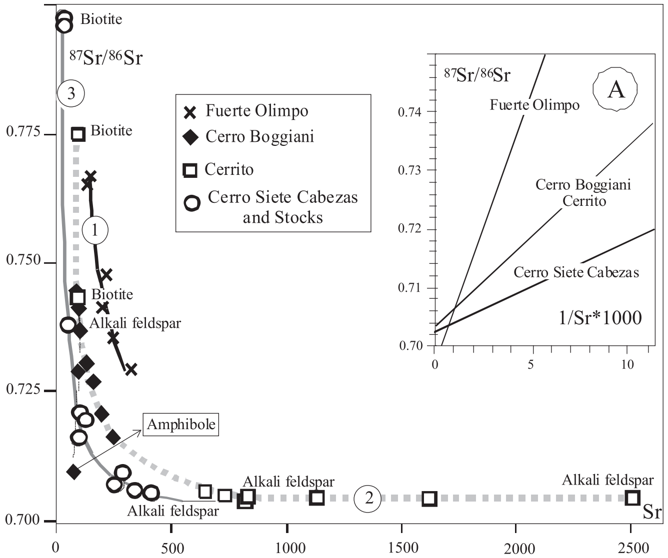

Fig. 5. Strontium content vs. $^{87}Sr/^{86}Sr$ relationships for magmatic rock-types from the Alto Paraguay River (see Velázquez et al., 1996). Inset A. 1000/Sr vs. $^{87}Sr/^{86}Sr$ correlation for the whole Na–alkaline population. Cerrito samples also include Ilha do Fecho dos Morros, Morro de São Pedro and Pão de Açúcar.

1.8–1.6 Ga were affected by another metamorphic event at 1.3 Ga (Cordani et al., 2010).

Previous studies (Gibson et al., 2006) concluded that the outcrops of magmatic rocks between Porto Murtinho and Fuerte Olimpo along the Paraguay River are alkaline complexes of Early Cretaceous age. In contrast, the geochronological data presented and discussed in this study confirm the existence of two main types of magmatic rocks with different ages, namely Mesoproterozoic rhyolites and Upper Permian to Middle Triassic alkaline complexes (see Gomes et al., 2000, 2013; Comin-Chiaramonti et al., 2005). The rhyolites are subalkaline and show ignimbritic textures. In contrast, the alkaline rocks have a sodic affinity, and two main suites can be defined using petrochemical features and geochemical trends (agpaitic index and Sr vs. $^{87}Sr/^{86}Sr$):

1) an agpaitic suite undersaturated in silica (Cerro Boggiani, Pão de Açúcar, Fecho dos Morros and Cerrito), and
2) a miaskitic suite occasionally oversaturated in silica (Cerro Siete Cabezas).

The isotopic dating methods have some limitations due to the mineralogical characteristics of the analyzed materials. However, the critical interpretation of the available data reveals the following ages:

1) *K–Ar* reliable “minimum ages” of biotites: 256–241 Ma (Pão de Açúcar), 252 Ma (Morro Conceição) and 249–244 Ma (Cerro Siete Cabezas); the average age for the six Na–alkaline complexes is 248.8 ± 4.8 Ma.
2) *Ar–Ar* plateau ages: 1303 ± 3 Ma for Fuerte Olimpo, and 241.8 ± 1.1 Ma (average age) for all the Na–alkaline complexes.
3) *Rb–Sr* isochrons: 1423 ± 240 Ma for Fuerte Olimpo; 248 ± 4 Ma for Cerro Boggiani, Fecho dos Morros and Cerrito; 243.5 ± 23 Ma for Cerro Siete Cabezas, Stock I and Stock II.
4) *Sm–Nd* isochrons: 1301 ± 26 Ma for Fuerte Olimpo; 256 ± 3 Ma for Cerro Boggiani, Fecho dos Morros and Cerrito; 257 ± 3 Ma for Cerro Siete Cabezas, Stock I and Stock II.

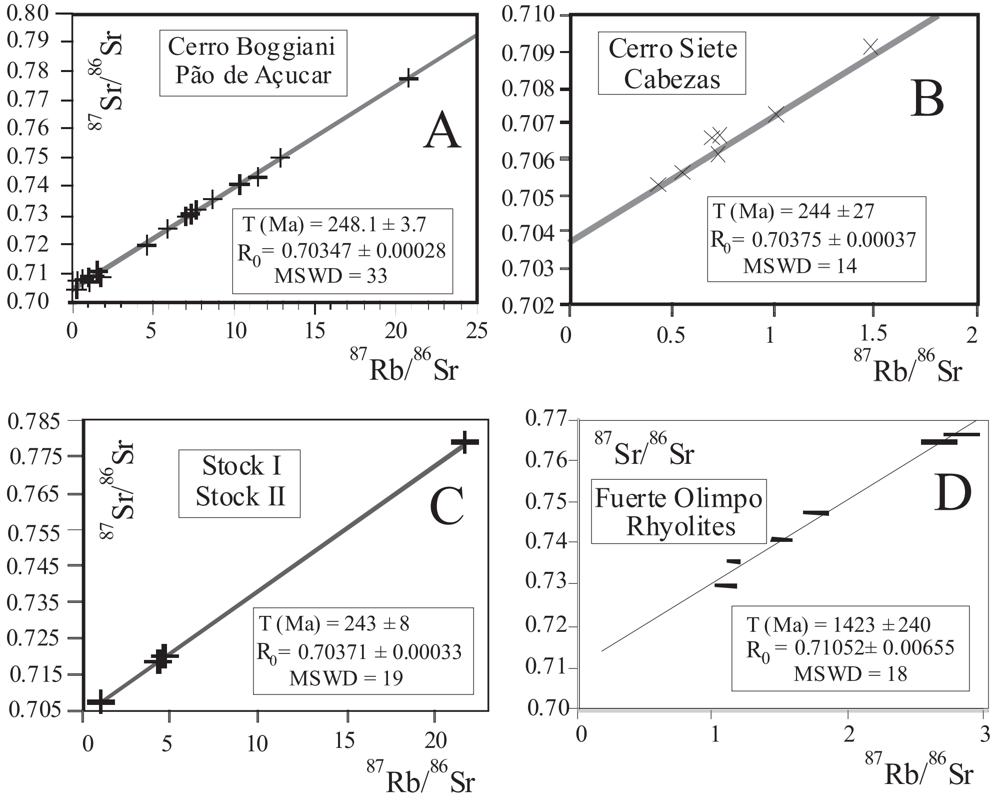

Fig. 6. Sr–Rb isochrons for the alkaline rocks from Alto Paraguay (A – agpaitic suite; B and C – miaskitic suites; D – Fuerte Olimpo rhyolites; see also Velázquez et al., 1996). Pão de Açúcar data include the samples from Cerrito, Ilha do Fecho dos Morros, Morro de São Pedro and Pão de Açúcar (see Table 2). R_0: initial isotopic $^{87}Sr/^{86}Sr$.

Table 3

Sm and Nd contents, and ^{143}Nd/^{144}Nd measured isotopic ratios for the samples from Alto Paraguay (whole rock).

Locality sample	Rock-type	Sm	Nd	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	ε^t_{Chur}	T_{DM}
Cerro Boggiani							
RP-27[b]	Nephelinic syenite	2.5	17.0	0.089 (1)	0.512487 (8)	0.58	780
RP-29[a]	Nephelinic syenite	3.0	20.1	0.090 (1)	0.512489 (7)	0.57	785
RP-30[b]	Nephelinic syenite	4.1	31.0	0.080 (2)	0.512473 (9)	0.60	745
RP-40[b]	Peralkal. Phonolite	9.0	59.9	0.091 (1)	0.512491 (8)	0.59	787
Pão de Açucar							
RP-89[b]	Nephelinic syenite	9.2	56.0	0.099 (1)	0.512504 (10)	0.57	825
RP-91[b]	Nephelinic syenite	11.7	64.2	0.110 (2)	0.512523 (9)	0.58	881
RP-95[b]	Nephelinic syenite	13.4	66.0	0.123 (2)	0.512544 (11)	0.58	963
Cerrito							
RP-80[a]	Nephelinic syenite	9.2	56.0	0.099 (1)	0.512504 (10)	0.57	826
RP-87[b]	Nepheline syenite	7.9	53.8	0.089 (1)	0.512488 (9)	0.60	778
Nd$_i$: 0.512338 (1)							
Cerro 7 Cabezas							
RP-61[b]	Nepheline syenite	16.0	77.0	0.126 (2)	0.512591 (8)	1.44	916
RP63[b]	Nepheline syenite	14.91	68.0	0.132 (2)	0.512601 (9)	1.14	972
RP-66[a]	Nepheline syenite	8.09	47.7	0.103 (3)	0.512553 (12)	1.46	784
RP-74[b]	Nepheline syenite	9.40	52.8	0.108 (1)	0.512559 (7)	1.41	812
RP-75[b]	Nepheline syenite	16.41	79.0	0.125 (2)	0.512588 (7)	1.38	906
Stock-I RP-44[b]	Syenite	5.6	26.9	0.126 (3)	0.512590 (9)	1.41	920
Stock-I RP-47[b]	Alkali granite	8.0	44.0	0.110 (1)	0.512563 (9)	1.40	823
Stock II RP-212[b]	Nepheline syenite	8.8	42.4	0.125 (2)	0.512588 (9)	1.38	919
Stock II RP-214[b]	Nepheline syenite	8.1	38.7	0.127 (2)	0.512592 (6)	1.58	923
Nd$_i$: 0.512379 (9)							
Fuerte Olimpo							
RP-10[a]	*Rhyolite*	*3.4*	*46.1*	*0.045 (2)*	*0.511004 (8)*	*−6.54*	*1873*
RP-16[a]	*Rhyolite*	*10.1*	*51.0*	*0.119 (1)*	*0.511633 (7)*	*−6.79*	*2299*
RP-18[a]	*Rhyolite*	*5.0*	*45.0*	*0.067 (1)*	*0.511192 (9)*	*−6.64*	*1963*
RP-19[a]	*Rhyolite*	*9.2*	*56.0*	*0.089 (2)*	*0.511475 (7)*	*−6.47*	*2130*
RP-20[a]	*Rhyolite*	*2.8*	*42.9*	*0.039 (1)*	*0.510954 (6)*	*−6.66*	*1862*
RP-22[a]	*Rhyolite*	*5.9*	*45.2*	*0.079 (1)*	*0.511295 (8)*	*−6.58*	*2015*
Nd$_i$: 0.51062 (1)							
Porto Murtinho							
AZ-2[b]	Monzogranite	5.5	28.0	0.119 (1)	0.511743 (7)	−1.47	2137
Nd$_i$: 0.51070 (1)							

Analytical 2σ uncertainties are in brackets. Model ages and T_{DM} were calculated according to: ε(source) = 0.25 T^2 − 3T + 8.5 (Ludwig, 1988).

[a] This work.

[b] Comin-Chiaramonti et al. (2005).

Although there is clearly a need for a more extensive selection of whole-rock and mineral samples to minimize any effects of geochemical disequilibria (e.g., reaction rims, exsolution, hydrothermal and weathering alterations) on the Rb–Sr and K–Ar isotopic data, the magmatic events along the Alto Paraguay River seem to be well constrained at the Mesoproterozoic and Permian–Triassic transitions, as also confirmed by Ar–Ar ages (Fig. 4). Moreover the standard deviations on the available age data do not support chronologically distinct magmatic pulses for the two alkaline suites, and their low initial ^{87}Sr/^{86}Sr ratios seem to confirm the hypothesis of a common, isotopically homogeneous mantle source, and of rapid rates of ascent of the generated alkaline magmas. This is also supported by other Na–alkaline occurrences along the Paraguay River (Asunción and Misiones regions) which are interpreted as related to, and driven by the reactivation of pre-existing lithospheric discontinuities which promoted local decompressional melting of their mantle sources (Velázquez et al., 2006; see Fig. 8).

In contrast with the Na–alkaline complexes, the Fuerte Olimpo rhyolites have a significantly older Mesoproterozoic age, and their

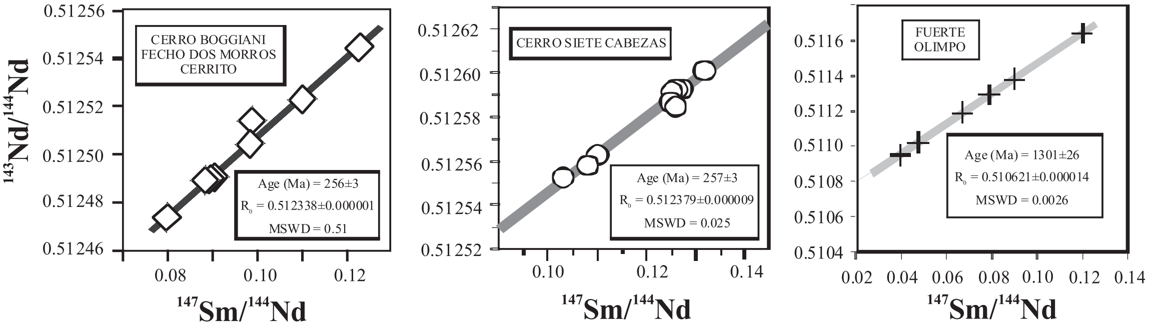

Fig. 7. Sm–Nd isochrons for the alkaline rocks from Alto Paraguay (agpaitic and miaskitic suites) and for the Fuerte Olimpo rhyolites.

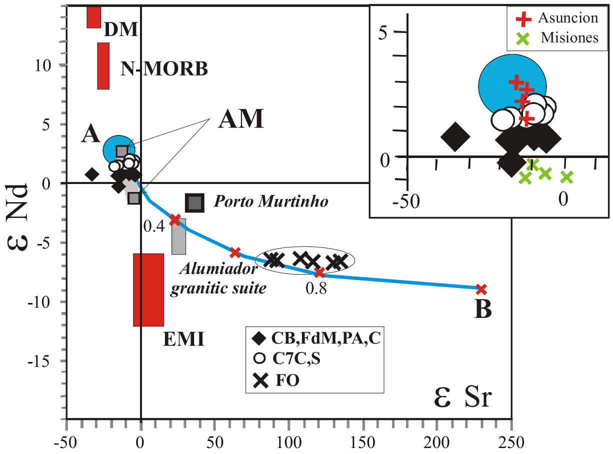

Fig. 8. Epsilon time-integrated values of Nd and Sr (cf. Tables 2 and 3) for the Alto Paraguay rock-types: CB (Cerro Boggiani); FdM (Fecho dos Morros); Pa (Pão de Açúcar); C (Cerrito); C7C (Cerro Siete Cabezas); S (Stocks); and FO (Fuerte Olimpo). For comparison, epsilon values for the nephelinites from San Juan Bautista and Asunción regions (AM) are also shown, as well as those for the Porto Murtinho granite (Comin-Chiaramonti et al., 2005) and Alumiador granitic suite (Cordani et al., 2010). Inset: enlargement of the area around A. The AB curve was fitted using the following end member composition: Mantle Component A, εNd = 3.0, εSr = −12.5; Crustal Component B, εNd = −9.0, εSr = 227.2 (cf. McCulloch and Chappel, 1982; DePaolo, 1988). DM, N-MORB and EMI fields after Hart and Zindler (1989).

initial $^{87}Sr/^{86}Sr$ ratio of 0.71052 suggests the contribution of an old crustal component.

Finally, there appears to be a striking similarity between the Alto Paraguay Province and the "uncontaminated" Na–alkaline rocks from the Velasco Province of eastern Bolivia (Fletcher and Beddoe-Stephens, 1987), emplaced into Precambrian gneisses (1366 Ma) during the Early Cretaceous (143–134 Ma, initial $^{87}Sr/^{86}Sr = 0.7045$, Rb/Sr = 0.16; Darbyshire and Fletcher, 1979). Both provinces (ε^{t}Sr = −7 and −10, respectively) belong to the southwestern part of the Amazon craton (e.g. Teixeira et al., 1989), and are suggestive of the contribution of a peculiar lithospheric mantle source distinct from the mantle source with "potassic" affinity of the intracratonic Paraná Basin (Comin-Chiaramonti et al., 1996).

All the Na–alkaline complexes as well as the Fuerte Olimpo rhyolites are restricted to a narrow N–S trending lineament parallel to the Paraguay River and characterized by extensional earthquakes with hypocentres shallower than or equal to 70 km (Asunción Arch of Berrocal and Fernandes, 1996). Paleomagnetic results delineate different rotational paths at about 18–20° latitude South, roughly corresponding to the Chaco-Pantanal basin, and also indicating extensional tectonics (Randall, 1998). In this context, the Asunciòn Arch may represent an extensional lineament that has existed since at least Paleoproterozoic times.

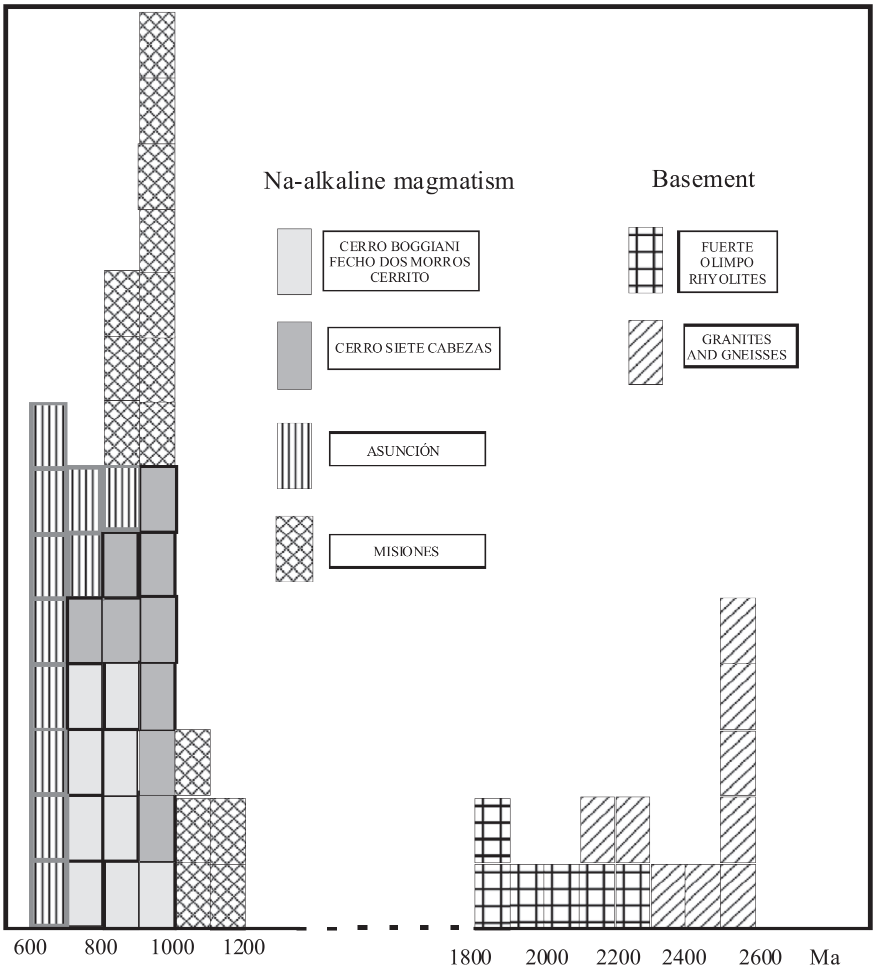

Fig. 9. Sm–Nd (T_{DM}) model age histograms for Na–alkaline rock-types from distinct Paraguayan regions and for Precambrian rocks from northern Paraguay (data from this study and Comin-Chiaramonti et al., 2005; Cordani et al., 2010).

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