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Sodic alkaline magmatism in Eastern Paraguay revisited: geochemical and petrological implications

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Abstract

Associated with subordinate potassic rocks, Mesozoic to Cenozoic sodic alkaline rocks are represented by four distinct provinces in Eastern Paraguay: Alto Paraguay, Central, Misiones, and Asunción; additional Rio Apa and Amambay provinces are exclusively of potassic affinity. Alkaline magmatism is clearly controlled by a tectonic extensional regime that generated NW-SE-trending faults and grabens. It varies in composition, with the intrusive sodic rocks mainly composed of foid syenites and quartz-bearing syenites and the potassic ones of syenites, syenogabbros, and gabbros, all of which are accompanied by fine-grained hypoabissal and volcanic counterparts. In the Central Province, potassic and sodic rocks occur together and are represented by two distinct magmatic series: basanites-phonolites and alkali basalts-trachytes/trachyphonolites. Ultramafic sodic rocks (ankaratrites and nephelinites) are uniquely found in the Misiones and Asunción provinces. In general, the sodic rocks exhibit LILE enrichment, high field strength elements depletion, and Nb-Ta positive anomalies in the mantle's normalized incompatible elements (IE) distribution. Chondrite-normalized rare earth element (REE) diagrams point to strong REE enrichment and high light/heavy rare earth element fractionation in different subparallel patterns. Conversely, the potassic rocks display negative anomalies of Nb-Ta and are fractionated in REE. In the initial Sr_i versus Nd_i diagram, the sodic rocks approach to bulk earth, whereas the potassic ones plot into the Sr-enriched quadrant. Sr-Nd-Pb isotope data suggest that a high U/Pb mantle component played an important role in the genesis of the Late Early Cretaceous and Tertiary sodic magmas, while an enriched mantle component dominated the Early Cretaceous potassic magmas. The close association of potassic and sodic rocks implies that their parental magmas derived from a subcontinental mantle variable in composition enriched in IE.

KEYWORDS: alkaline magmatism; geochemistry; petrology; Eastern Paraguay.

INTRODUCTION

The north-south Paraguay River lineament, which corresponds to the Asunción Arch described by Almeida (1983), is an anticlinal structure established in the Early Paleozoic, responsible for the separation of Paraguayan territory into two large areas quite distinctive in geology, geophysics, geomorphology, and climate (Fig. 1). To the west, it is formed by part of the Gran Chaco Basin and Pantanal wetland sedimentary cover, an alluvial plain of continental origin consisting mainly of clays and sands of Paleogene to Quaternary age. To the east, a region commonly referred to in literature as Eastern Paraguay, includes the westernmost side of the undeformed Paraná Basin with sedimentation beginning in the Ordovician and going up to Jurassic-Cretaceous times. Magmatic activity in this area is represented by Early Cretaceous flood tholeiite basalts of the Serra Geral Formation (Piccirillo and Melfi 1988, and therein references) and by different episodes of alkaline magmatism of variable age and composition. Basement formations, mainly Precambrian to Early Paleozoic, comprise granitic intrusions, rhyolitic flows, and high- to low-grade metasedimentary rocks present in two highs, Caacupú, at the south, and Apa, at the north. They are considered to be the northern occurrence of the Rio de La Plata craton and the southernmost tip of the Amazon craton, respectively (Fúlfaro 1996).

Alkaline rocks of sodic and potassic composition are described in six different areas of Eastern Paraguay, associated with rocks of different formations and ages (Fig. 2). The sodic varieties occur as isolated bodies or, in a few cases, are present in subordinate association with potassic types.

To the north of the country, sodic magmatism is represented by a number of ring complexes and stocks (Cerro Siete Cabezas, Cerro Pedreira, Morro Distante, Morro Conceição, Fecho dos Morros, and Cerro Boggiani), a volcanic field (Pão de Açúcar), minor bodies, and dykes, all of them occurring on both sides of the Paraguay River and emplaced along a narrow structural belt near the border of Mato Grosso do Sul (Brazil) and Paraguay. These rocks, which correspond to the Alto Paraguay Province (Gomes *et al.* 1996a, Comin-Chiaramonti *et al.* 2005), lie mainly to the north and south of Porto Murtinho city and extend over 40 km along the river.

In the east-central part of the Paraguayan territory, magmatism is documented by a great number of scattered dykes, swarm dykes, and plugs across the Asunción-Villarrica (ASU) graben, the dominant rifting structure over the whole area.

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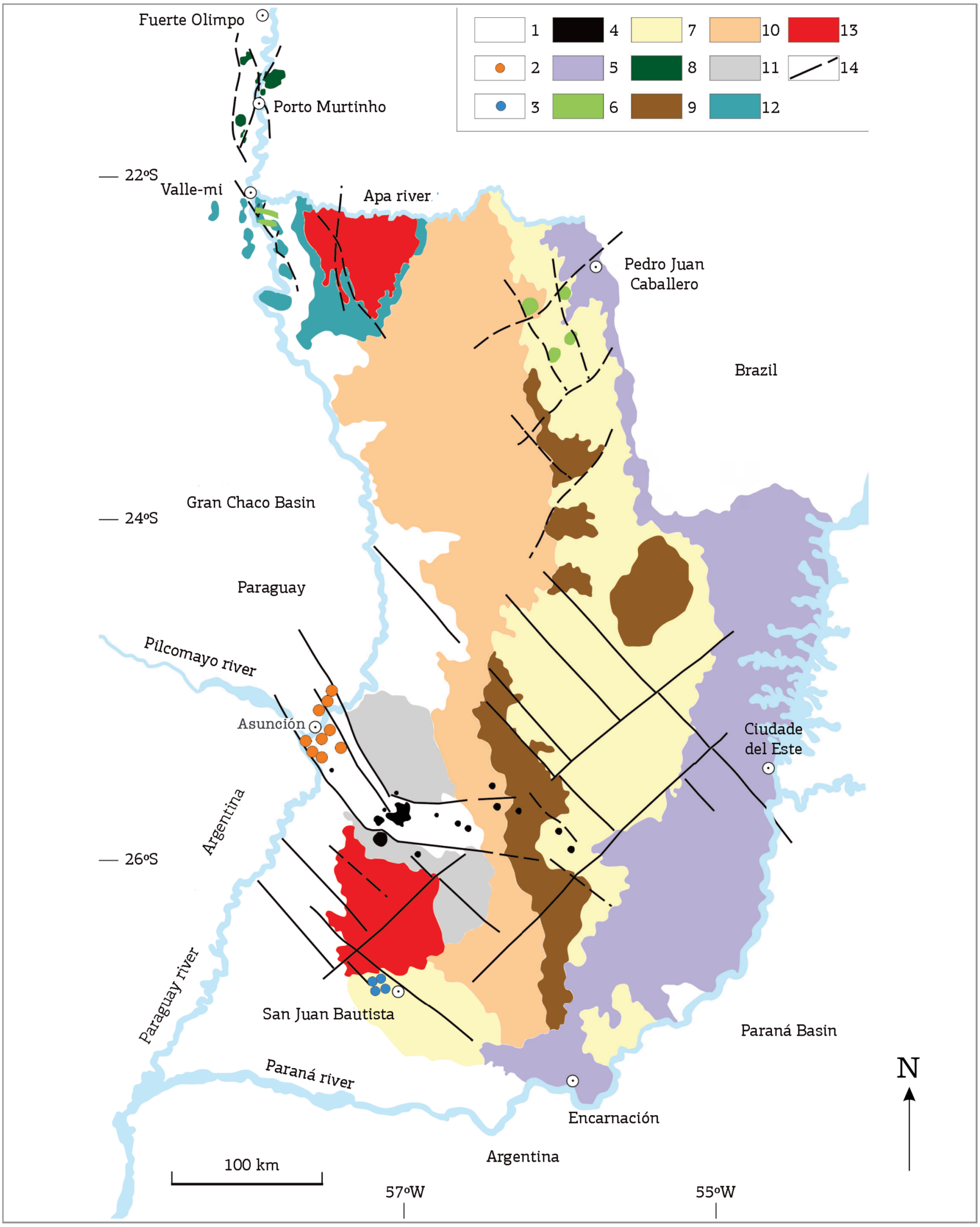
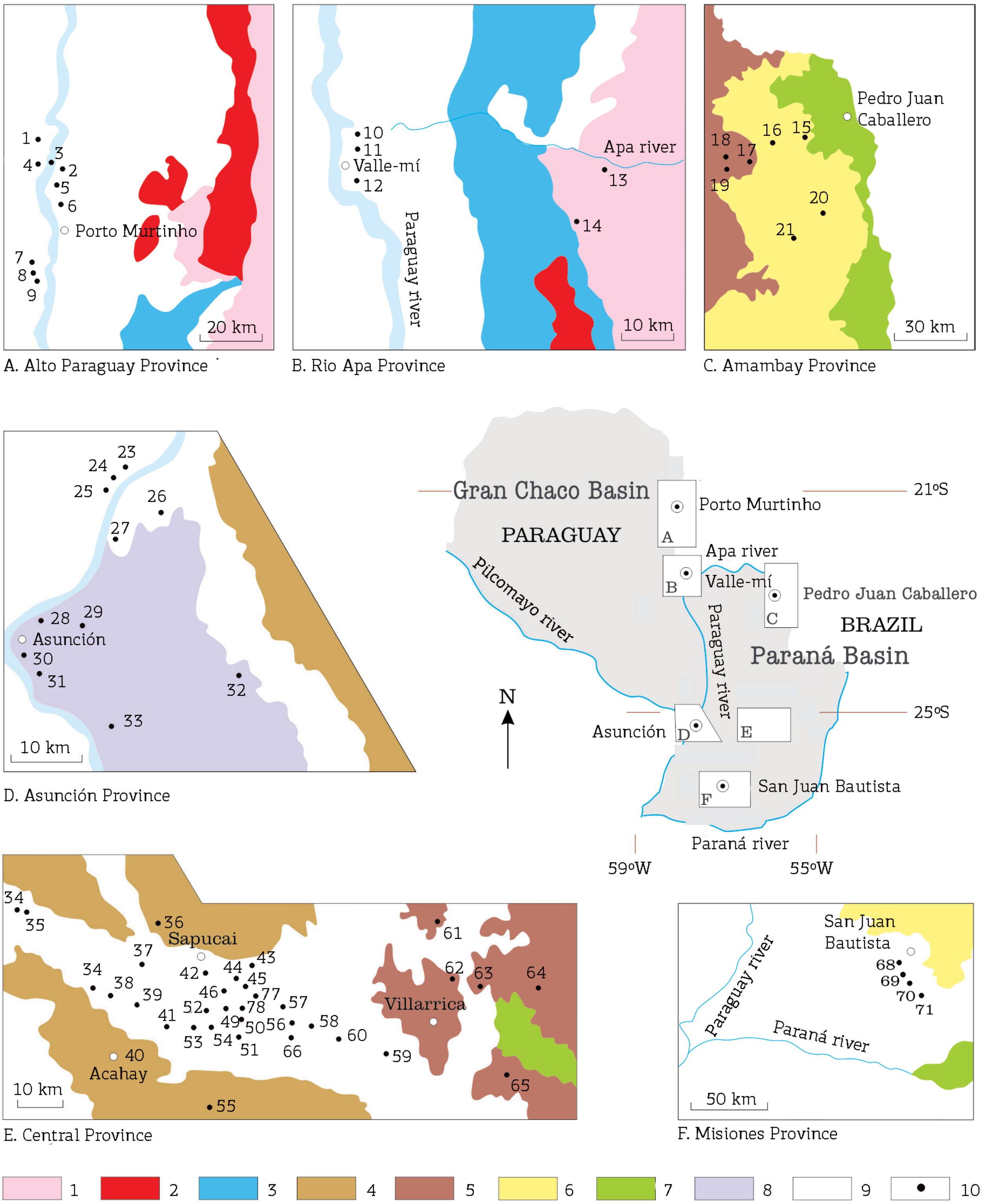


1. Quaternary-Tertiary sedimentary rocks; 2. Tertiary alkaline rocks (Asunción Province); 3. Late Early Cretaceous alkaline rocks (Misiones Province); 4. Early Cretaceous alkaline rocks (Central Province); 5. Early Cretaceous tholeiitic rocks (Paraná Basin); 6. Early Cretaceous alkaline rocks (Rio Apa and Amambay provinces); 7. Jurassic-Cretaceous sedimentary rocks (Misiones Formation); 8. Permo-Triassic alkaline rocks (Alto Paraguay Province); 9. Permian sedimentary rocks (Independencia Group); 10. Permo-Carboniferou sedimentary rocks (Coronel Oviedo Group); 11. Ordovician-Silurian sedimentary rocks (Caacupé and Itacurubí groups); 12. Cambro-Ordovician platform carbonates (Itapucumí Group); 13. Archean and Neoproterozoic crystalline formations. 14. Major tectonic lineaments and faults.

Figure 1. Simplified geological sketch map showing the Eastern Paraguay geology and the alkaline magmatism distribution (Comin-Chiaramonti *et al.* 1997, 1999 and unpublished geological maps.

Numerous bodies of potassic and subordinate sodic composition are encompassed by the Central Province and have been investigated by several authors (Gomes *et al.* 1989, Velázquez *et al.* 2011, Comin-Chiaramonti *et al.* 1992, 1996b, 1997, 2013).

Sodic magmatism is also present in the vicinities of Asunción as pointed out by many intrusions (Cerro Patiño, Cerro Verde, Cerro Lambaré, Cerro Límpio, Cerro Ñemby, Nueva Teblada, Remanso Castillo, and Cerro Tacumbú, for instance), forming



1. and 2. Basement formations; 3. Cambro-Ordovician Itapucumí rocks; 4. Ordovician-Silurian Caacupé and Itacurubí sedimentary rocks; 5. Permo-Carboniferous Coronel Oviedo sedimentary rocks; 6. Permian Independencia sedimentary rocks; 7. Early Cretaceous Paraná Basin tholeiites; 8. Tertiary Patiño sediments; 9. Quaternary sediments; 10. Alkaline outcrops.

Figure 2. General distribution of alkaline occurrences in Eastern Paraguay area (modified and simplified after Velázquez *et al.* 1996).

plugs, lava flows, and dykes included in the Asunción Province (Bitschene 1987, Comin-Chiaramonti *et al.* 1991, 2013). It represents the most recent alkaline activity on the western border of the Paraná Basin (Livieres and Quade 1987).

In southern Paraguay, the sodic magmatism is shown by rocks of the Misiones Province (Velázquez *et al.* 2006) occurring as plugs (Cerro Guayacán, Estancia Guavirá-y, Estancia Ramirez) and a small dyke (Cerro Caá Jhovy), all intrusions near the localities of San Juan Bautista and San Ignacio.

A magmatism of potassic composition clearly characterizes the additional Paraguayan provinces of Rio Apa and Amambay, both lying in the northeastern area (Gomes *et al.* 2011, Comin-Chiaramonti *et al.* 2014). The first province comprises small dykes found near the Valle-mí city, not far from the Apa river mouth, whereas the second one consists of intrusives and associated carbonatites spread over a large area, having as main geological features the circular complexes of Cerro Chiriguelo and Cerro Sarambí, outcrops 15 and 17 in Fig. 2C, respectively.

Table 1 lists the mostly known Eastern Paraguay alkaline occurrences of sodic composition.

Investigation of the alkaline magmatism in Eastern Paraguay has been the subject of numerous studies performed over the past decades by a group of Brazilian, Italian, and Paraguayan researchers, with the large amount of data collected being discussed in numerous contributions on multiple aspects of the rocks. However, despite the vast scientific production on the matter, it seems convenient to draw some attention to the

Table 1. Sodic alkaline occurrences of Eastern Paraguay.

Locality	Body formation	Rock types	Chemistry	Age	Source
Alto Paraguay Province					
1. Cerro Boggiani	stock, dyke	ns, pho,	Na	MT	1
2. Pão de Açúcar	stock, lava flow, dyke	s, ns, tpho, pho, ig, tu	Na	MT	1
3. Fecho dos Morros	stock, dyke	ns, pho	Na	MT	1
4. Cerrito	stock, dyke	s, ns, pho	Na	MT	1
5 Morro Distante	stock	s, ns	Na	MT	1-3
6. Cerro Pedreira	stock, dyke	s, ns, qt, rh	Na	MT	1-3
7. C. Siete Cabezas	stock	ns	Na	MT	1-3
8. Stock I	stock	qs	Na	MT	1-3
9. Stock II	stock	ns, qs	Na	MT	1-3
Asunción Province					
23. Cerro Verde	plug	ne	Na	P	4,5
24. Villa Hayes	plug	Ne	Na	P	4,5
25. Cerro Confuso	plug	pho	Na	P	4,5
26. Cerro Límpio	dyke	ne	Na	P	4,5
27. Remanso Castillo	dyke	ne	Na	P	4,5
28. San Jorge	dyke	ab	Na	P	4,5
29. Jardin Botânico	lava flow	ne	Na	P	4.5
30. Cerro Tacumbú	plug	ne	Na	P	4,5
31. Cerro Lambaré	plug	ne	Na	P	4, 5
32. Cerro Patiño	dyke	ne	Na	P	4, 5
33. Cerro Ñemby	plug	ne	Na	P	4, 5
Central Province					
39. Cerro Yarigua-á	lava dome, dyke	pho	Na	EC	6-8
41. Cerro Gimenez	lava dome	pho, tpho	Na	P	6-8
42. Sapucai	lava flow, dyke swarm	ab, te, pho, tr, ag, ex	Na, K	EC	6-8
45. Cerro Yaguarú	dyke	te	Na, K	EC	6-8
46. Catalán	lava dome, dyke	te, pho, ab	Na, K	EC	6-8
49. A. Paso Villán	lava dome, dyke	te	Na, K	EC	6-8
53. Cerro Medina	lava dome	pho, tr	Na	P	6-8
58. Cerrito	plug	te	Na	EC	6-8
59. Cerro Itapé	dyke	pho	Na	EC	6-8
Misiones Province					
68. Cerro Caá-Jhovy	dyke	pho	Na	LEC	9
69. Estancia Ramirez	plug	te, ne	Na	LEC	9
70. Estancia Guavirá-y	plug	an, ne	Na	LEC	9
71. Cerro Guayacán	plug	ba	Na	LEC	9

ab: alkaline basalt; ag: alkali gabbro; na: ankaratrite; ba: basanite; ex: essexite; ig: ignimbrite; ne: nephelinite; ns: nepheline syenite; pho: phonolite; qt: quartz trachyte; rh: rhyolite; s: syenite; te: tephrite; tpho: trachyphonolite; tr: trachyte; tu: tuff; EC: Early Cretaceous; LEC: Late Early Cretaceous; MT: Middle Triassic; P: Paleogene.

Source: 1. Velázquez *et al.* (1996, 1998); 2. Gomes *et al.* (1996a); 3. Comin-Chiaramonti *et al.* (2005); 4. Bitschene (1987); 5. Comin-Chiaramonti *et al.* (1991); 6. Gomes *et al.* (1989); 7. Comin-Chiaramonti *et al.* (1991, 1992, 1996a, 1997, 2013); 8. Velázquez *et al.* (2011); 9. Velázquez *et al.* (2006).

sodic rocks, which, albeit representing a small volume compared to their associated potassic counterparts, are of great importance in the understanding of the alkaline magmatism across the entire region. This study aimed to provide general information on the sodic alkaline magmatism events that took place in Eastern Paraguay. Chemical data and other evidence presented here are all taken from the literature and constitute important contributions to the discussion of the sodic rock products and their role in alkaline magmatism.

TECTONIC SETTING

Geological and geophysical evidence for Eastern Paraguay indicates that tectonic structures exerted a clear control over the emplacement of alkaline rocks (DeGraff 1985, Livieres and Quade 1987, Comin-Chiaramonti *et al.* 1999, Riccomini *et al.* 2005). A seismically active (Berrocal and Fernandes 1996) N-S-trending linear belt parallel to the Paraguay River course is believed to be the main conditioning factor for the sodic magmatism in the northern part of the country. In addition to the hypothesis of N-S-trending faults (Velázquez *et al.* 1998), other different tectonic controls are suggested in the literature, such as the Rio Apa Arch uplift (Livieres and Quade 1987) or a cratonic margin (Velázquez *et al.* 1996). More recently, Ramos *et al.* (2010) interpreted the alignment of the Paraguay River as marking the boundary between the Pampia cratonic blocks, to the West, and the Rio Apa, to the East.

The prominent Asunción Rift, a 25–40 km wide and 200 km long complex, mostly NW to E-W-oriented structure extending from Asunción to Villarrica, played an important role in the emplacement of alkaline occurrences in the Central and Asunción provinces in east-central Paraguay (Riccomini *et al.* 2001, 2002, Comin-Chiaramonti *et al.* 2013). The rift, linked to a general NE-SW extensional event that started at least as early as Triassic times (Comin-Chiaramonti *et al.* 1992, 1996a, 1999), is almost symmetrical and defined by major faults along each margin. It may be subdivided into three main segments of varying orientation, extends up to 100 km into the Chaco Basin (Fig. 1), and is characterized by petrographic associations distinct in both age and composition. Magmatism is controlled by NW-SE-striking deep lithospheric faults and is also related to the gravimetric low situated beneath the Asunción region (Riccomini *et al.* 2001, 2002).

Magnetometric and gravimetric data indicate important NW-SE-striking structural lineaments over 150 km long at approximately 100 km of the Asunción Rift, suggesting crustal fracturing (Santa Rosa Graben: DeGraff and Orué 1984, DeGraff 1985). More recent investigations by Velázquez *et al.* (2002, 2006) confirmed that the alkaline bodies of the Misiones Province were emplaced along NW-SE structures under a NE-SW-trending extension.

Alkaline magmatism of potassic composition in the Apa region has low expression, and it is represented by a few outcrops concentrated in the neighborhood of Valle-mí city on the margins of the Paraguay River. They are intruded into a Cambro-Ordovician carbonate platform (Itapucumí Group) along NE-SW-trending faults (Comin-Chiaramonti *et al.* 2014). On the other hand, the emplacement of potassic alkaline-carbonatitic rocks from the Amambay area is clearly controlled by the NE-SW-trending Ponta, Porã Arch (Livieres and Quade 1987).

GEOCHRONOLOGICAL BACKGROUND

The potassic and sodic alkaline magmatism of Eastern Paraguay is characterized by an age span of almost 200 Ma, as evidenced by four distinct episodes: Middle Triassic (Alto Paraguay Province), bimodal Early Cretaceous distribution (Rio Apa-Amambay provinces and Central Province), Late Early Cretaceous (Misiones Province), and Paleogene (Asunción Province). Many results available in the literature (Table 1 of Comin-Chiaramonti *et al.* 2007), produced by different analytical techniques (K/Ar, Rb/Sr, non-plateau Ar/Ar, fission track) using mineral separates (alkali feldspar, plagioclase, amphibole, and biotite) or whole rock samples, are not consistent and seem to be affected by complexities linked to earlier subsolidus reactions and exsolutions, hydrothermal alteration, and weathering (Velázquez *et al.* 1992, 1996). More precise and recent Ar/Ar determinations selected out of a set containing 76 analyses are presented by Comin-Chiaramonti *et al.* (2007), looking for a better definition of the alkaline magmatism ages in Eastern Paraguay. Data are reported in Table 2 and displayed in the histograms in Fig. 3.

A Middle Triassic age representing the oldest alkaline magmatic activity in the Paraná Basin is suggested by old K/Ar, Rb/Sr, and Ar/Ar data (Amaral *et al.* 1967, Comte and Hasui 1971, Gomes *et al.* 1996a, Velázquez *et al.* 1996) placing the event in the 255–210 Ma interval. New Ar/Ar measurements by Comin-Chiaramonti *et al.* (2007) for the complexes of Cerro Boggiani and Cerro Siete Cabezas and its satellite Stock I and further information on the Cerro Pedreira and Pão de Açúcar occurrences introduced by Comin-Chiaramonti *et al.* (2015) allow to set an age span of 239.9 ± 0.9 to 242.6 ± 0.4 Ma with an average value of 241.8 ± 1.1 Ma, which is the preferred age assumed for the Alto Paraguay Province (Fig. 3). Datings in the range of 250–260 Ma (Rb/Sr and Sm/Nd isochrones) are also reported in the literature (Velázquez *et al.* 1996, Comin-Chiaramonti *et al.* 2015), but due to analytical uncertainties, they remain questionable.

An Early Cretaceous age of 126 Ma has been proposed by Gomes and Comin-Chiaramonti (2017) for intrusive rocks of the Central Province and their associated potassic and sodic dykes in central-southeastern Paraguay. This age is assumed based on grouped Ar/Ar histograms (126–128 Ma: Gomes *et al.* 2003; and 125–128 Ma: Comin-Chiaramonti *et al.* 2007) combined with age determinations already presented by Bitschene (1987), Velázquez *et al.* (1992), and Gibson *et al.* (2006). Data on the geochronology of the Central Province alkaline rocks are also found in Milan (2003) and Comin-Chiaramonti *et al.* (2007). A total of 12 Ar/Ar spectra, mostly taken from Milan (2003), are made available by Comin-Chiaramonti *et al.* (2007) for various occurrences that include the largest alkaline complexes (Sapucai and Acahay), indicating as extreme age values 124.6 ± 0.2 Ma (Cerro Fidel) and 128.8 ± 0.4 Ma

Table 2. New radiometric age determinations for Eastern Paraguay alkaline rocks*.

Locality	Rock types	Material	Plateau age (Ma)	Isochron age (Ar/Ar)
Alto do Paraguay Province				
Stock I (2)	s	Bi	240.6 ± 0.4	240 ± 2
C. Siete Cabezas (2)	s	Bi	241.9 ± 0.4	239 ± 3
Cerro Boggiani (1)	pho	Bi	241.3 ± 0.7	241 ± 2
Rio Apa Province				
Valle-mí (2)	ba	Bi	138.7 ± .0.2	139.0 ± 0.3
Amambay Province				
Cerro Chiriguelo (1)	tr	Bi	137.6 ± 0.7	138.1 ± 1.7
Cerro Sarambí (1)	gl	Bi	139.3 ± 0.5	139.1 ± 0.9
Central Province				
Cerro Km 23 (1)	exg	Bi	127.7 ± 0.1	
Cerro San Benito (1)	exg	Bi	127.4 ± 0.3	127.1 ± 1.9
Cerro Santa Elena (2)	ex	Bi	125.6 ± 0.2	126.2 ± 0.5
Mbocayaty (1)	tbas	Bi	126.4 ± 0.1	126.5 ± 0.9
Aguapety Portón (2)	ex	Bi	126.2 ± 0.2	127.2 ± 0.7
Cerro Cañada (1)	ag	Bi	126.1 ± 0.5	127.6 ± 1.4
Cerro Cañada (2)	ij	Bi	126.3 ± 0.2	126.2 ± 0.9
Cerro Cañada (1)	ag	Bi	127.5 ± 0.2	
Cerro San José (1)	sg	Bi	126.4 ± 0.4	126.4 ± 3.9
Cerro San José (1)	sg	Bi	128.5 ± 0.3	
C. Potrero Ybaté (1)	sg	Bi	128.5 ± 0.3	
Potrero Ybaté (1)	sd	Bi	124.1 ± 0.6	
Cerro Verde-Sapucai (1)	ex	Bi	124.6 ± 0.7	127.1 ± 1.4
Cerro Fidel-Sapucai (1)	tpho	Bi	126.4 ± 0.2	128.6 ± 2.9
Sapucai (2)	tand	Bi	126.2 ± 0.1	126.2 ± 0.7
Cerro Santo Tomás (1)	sd	Bi	128.8 ± 0.4	127.7 ± 1.1
Cerro Santo Tomás (1)	ba	Bi	127.2 ± 0.6	129.2 ± 3.1
Cerro Acahay (1)	tbas	WR	127.0 ± 0.2	126.5 ± 1.5
Cerro Acahay (1)	ag	Bi	123.6 ± 0.5	
Cerro Arrúa-í (1)	sd	WR	129.0 ± 0.2	126.2 ± 1.7
Misiones Province				
Estancia Guavirá-y (1)	ne	WR	119.8 ± 0.8	118 ± 7
Estancia Ramirez (1)	ne	WR	118.3 ± 0.6	
Cerro Caá-Jhovy (1)	pho	WR	117.9 ± 0.9	
Cerro Guayacán (1)	te	WR	117.2 ± 0.2	119.0 ± 1.3
Asunción Province				
Cerrito (1)	ne	WR	56.0 ± 0.5	
Benjamin Aceval (1)	ne	WR	56.4 ± 0.9	
Cerro Verde (1)	an	WR	61.3 ± 0.3	
San Jorge (1)	an	WR	57.0 ± 0.3	
Cerro Tacumbú (1)	an	WR	58.4 ± 0.4	
Cerro Ñemby (1)	an	WR	60.7 ± 0.6	59 ± 2

ag: alkali gabbro; Bi: biotite; an: ankaratrite; ba: basanite; ex: essexite; exg: essexitic gabbro; gl: glimmerite; ij: ijolite; ne: nephelinite; pho: phonoliue; s: syenite; sd: syenodiorite; sg: syenogabbro; tand: trachyandesite; tbas: trachybasalt; te: tephrite; tpho: trachyphonolite; tr: trachyte; WR: whole rock.
*analyses performed at the (1) Geochronology Research Laboratory, Universidade de São Paulo, Brazil, and at the (2) Berkeley Geochronology Center, University of California, USA.
Source: simplified after Comin-Chiaramonti *et al.* (2007).

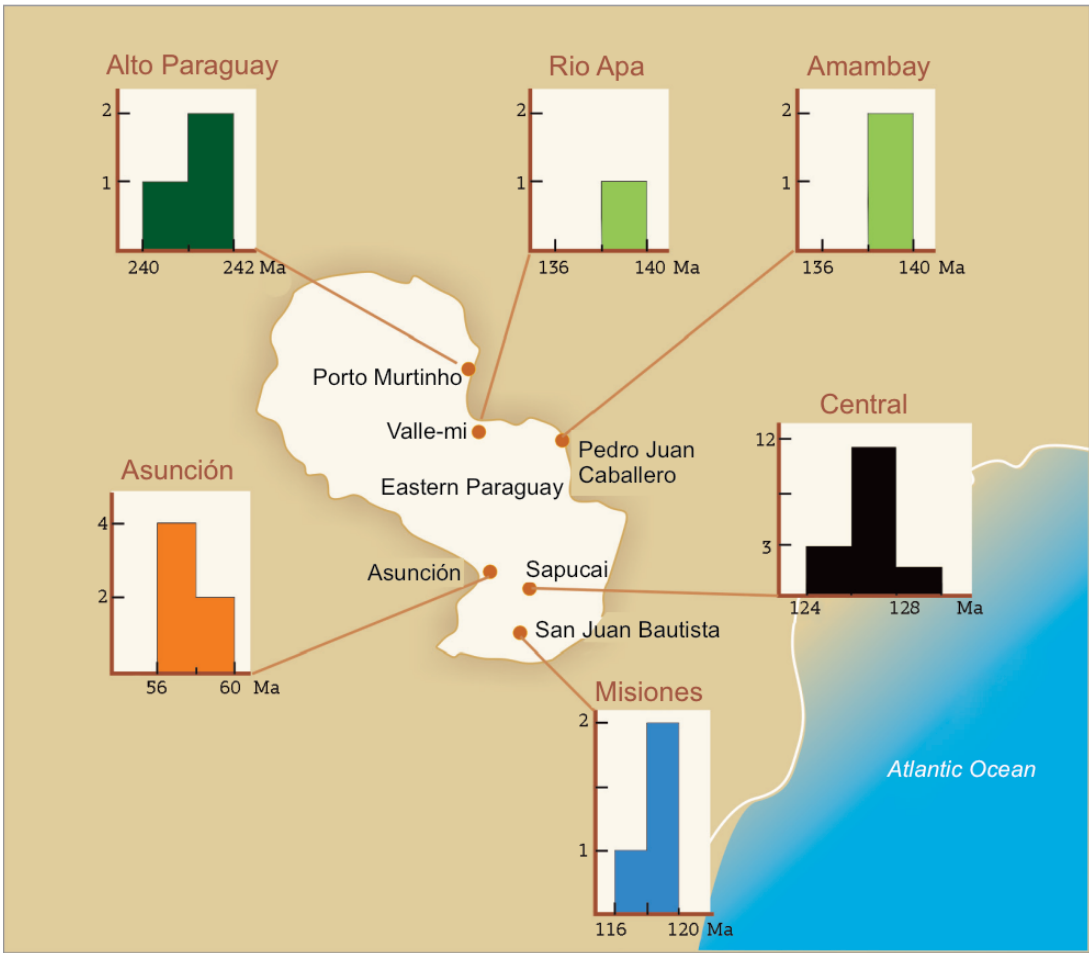


Figure 3. Ar/Ar radiometric ages for Eastern Paraguay alkaline rocks shown in histograms.

(Cerro Santo Tomás) (Table 2) and a modal class of 126–128 Ma in the histogram of Fig. 3.

A sodic event of younger age is recorded near the localities of San Juan Bautista and San Ignacio in the southernmost part of the country. It is represented by the volcanic rocks of the Misiones Province, all of them emplaced into Paleozoic sedimentary formations. Ar/Ar determinations for these intrusions point to an average age of 118.3 ± 1.6 Ma (Velázquez *et al.* 2006). Miniplateau ages are reported by Comin-Chiaramonti *et al.* (2007) for three lava flow occurrences: 119.8 ± 0.8 Ma (Estancia Guavirá-y), 118.3 ± 0.6 Ma (Estancia Ramirez), and 117.2 ± 0.2 Ma (Cerro Guayacán), and 117.9 ± 0.9 Ma for the dyke (Cerro Caá-Jhovy) (Table 2). A modal class of 118–120 Ma is shown in the histogram of Fig. 3.

Records of the youngest sodic alkaline episode to take place in Eastern Paraguay are mainly concentrated in the neighborhood of Asunción. They consist of various plugs and dykes of sodic affinity belonging to the Asunción Province. A great number of radiometric determinations are available in the literature for these rocks (see table 1 of Comin-Chiaramonti *et al.* 2007), with the more recent and highly precise Ar/Ar data reported by Gomes *et al.* (2003) indicating ages within the 56–58 Ma interval (Fig. 3). An average determination of 58.7 ± 2.4 Ma is suggested by Milan (2003) and Comin-Chiaramonti *et al.* (2007) for Asunción rocks based on plateau and miniplateau ages.

Potassic rocks closely associated with the sodic ones in the Central Province are Early Cretaceous in age and were emplaced in a short time span after the peak activity of the Paraná tholeiitic flood volcanism (133 Ma; Thiede and Vasconcelos 2010). On the other hand, the Rio Apa and Amambay potassic magmatisms are predating the tholeiites, with plateau ages of 138.7 ± 0.2 Ma for the first province and ranging from 139.3 ± 0.5 to 137.6 ± 0.7 Ma for the second one (Table 2).

Marked differences exist between the alkaline magmatism events that took place on the western and eastern margins of the Paraná Basin, as previously pointed out by Gomes *et al.* (1996b). The Early Cretaceous (~139 Ma, Gomes and Comin-Chiaramonti 2017) potassic magmatism event, predating the tholeiitic flood basalts of the Paraná Basin, is restricted to northeastern Paraguay, being represented by the Rio Apa and Amambay provinces. The potassic-sodic event (~126 Ma, Gomes and Comin-Chiaramonti 2017) recorded in rocks of the Central Province is possibly contemporary to a ~130 Ma potassic episode associated with the Ponta Grossa Arch Province in Brazil and tholeiitic lava flows of the Paraná Large Igneous Province (Thiede and Vasconcelos 2010, Janasi *et al.* 2011). The Late Early Cretaceous sodic rocks (~118 Ma, Velázquez *et al.* 2006) of the Misiones Province have no equivalents in Brazil. Conversely, the mostly potassic 100–110 Ma alkaline event related to the Itapirapuã and Banhadão intrusions in the Ribeira Valley (Gomes *et al.* 2018) is not represented in Eastern

Paraguay. The same applies to the 80–90 Ma (Late Cretaceous) potassic episode represented by voluminous, widely distributed rocks on the Brazilian side of the basin. A highly chemically and petrographically distinct Tertiary sodic volcanism is observed in Eastern Paraguay, mainly in the Asunción rift area. In Brazil, sodic rocks of the same age occur as plugs in areas such as Jaboticabal and Volta Redonda and as small dykes cropping out along coastal segments of Rio de Janeiro and São Paulo.

PETROGRAPHY

The Alto Paraguay Province

The Alto Paraguay Province consists of at least seven major semi-circular to circular intrusions, minor bodies, and a few dykes. Except for the Pão de Acúcar volcanic complex, the rocks are predominantly intrusive. Nepheline- and quartz-bearing syenites are abundant and widespread, while dykes exhibit a more varied composition, with the main petrographic types corresponding to phonolites, trachyphonolites, quartz trachytes, and alkali rhyolites. Foid (nepheline, sodalite) syenites, especially those present in the Cerro Boggiani massif, contain mineral assemblages that are typical of miaskitic-agpaitic rocks. The cone formed by the Morro Pão de Açúcar, an area sampled by Comin-Chiaramonti *et al.* (2005), differs significantly in composition by including syenitic rocks at the base covered by trachyphonolitic lavas, which, in turn, are topped by ignimbrites. Its steep topography and dense vegetation are limiting factors for field geology work. Sampling of rocks was only allowed along a narrow and dirty path occasionally used for maintenance services of electronic equipment installed on the top of the cone.

The Central Province

Magmatism in the Central Province is predominantly of potassic affinity, represented by syenitic, syenogabbric and gabbric stocks, lava flows, lava domes, plugs, and numerous dykes of varied composition. In the Sapucai area, where the largest concentration of bodies is found, the dykes are characterized by forming swarm dykes encompassing over 200 intrusions of variable dimensions and composition (Gomes *et al.* 1989, Comin-Chiaramonti *et al.* 1992, Velázquez *et al.* 2011). In general, the Central Province rocks occur mainly as shallow intrusive bodies that can be grouped into two main series: basanites to phonolites (B-P) and alkali basalts to trachyphonolites/trachytes (AB-T) and their medium- to coarse-grained equivalents, according to Comin-Chiaramonti *et al.* (1996a). The associated sodic magmatism event is clearly of subordinate expression, being represented by dozens of dykes and some intrusions mainly found in the central parts of the Asunción rift zone. They mostly consist of peralkaline phonolites and phonolites, whereas tephrites, alkali basalts, hawaiites, and mugearites are scarce.

The Misiones Province

Investigated in detail by Velázquez *et al.* (2006) based on geological, geophysical (magnetometric and gravimetric), and geochronological data, the Misiones volcanic province comprises ankaratrites, nephelinites, and tephrites (Estancia Guavirá-y, Estancia Ramirez, and Cerro Guayacán) in addition to peralkaline phonolites (Cerro Caá Jhovy) as main rock types. Subordinate basanites are also present. Ankaratrites and nephelinites contain spinel peridotite xenoliths that are similar to those present in volcanic Tertiary rocks of the Asunción Province.

The Asunción Province

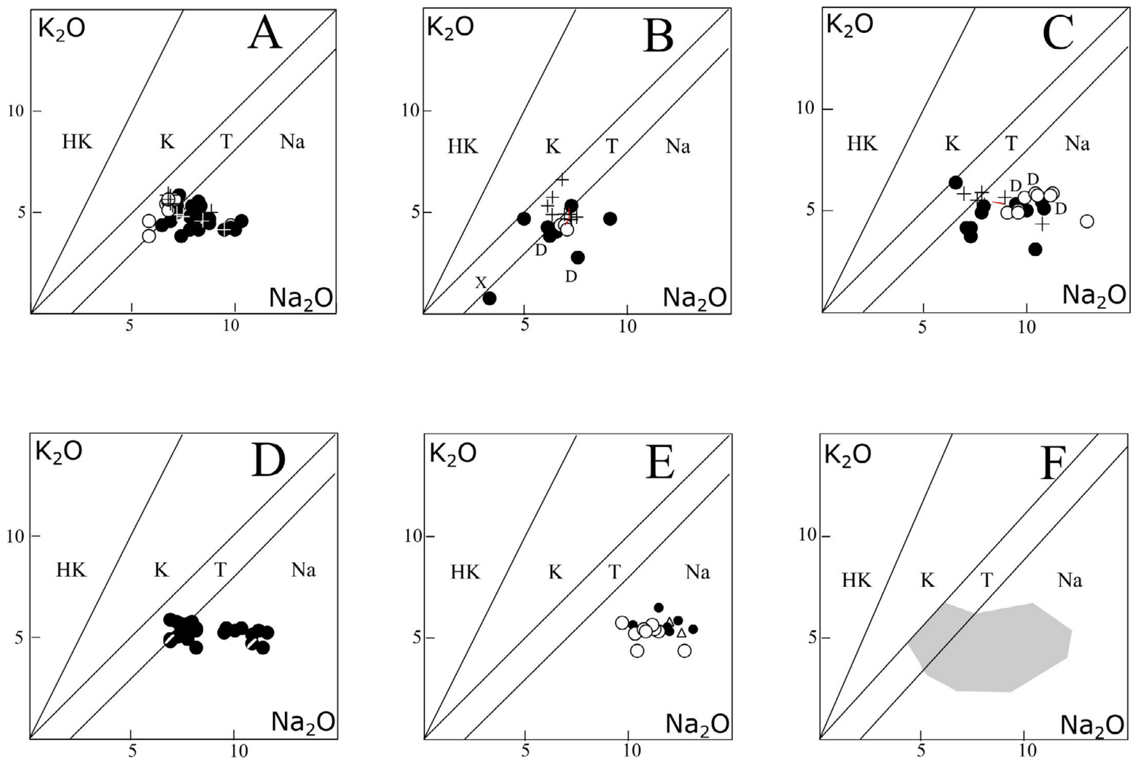
The Asunción Province clusters numerous volcanic rock occurrences (15) cropping out as plugs, lava flows, and dykes a few tens of kilometers from Asunción, the capital city of Paraguay (Bitschene 1987, Comin-Chiaramonti *et al.* 1991). The rocks included are mainly nephelinites-ankaratrites (45%) and phonolites (42%). The ultramafic rock-types contain variable amounts of crustal (sedimentary, metamorphic, and volcanic) and mantle (spinel lherzolite, harzburgite, and dunite) protogranular nodules up to 45 cm in diameter and glassy patches of xenoliths corresponding to "blebs" (Maaløe and Prinzlau 1979) enriched in K_2O and incompatible elements (Comin-Chiaramonti *et al.* 1991). Peralkaline phonolites are also present, occurring as small dykes and plugs (Cerro Gimenez, Cerro Medina) at central areas of the rift.

The potassic provinces of Rio Apa and Amambay are petrographically different. The first one is only represented by basanites cropping out as a few small dykes close to the San Lazaro village. These rocks have as their main feature the presence of *ocelli* of primary carbonate as exsolved material. The second province presents a more complex composition, with clustering mafic-ultramafic rocks and associated carbonatites forming intrusive ring complexes and dykes. The silicate assemblage includes rocks of syenitic to pyroxenitic composition, together with shonkinites and fenites, as well as fine-grained varieties (phonolites, trachytes and trachyphonolites) and small bodies (plugs, dykes). Alkaline magmatism in this area also consists of some additional small intrusions poorly geologically known, such as Arroyo Gasory, Cerro Apuá, and Cerro Guazú, for instance (outcrops 16, 18, and 21, respectively, in Fig. 2C).

GEOCHEMISTRY

The terms *sodic* and *potassic* were proposed by Comin-Chiaramonti *et al.* (1996a) for rocks of central-eastern Paraguay containing $Na_2O-2 \geq K_2O$ and $1 < K_2O/Na_2O \leq 2$ in their chemical composition, respectively. Rocks of intermediate composition would better fit a transitional field defined by $Na_2O-2 < K_2O$ to $K_2O/Na_2O \leq 1$. K_2O and Na_2O contents are commonly applied to variation diagrams for the classification and correlation of alkaline rocks (Middlemost 1975, Le Bas *et al.* 1986, Le Maitre 1989).

K_2O versus Na_2O diagrams for the Alto Paraguay Province complexes are shown in Fig. 4, with nearly all diagrams corresponding to sodic terms. A few samples occupy the transitional field. Potassic types are not represented. Figure 4F exhibits the cumulative distribution for the whole province.



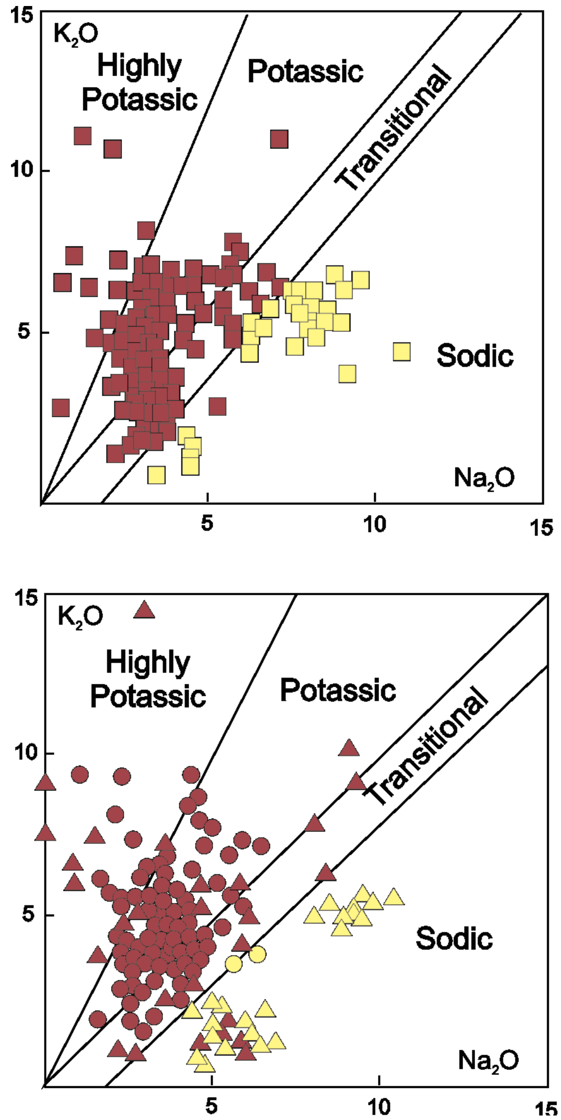
Na: sodic (Na_2O-2 ≥ K_2O); T: transitional (Na_2O- 2 < K_2O to K_2O/Na_2O ≤ 1); K: potassic (1 < K_2O/Na_2O ≤ 2); HK: highly potassic (K_2O/Na_2O > 2) (Comin-Chiaramonti *et al.* 1996b, modified). Symbols in *A*: • Cerro Siete Cabezas, o Stock I, + Stock II; in *B*; •. Cerro Pedreira. o Morro Distante, + Morro Conceição, D dyke, X, xenólito; in *C*: • Cerrito, o Ilha Fecho dos Morros, + Morro de São João; in *D*: • Pão de Açúcar; in *E*: Cerro Bogianni, • intrusives, o extrusives.

Figure 4. K_2O versus Na_2O variation diagrams for Alto Paraguay Province complexes (Comin-Chiaramonti *et al.* 2005, modified): (A) Cerro Siete Cabezas and Stocks; (B) Cerro Pedreira, Morro Distante and Morro Conceição; (C) Fecho dos Morros: Cerrito, Ilha Ferro dos Morros and Morro de São Pedro; (D) Pão de Açúcar; I Cerro Boggiani; (F) General distribution for the whole province (Gomes and Comin-Chiaramonti 2017).

Bearing the highest Na_2O concentrations and alkali indexes (Na+K/Al > 1 ratios), Cerro Boggiani rocks are characterized by a complex chemical composition, including Th-U oxides/silicates, Nb-oxide, rare earth element (REE)-Sr-Ba carbonates-fluorcarbonates-phosphates, and Zr-Na-rich silicates. This composition is responsible for the unusual mineral assemblage typical of agpaitic rocks containing late-stage magmatic to deuteric/metasomatic halogen-bearing Na-Ca-HFSE phases (Comin-Chiaramonti *et al.* 2016, Gomes *et al.* 2021). The sodic population described in the rocks of the Central Province is mainly present in volcanic and hypabyssal rocks (Fig. 5). The undersaturated sodic volcanic rocks of the Misiones Province fall into two distinct assemblages (Fig. 6). The first group includes ultramafic plugs (ankaratrites and nephelinites) and the second is represented by a peralkaline phonolite dyke. The alkali diagram for the Asunción Province volcanics (plugs, lava flows, and dykes) is illustrated in Fig. 7. Average chemical analyses for eight different nephelinite occurrences (Cerro Patiño, Cerro Verde, Cerro Lambaré, Cerro Límpio, Cerro Ñemby, Nueva Teblada, Remanso Castillo, and Cerro Tacumbú) after Comin-Chiaramonti *et al.* (1991) lie entirely in the sodic field.

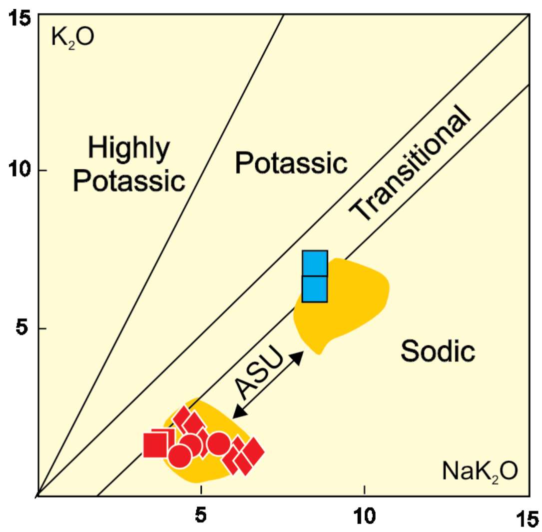
Mantle-normalized incompatible element (IE) patterns for potassic and sodic rocks and associated tholeiitic lavas are shown in Fig. 8. Although Nb-Ta positive anomalies probably represent a primary feature (i.e., related to a mantellic source of the parental magmas, according to Comin-Chiaramonti *et al.* 2005), IE spidergrams for less evolved Alto Paraguay sodic magmatic rocks reflect a derivative composition (i.e., negative Sr and Ti values). The different complexes of the province also have in common P and occasionally Th and K negative spikes in addition to pronounced positive Nb-Ta anomalies, as demonstrated by the Cerro Siete Cabezas and Stock I spidermans, for instance (Fig. 9). Similarly, as these petrographic types, Late Early Cretaceous (Misiones Province) and Tertiary (Asunción Province) sodic rocks display strong affinities and similar behavior (Fig. 10), characterized by enrichment in lithophile elements (LILE), depletion in high field strength elements (HFSE), and positive Nb-Ta anomalies (Comin-Chiaramonti *et al.* 1997, 2007). When compared to the sodic lithotypes, potassic rocks (pre- and post-tholeiites) (Fig. 8A) do not exhibit significant differences, except for the slightly negative Nb-Ta anomalies. The two series (high-Ti and low-Ti) of Early Cretaceous Paraná tholeiitic lavas show a similar behavior (Fig. 8B). However, despite the characteristically potassic negative Nb-Ta anomalies found in tholeiites, their pattern is quite distinct in comparison to that of the alkaline rocks, as indicated by the low element abundances and high LILE/HFSE ratios.

Regardless of alkali or differentiation indexes, chondrite-normalized diagrams after Boynton (1984) for REE attest to the strong REE enrichment of Alto Paraguay Province sodic rocks,



Dykes: squares; intrusives and volcanics: circles and triangles.

Figure 5. K_2O versus Na_2O variation diagrams for rock types of Central Province (Comin-Chiaramonti *et al.* 1997).



Full circles, diamonds, and square: mafic-ultramafic rocks; open squares: peralkaline phonolites.

Figure 6. K_2O versus Na_2O variation diagrams for sodic rocks of Misiones Province (Velázquez *et al.* 2006). Also shown are the compositional fields for low and high sodic varieties of Central Province (ASU, Comin-Chiaramonti *et al.* 1996b).

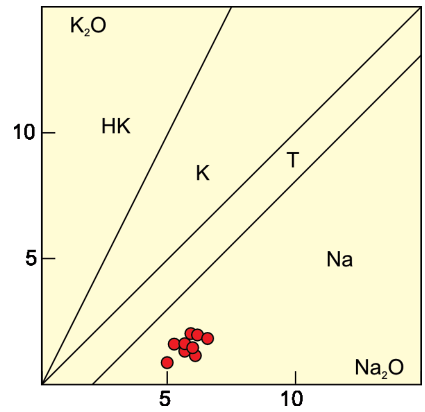
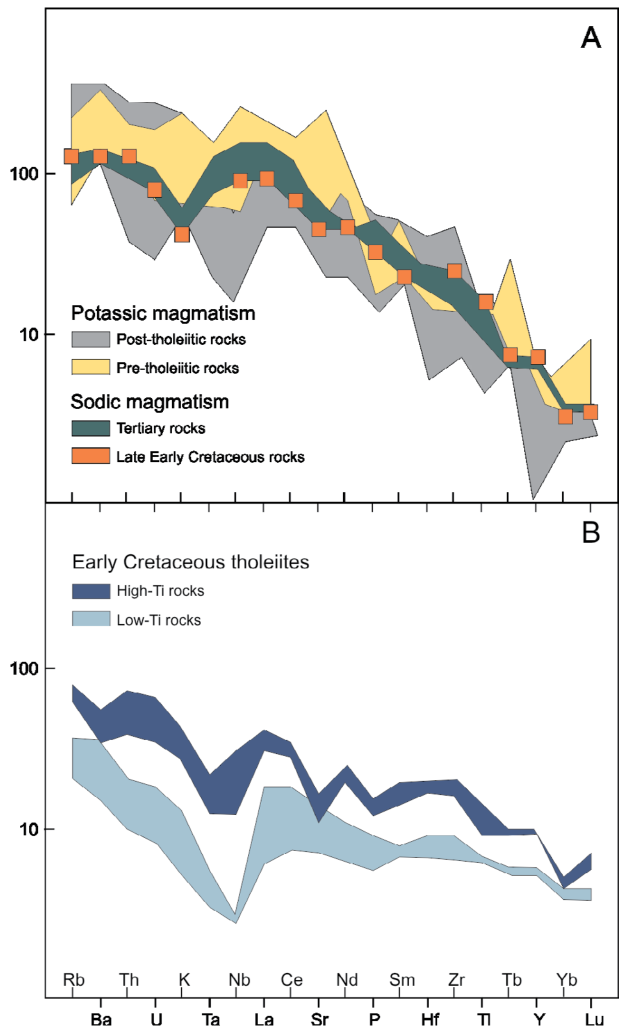


Figure 7. K_2O versus Na_2O variation diagrams for sodic rocks of Asunción Province. Average nephelinite analyses are from Comin-Chiaramonti *et al.* (1991). For legends, see Fig. 4.



Sources: Comin-Chiaramonti *et al.* (1997) and Antonini *et al.* (2005).

Figure 8. Trace-element data normalized to primitive mantles (Sun and McDonough 1989) for Eastern Paraguay rocks (A: alkaline; B: tholeiite). Sodic magmatism represented by Misiones (Late Early Cretaceous) and Asunción (Tertiary) provinces.

their high light/heavy REE (LREE/HREE) fractionation, and the presence of diverse patterns pointing to a steady decrease from La to Sm and Gd to Lu, flat HREE, a concave upward with HREE decreasing, or the negative Eu/Eu* anomalies in several occurrences, for instance (Fig. 11). A similar, smooth behavior characterizes the sodic rocks of the Misiones and

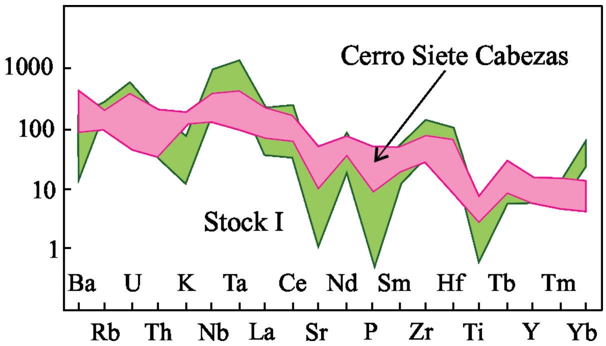
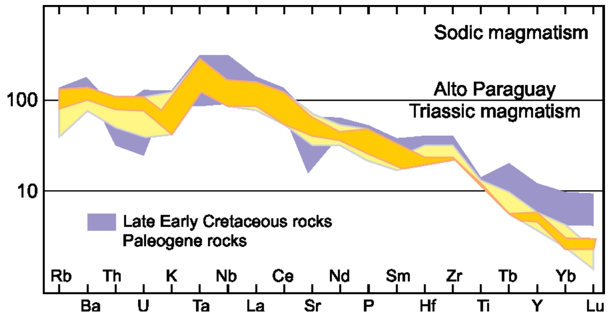
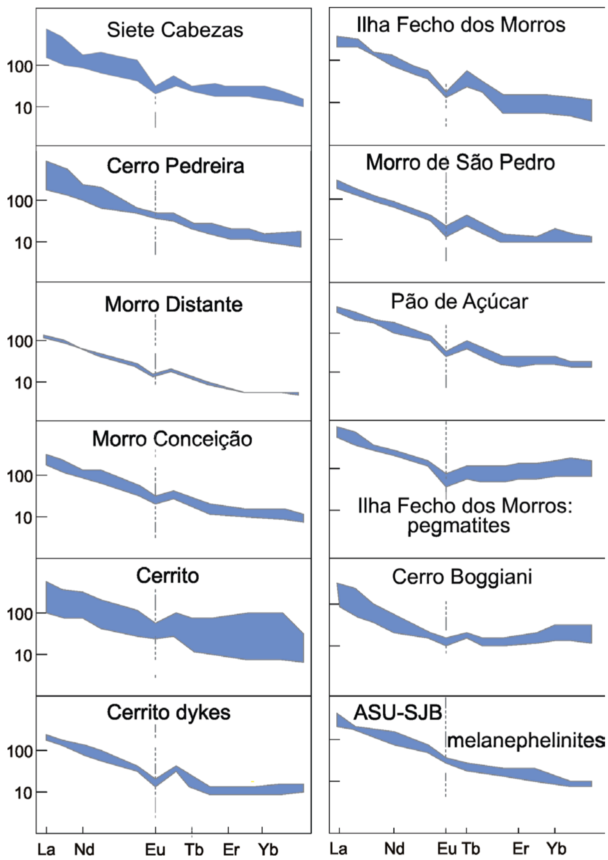


Figure 9. Mantle-normalized incompatible elements distribution for the Cerro Siete Cabezas complex and Stock I (Comin-Chiaramonti *et al.* 2005).



Source: Comin-Chiaramonti *et al.* (2007).

Figure 10. Trace-element data normalized to primitive mantles (Sun and McDonough 1989) for Eastern Paraguay sodic rocks of the Alto Paraguay, Misiones, and Asunción provinces.



Source: Comin-Chiaramonti *et al.* 2005 (simplified).

Figure 11. Chondrite-normalized (Boynton 1984) REE distribution for occurrences of the Alto Paraguay, Central (ASU: Asunción-Sapucai rift), and Misiones (JB: San Juan Bautista) provinces.

Asunción provinces (Fig. 12). A noteworthy U-shaped pattern is observed in peralkaline Misiones Province phonolites of the Cerro Caá Jhovy dyke, with a highly steep LREE to intermediate REE profile and HREE enrichment.

The widely distributed Sr-Nd isotopic composition of alkaline rocks in Eastern Paraguay defines a trend that is similar to the "low-Nd array" of Hart and Zindler (1989), also referred to as "the Paraguayan array" by Comin-Chiaramonti *et al.* (1995). Sr and Nd contents are highly variable, with pre- and post-tholeiites potassic rocks showing higher $^{87}Sr/^{86}Sr$ (Sr_i) and lower $^{143}Nd/^{144}Nd$ (Nd_i) ratios in the conventional $(^{87}Sr/^{86}Sr)_i$ versus $(^{143}Nd/^{144}Nd)_i$ isotope correlation diagram (Fig. 13). Sodic rocks, on the other hand, fall close to BE, varying from depleted to enriched compositions. Notably, Sr_i and Nd_i for the associated tholeiites (high- and low-Ti) are intermediate between potassic and sodic terms. High Sr_i carbonatites, represented by samples from the Cerro Chiriguelo and Cerro Sarambí complexes (Amambay Province), occur

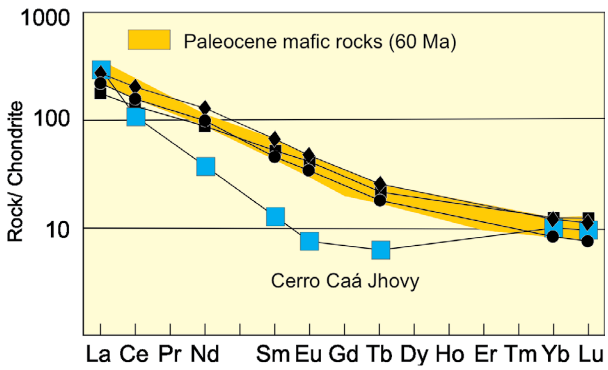
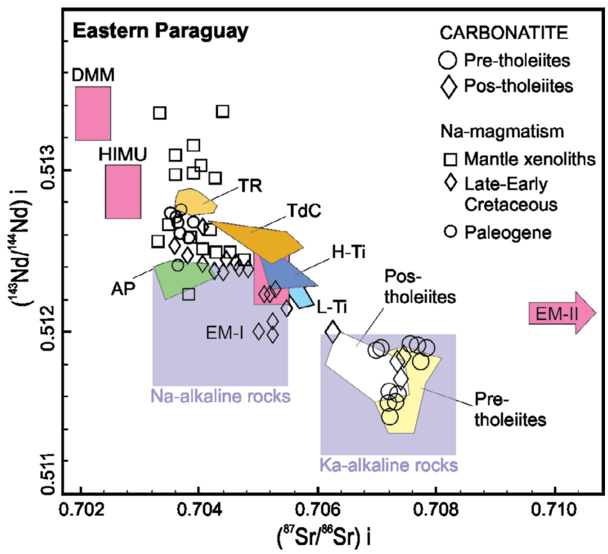


Figure 12. Chondrite-normalized (Boynton 1984) REE distribution for alkaline sodic rocks of the Misiones and Asunción provinces (Velázquez *et al.* 2006). Symbols for the Misiones rocks as in Fig. 4.



AP: Alto Paraguay; TR: Trindade; TdC: Tristan da Cunha; H-Ti: high-TiO_2 tholeiites; L-Ti: low-TiO_2 tholeiites; DMM, EMI, EMII, HIMU: Mantle component fields (after Hart and Zindler 1989).

Figure 13. Sr_i versus Nd_i diagram for Middle Triassic, Late Early Cretaceous to Tertiary alkaline rocks in Eastern Paraguay (Comin-Chiaramonti *et al.* 2007).

in contact with pre-tholeiitic potassic rocks in northeastern Paraguay. In the tholeiitic and carbonatitic rocks, Sr_i and Nd_i contents range from 0.70636 to 0.70721 and from 0.51165 to 0.51194, respectively (Antonini *et al.* 2005). These values are very distinctive compared to those reported for sodic rocks (Alto Paraguay: Sr_i = 0.70350–0.70570, Nd_i = 0.51123–0.51207; Misiones: ca. 118 Ma, Sr_i = 0.70435–0.70524, Nd_i = 0.51225–0.51242; Asunción: ca. 60 Ma, Sr_i = 0.70362–0.70392, Nd_i = 0.51259–0.51277), which plot toward HIMU-DMM mantle components in the depleted quadrant (Velázquez *et al.* 2006, Comin-Chiaramonti *et al.* 2007, Gomes *et al.* 2013).

Pb isotope data available for a few Paraguayan alkaline and tholeiitic rocks are presented in Antonini *et al.* (2005) and Comin-Chiaramonti *et al.* (2007). Distinct Pb isotopic compositions are noted between the sodic alkaline types of Misiones and Asunción provinces and their potassic analogues. Late Early Cretaceous sodic rocks of the Misiones Province are characterized by initial Pb compositions $(^{206}Pb/^{204}Pb)_i$ = 18.211, $(^{207}Pb/^{204}Pb)_i$ = 15.628, and $(^{208}Pb/^{204}Pb)_i$ = 37.963, approaching those of Early Cretaceous low-Ti tholeiites of southern Paraná (Marques *et al.* 1999). Tertiary rocks of the Asunción Province, on the other hand, present isotopic ratios $(^{206}Pb/^{204}Pb)_i$ = 18.964, $(^{207}Pb/^{204}Pb)_i$ = 15.678, and $(^{208}Pb/^{204}Pb)_i$ = 38.484) that appear shifted toward the HIMU field (Fig. 14). Initial Pb isotopic compositions for the most primitive lithologies of pre- and post-tholeiitic Early Cretaceous potassic magmatism show $(^{206}Pb/^{204}Pb)_i$, $(^{207}Pb/^{204}Pb)_i$, and $(^{208}Pb/^{204}Pb)_i$ values ranging between 16.888–17.702, 15.433–15.620, and 37.156–37.915, respectively (Antonini *et al.* 2005). The ratios for Paraguayan tholeiites are generally in agreement with those reported by Marques *et al.* (1999) for Brazilian equivalent rocks.

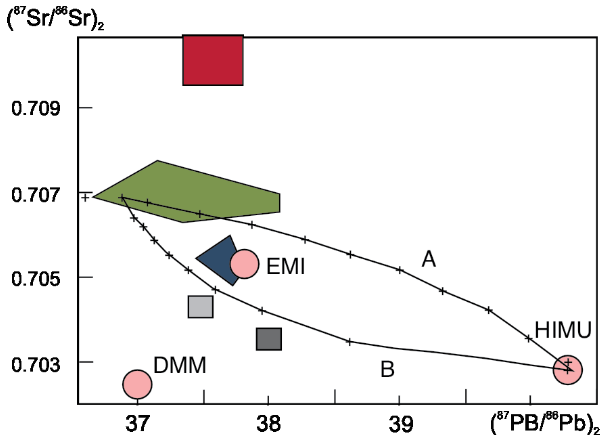


Figure 14. Isotopic mixing curves (A and B) between HIMU and potassic magmas of central-southeastern Paraguay in $(^{87}Sr/^{86}Sr)_i$ versus $(^{208}Pb/^{204}Pb)_i$ diagram (Antonini *et al.* 2005, simplified). Mantle components DMM, EMI, and HIMU in pink after Hart and Zindler (1989); tholeiite field in blue after Marques *et al.* (1999); Paraguay basement field in red and other information after Antonini *et al.* (2005). Gray and black squares represent Late Early Cretaceous (Misiones Province) and Tertiary (Asunción Province) sodic mafic rocks, respectively. Cretaceous alkaline potassic rocks are in green.

PETROLOGY

Petrological considerations on the alkaline magmatism that affected Eastern Paraguay are found in various papers, the most recent contributions being those of Comin-Chiaramonti *et al.* (1997, 2005, 2007, 2015, 2016), Antonini *et al.* (2005), Velázquez *et al.* (2006), Gomes *et al.* (2013), and Gomes and Comin-Chiaramonti (2017). Distinct alkaline magmatic events are recognized in the region: an Early Cretaceous potassic one with associated flood tholeiites and a sodic one that manifested over different times (Middle Triassic, Early and Late Early Cretaceous, and Tertiary) and places (northern, northeastern, central, and southern areas of the country). In the central region, two similar but distinct parental magmas emerge for the potassic magmatism that gave origin to two strongly REE-fractionated rock series showing negative Ta-Nb-Ti anomalies (Comin-Chiaramonti *et al.* 1997). These series form a compositional continuum from moderately to strongly potassic, their petrography varying from basanite to phonolite (B-P) and from alkali basalt to trachyte or trachyphonolite (AB-T). A slightly positive Ta and Nb anomaly characterizes the sodic rock compositions associated with them.

In general, the alkaline rocks of Eastern Paraguay are interpreted by some authors (Comin-Chiaramonti *et al.* 1997, 2005, 2007, Velázquez *et al.* 2006, Gomes *et al.* 2013) as products of fractional crystallization processes acting on alkaline mafic to ultramafic parental magmas. These processes are believed to have operated at shallow surface levels over a long period of time, with the alkaline types originating from a low degree of partial melting of geochemically enriched mantle lithologies. Basanite and nephelinite (which are plagioclase-bearing and plagioclase-free rock types, respectively) are mainly suggested as primary magmas. Basanites are rock types relatively common as small dykes in various alkaline complexes found not only in Paraguayan territory but also in Brazilian territory. They occur internally in intrusive bodies or penetrate country rocks. However, geochemical evidence indicates that in some occurrences, additional genetic processes (e.g., crustal contamination and mixing of magmas) may also have played an important role in the generation of the alkaline magmas. Thus, isotopic data for oversaturated syenites of satellite Cerro Siete Cabezas bodies (Stocks I and II) in the Alto Paraguay Province yielded high $^{87}Sr/^{86}Sr$ ratios, with the highest values (0.70988 and 0.71602) being exhibited by Stock I samples, bearing 23.61 and 14.57% contents of quartz normative, respectively, once compared to the constant number of 0.70380 ± 0.00006 for the main occurrence. Stock II shows Sr_i ratios varying between 0.70374 and 0.70767. These high values are interpreted by Comin-Chiaramonti *et al.* (2005) as resulting from crustal contamination (or mixing of different magma types) by basement composition (Fuerte Olimpo rhyolites and Porto Murtinho granite) affecting less evolved rocks of the main complex. Data demonstrate that, in any case, the contamination is limited to less than 10% of crustal components. Evidence of crustal contamination (or mixing processes) involving mantle-derived magmas and crustal materials is also presented by Velázquez *et al.* (2006) for one of two sources related to the generation of Misiones sodic magmas.

Mantle initial isotopic ratios (Sr_i = 0.70430–0.70473 and Nd_i = 0.51242) characterize the Estancia Guavirá-y and Cerro Guayacán occurrences, whereas crustal geochemical signatures (i.e., Sr_i = 0.70517–0.70523 and Nd_i = 0.51206–0.51226) are exhibited by the Estancia Ramirez and Cerro Caá Jhovy volcanics. Simple mixing calculations performed by Velázquez *et al.* (2006) indicate that the Estancia Ramirez samples may correspond to a mixing process between a parental liquid represented by the Estancia Guavirá-y ultramafics and ~8% of the lower crust. On the contrary, the Cerro Caá-Jhovy felsic rocks may consist of a mixing involving a high amount (~30%) of upper crust material. Regional rocks, amphibolites in the first case and metarhyolites in the second, would be the contaminants. It is to be noted that the time-integrated isotope ratios for the Tertiary Asunción nephelinitic rocks, of similar composition to those of Misiones, are $Sr_i = 0.70367 \pm 0.00011$ and $Nd_i = 0.51269 \pm 0.00005$.

Sr-Nd isotope data plotting close to the BE and transitional to the Paraná flood tholeiites confirms the distinction between sodic rocks and potassic types, the latter showing enrichment in radiogenic Sr and low concentrations in Nd. Sr-Nd-Pb isotopic systematics indicate that two mantle components could have been involved in the genesis of alkaline magmas in Eastern Paraguay. An extreme and heterogeneous EMI component prevailed in the Early Cretaceous potassic magmatism that mimics coeval flood tholeiites in terms of isotopic composition. A HIMU-depleted component played an important role in the Late Early Cretaceous and Tertiary sodic magmatism events (Antonini *et al.* 2005). Different contributions of EMI and HIMU components could also explain the Sr-Nd-Pb isotopic heterogeneity of the Early Cretaceous flood tholeiites. Comin-Chiaramonti *et al.* (2007) pointed out that the enriched isotopic signatures of the Early Cretaceous alkaline magma decrease from west (Paraguay) to east (Brazil) and that a decrease is also noticed in magmatism between both countries, suggesting that magmatism in the Paraná-Angola-Etendeka system relates to both large- and small-scale mantle source heterogeneities.

The generation of different magma types (tholeiitic, potassic, and sodic) over a relatively short temporal range in a relatively restricted area, as in the Central Province case, may simply reflect metasomatized lithospheric source(s) whose heterogeneities can be preserved, as also shown by O-C and Sr-Nd isotopic systematics (Comin-Chiaramonti *et al.* 1996b).

Nd model ages (depleted mantle, T^{DM}; cf. DePaolo 1988) reveal that, in general, T^{DM} values are comparable among potassic Paraguayan magmas and Paraná tholeiites but are relatively higher to the sodic Paraguayan magmas (Comin-Chiaramonti *et al.* 1997). In the potassic alkaline rocks, T^{DM} increases from pre-tholeiites (northeastern Paraguay; Rio Apa and Amambay provinces) to post-tholeiites (central-southern Paraguay; Central Province). According to Comin-Chiaramonti *et al.* (2007), age peaks are observed at 1.1–1.4 Ga (for f = 0.5–0.7) and 1.7 Ga (for f = 0.4–0.5), respectively. For the sodic alkaline rocks (northern and central-southeastern Paraguay; Alto Paraguay, Misiones, and Asunción provinces), T^{DM} values correspond to 0.9, 1.0, and 0.6 Ga, respectively (for f = 0.4–0.5). These model ages indicate that separate, chemically distinct metasomatic events showing strong differences in Ti, LILE, and HFSE concentration may have taken place from Mesoproterozoic to Neoproterozoic as precursors to the alkaline and tholeiitic magmas of the Paraná-Angola-Etendeka system. Also, in accordance with those authors, isotopically distinct magmas were generated following two subcontinental upper mantle enrichment events at 2.0–1.4 and 1.0–0.5 Ga, respectively. Significant amounts of H_2O, CO_2, and F were also expected in the mantle source based on the association of carbonatites (Amambay Province) and pre-tholeiitic potassic alkaline rocks.

The close association of potassic and sodic magmas observed in the Paraná Basin implies the presence of appropriate lithospheric sources for the adjacent and coeval flood tholeiites as well. The origin and emplacement of these rocks took place before the opening of the South Atlantic and appear to be linked to early stages of lithospheric extension associated with an anomalously hot mantle (Piccirillo and Melfi 1988, and references). The alkaline rocks of Eastern Paraguay had their origin related to distinct portions of a large- and small-scale, vertically and horizontally heterogeneous lithospheric mantle source, showing chemical evidence of having undergone incompatible element enrichment by metasomatic processes and bearing as special components H_2O, CO_2, and F, as indicated by the presence of carbonatites.

Results achieved by Velázquez *et al.* (2006) while investigating sodic rocks in the Misiones Province supported the idea that magma genesis and emplacement of the sodic alkaline rocks in southeastern Paraguay are related to and probably driven by a reactivation of preexisting lithospheric discontinuities in various South American blocks, which promoted local decompression melting of previously enriched mantle sources.

An alternative origin for the alkaline magmatism at the margin of the Paraná Basin involves mantle plume activity (Tristan da Cunha plume for Early Cretaceous and Trindade plume for Late Cretaceous occurrences), as proposed by some authors (Gibson *et al.* 1995a, 1995b, 1997, 1999, 2006, Thompson *et al.* 1998). This controversial model is subject to various discussions in the literature, with the hypothesis being mainly constrained by the distinct lithospheric mantle characteristics (Comin-Chiaramonti *et al.* 1997, 2007) and by paleomagnetic results implying plume mobility and migration (Ernesto *et al.* 2002, Ernesto 2005). However, as emphasized by Comin-Chiaramonti *et al.* (1997), the model does not preclude that thermal perturbations from the asthenosphere may have triggered magmatic activity in the lithospheric mantle in Eastern Paraguay. In general, the geochemistry and Sr-Nd-Pb isotope systematics of the alkaline rocks are consistent with a lithospheric mantle(s) source enriched in incompatible elements by metasomatic processes. Yet, according to Ernesto *et al.* (2002), the over-simplified mantle plume model is not satisfactory for explaining the genesis of most continental flood basalts and the recurrent intraplate alkaline magmatism, and some alternative mechanisms and thermal sources must be found in the mantle without requiring direct material transference from the core-lower mantle boundary or the lower mantle to the lithosphere. Also regarding the theme, Marzoli *et al.* (1999) concluded that it is difficult to conciliate the geological data with the existing mantle plumes model for the sodic magmatism of the Misiones (118.3 Ma) and Asunción (58.7 Ma) provinces. Other considerations on the hypothetical role played by the Tristan da Cunha and Trindade plumes in the genesis of alkaline magmatism are found in the above references beyond the papers by Ernesto *et al.* (2000), Gomes *et al.* (2013), Omarini *et al.* (2016), and Gomes and Comin-Chiaramonti (2017).

CONCLUDING REMARKS

Field evidence and recent ^{40}Ar-^{39}Ar ages confirm previous radiometric data indicating that distinct alkaline magmatism occurred in Eastern Paraguay in areas strongly characteristically affected by extensional tectonics.

Middle Triassic to Tertiary alkaline rocks of sodic affinity are found in different regions of the Paraguayan territory, consisting of intrusive types (mostly silica-undersaturated to silica-oversaturated syenites) and their fine-grained counterparts (hypoabissal and volcanics). Notably, ultramafic varieties (ankaratrites and nephelinites) are present as plugs and dykes in the Misiones and Asunción provinces. These varieties contain abundant mantle xenoliths of spinel peridotite, representing two distinct facies (high and low in potassium). Based chiefly on textural features, Comin-Chiaramonti *et al.* (2010) attributed these facies to the action of asthenospheric metasomatic fluids on the lithospheric mantle.

The oldest alkaline sodic magmatic event in Eastern Paraguay is represented by evolved Middle Triassic rocks that occur along the Paraguay River at the boundary of the Chaco-Pantanal and Paraná basins. Early Cretaceous potassic alkaline rocks outcropping in Rio Apa-Amambay and Central province terrains pre- and post-date flood tholeiites of the Paraná Basin, respectively. However, only sodic magmatism events took place in Eastern Paraguay from the Early Cretaceous to the Tertiary, its expressions being concentrated in the Central, Misiones, and Asunción provinces.

The sodic and potassic rocks clearly differ in chemical composition based on their respective positive and negative Nb-Ta anomalies. They also differ in isotope content, with sodic rocks showing lower Sr-Nd values while potassic types are high in radiogenic Sr. Both types define an array from a depleted mantle source to the BE (sodic rocks and associated mantle xenoliths) to an enriched mantle source (potassic rocks and associated carbonatites). Tholeiites, in turn, are of intermediate composition. Sr-Nd-Pb isotopic data suggest that both mantle components could have nvolvevolved in the genesis of the alkaline magmas. A depleted mantle (HIMU) seems to have played an important role in the genesis of the Middle Triassic, Early Cretaceous, and Tertiary sodic rocks, while a heterogeneous and extremely enriched mantle (EMI) was prevalent in the Early Cretaceous potassic types (Antonini *et al.* 2005, Comin-Chiaramonti *et al.* 2007). Only sodic magmatism events are reported to have taken place in Eastern Paraguay from Early Cretaceous to Tertiary.

Mantle signatures may be related to metasomatic processes that affected the subcontinental upper mantle to varied degrees following roughly two main "enrichment" events that occurred in Proterozoic times (2.0–1.4 and 1.0–0.5 Ga) (Comin-Chiaramonti *et al.* 1997). It is proposed that the sources subject to varied degrees of isotope enrichment, as implied by the presence of potassic magmas, are derived from a depleted lithosphere mantle pervasively invaded by IE-C-H-rich fluids.

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