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INVITED REVIEW

# A synthesis on the alkaline magmatism of Eastern Paraguay

## *Uma síntese sobre o magmatismo alcalino do Paraguai Oriental*

**Celso de Barros Gomes[1]*, Piero Comin-Chiaramonti[2], Victor Fernandez Velázquez[3]**

**ABSTRACT:** *Alkaline magmatism occurs in six distinct areas of Paraguay and forms bodies of variable size, shape, composition and age. The oldest rocks are found in the north and correspond to the Permo-Triassic Alto Paraguay Province (241 Ma). Four Early Cretaceous events can be distinguished in Eastern Paraguay: the Rio Apa and Amambay Provinces (139 Ma), both predating the tholeiites of the Serra Geral Formation, are located in the northern and northeastern regions, respectively; and the Central (126 Ma) and Misiones Provinces (118 Ma) in the central-eastern and southern regions, respectively. The youngest alkaline rocks are volcanic rocks in Asunción of Tertiary age (59 Ma). Excluding the Alto Paraguay rocks influenced by the Amazonian craton, the emplacement of alkaline bodies is clearly controlled by a tectonic extensional regime that generated NW-SE-trending faults and grabens. Geochemically, Paraguayan alkaline rocks are predominantly miaskitic, with a potassic or sodic affinity, the former being characterized by strongly fractionated rare earth-elements, negative Ta-Nb-Ti anomalies, and high Sr and low Nd radiogenic isotopes. Sodic rocks have slightly positive Ta and Nb anomalies and are less enriched in Sr, approaching bulk earth values. Carbonatites behave similarly to the associated pre-tholeiites potassic rocks. The Sr-Nd-Pb isotope ratios suggest that two main mantle components were involved in the genesis of the Paraguayan rocks: an enriched mantle I component dominated the Early Cretaceous potassic magmatism, and an high $^{238}U/^{204}Pb$ ou high U/Pb component that was important for the late Early Cretaceous and Tertiary sodic magmatism. The close association of potassic and sodic suites, such as in the Asunción-Sapucai-Villarrica graben, indicates that their parental magmas were derived from a heterogeneous subcontinental mantle, enriched with incompatible elements.*

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

**RESUMO:** Magmatismo alcalino ocorre em seis áreas distintas do Paraguai e forma corpos variáveis quanto ao tamanho, forma, composição e idade. As rochas mais antigas são encontradas no Norte e correspondem à Província Permo-Triássica Alto Paraguai (241 Ma). Quatro eventos do Cretáceo Inferior são reconhecidos no Paraguai Oriental: as Províncias Rio Apa e Amambay (139 Ma), ambas predatando os toleítos da Formação Serra Geral, estão situadas, respectivamente, nas regiões norte e nordeste; e as Províncias Central (126 Ma) e Misiones (118 Ma), respectivamente, nas suas regiões centro-oriental e sudeste. As rochas alcalinas mais novas são as vulcânicas de Assunção, de idade Terciária (59 Ma). À exceção das rochas do Alto Paraguai influenciadas pelo cráton amazônico, a colocação dos outros centros alcalinos é claramente controlada por um regime tectônico extensional que gerou falhas e grábens de orientação NW. Geoquimicamente, as rochas alcalinas paraguaias são em sua quase totalidade miaskíticas, de afinidade potássica ou sódica, com as primeiras caracterizadas por intenso fracionamento dos elementos terras raras, anomalias negativas de Ta-Nb-Ti, e teores altos e baixos, respectivamente, de Sr e Nd radiogênico. Rochas sódicas apresentam anomalias positivas de Ta e Nb e são menos enriquecidas em Sr, com valores próximos ao da Terra global. Carbonatitos comportam-se similarmente às rochas potássicas pré-toleítos. Isótopos de Sr-Nd-Pb sugerem que dois componentes mantélicos estiveram envolvidos na gênese das rochas paraguaias: um componente EMI dominou o magmatismo potássico do Cretáceo Inferior, e um componente HIMU foi importante para o magmatismo sódico do final do Cretáceo Inferior e Terciário. A estreita associação entre as suítes potássica e sódica, como na região do gráben Assunção-Sapucai-Villarrica, indica que seus magmas parentais foram derivados de um manto subcontinental heterogêneo, enriquecido em elementos incompatíveis.

**PALAVRAS-CHAVE:** magmatismo alcalino; petrologia; geoquímica; Paraguai Oriental.

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## INTRODUCTION

The north-south Paraguay River Lineament, which corresponds to the Asunción Arch of Almeida (1983), is an anticlinal structure established in the Early Paleozoic dividing the Paraguayan territory into two large areas with distinctive geology, geophysics, geomorphology and climate (Fig. 1). To the west, there is the Paraguayan portion of the Gran Chaco Basin (and Pantanal wetlands), an alluvial plain of mostly continental origin consisting of unconsolidated clays and fine-grained sands of Tertiary and Quaternary age. To the east, the region called Oriental or Eastern Paraguay made up of the following units: 1) Precambrian basement rocks mainly represented by high- to low-grade metasedimentary lithotypes and rhyolitic flows to Early Paleozoic granitic intrusions, which crop out in two structural highs (Caacupú at the south South and Apa at the north), that are considered the northernmost exposure of the Rio de La Plata craton and the southernmost tip of the Amazonian craton, respectively (Fúlfaro 1996); 2) Silurian to Triassic continental and marine sediments that represent different formations in the western limit of the sedimentary intercratonic Paraná Basin; 3) magmatic rocks characterizing events of different ages and compositions. An extensive magmatism indicated by tholeiitic lava flows and dikes of the Serra Geral Formation covering the eastern side of the geological map of Fig. 1, and an alkaline magmatism that formed numerous occurrences throughout the entire area; 4) recent sediments primarily related to the Paraguay and Paraná rivers forming alluvial deposits.

Alkaline magmatism in Paraguay has been subject of systematic investigation for many years by research groups mostly from Brazil and Italy. Over 70 occurrences are presently known, and the mineralogy, petrography, geochemistry and geochronology of most of them have been studied to some extent. As a result, the literature regarding these rocks is very rich and includes two books (Comin-Chiaramonti & Gomes 1996, 2005), 30 chapters in these and other books, and a great number of articles published in the Brazilian and international literature. Reference papers on the last two decades have been produced by Comin-Chiaramonti *et al.* (2005, 2007b, 2007c, 2013a), Velázquez et *al.* (2006, 2011), Gomes *et al.* (2011) and Riccomini *et al.* (2001, 2005). The reference by Comin-Chiaramonti *et al.* (2007a, 2013b) dealt specifically with carbonatites.

This paper summarizes available information on different aspects of Eastern Paraguay alkaline rocks aiming the better knowledge of this important magmatic activitiy in the Brazilian Platform.

## TECTONIC SETTING

Alkaline complexes in the northern area of Paraguay, and bordering Brazil (Mato Grosso do Sul state), were emplaced along the Paraguay belt, a Cambrian suture between the southernmost tip of the Amazonian plate and the Paraná block (Ussami *et al.* 1999). This alkaline magmatism is assumed to have a relatively well-defined, rift-related continental structure extending over 40 km along the Rio Paraguay Arch, an active tectonic N-S lineament (Comin-Chiaramonti *et al.* 2005). Livieres & Quade (1987) associated this magmatism with the Rio Apa Arch, whereas Velázquez *et al.* (1996) connected it to a cratonic margin. Later, Velázquez *et al.* (1998) highlighted the possibility of a control via N-S-trending faults. More recently, by accounting for stresses related to the Cabo La Ventana orogeny that propagated into the inner parts of Brazilian Platform from a general N-S-trending, Riccomini *et al.* (2005) hypothesized a genetical relationship between the convergence in southwestern Gondwana and the Alto Paraguay alkaline magmatism.

Additional Paraguayan alkaline occurrences are clearly associated with major structures represented by the NW-SE-trending grabens or fault-controlled basins formed during the Late Mesozoic in response to NE-SW extensional tectonics active up to Upper Tertiary (DeGraff *et al.* 1981; Livieres & Quade 1987). Geological studies have distinguished two sets of major faults: an older, NE-SW-trending set, containing the N35E-trending Ponta Porã Arch as the most important tectonic feature controlling the emplacement of alkaline magma in the northeastern region, i.e., the Amambay area (Livieres & Quade 1987); and a younger, NW-SE-trending set, inherited from the Precambrian basement, showing the symmetrical Asunción-Sapucai-Villarrica (ASU) graben, which extends up to more than 100 km into the Chaco Basin, as the most outstanding tectonic feature in the central-eastern region. This graben is composed of three well-defined segments of varying orientation and is characterized by petrographic associations distinct in both age and composition. Another important NW-SE-trending graben system that influenced the emplacement of alkaline rocks approximately 100 km south of the ASU is the Santa Rosa graben (Velázquez *et al.* 1998, 2006). Occurrences in the central-eastern area are related to NW-SE-striking magnetic lineaments and to the gravimetric low situated beneath the Asunción region. This gravimetric low corresponds to a graben filled with fanglomeratic sediments containing nephelinite volcanic fragments and bombs (Riccomini *et al.* 2002). A systematic study of the faults and fracture patterns of some ultra-alkaline bodies combined with the available petrological data allowed Riccomini *et al.* (2001) to conclude that these rocks were emplaced along NW-SE-striking deep lithospheric

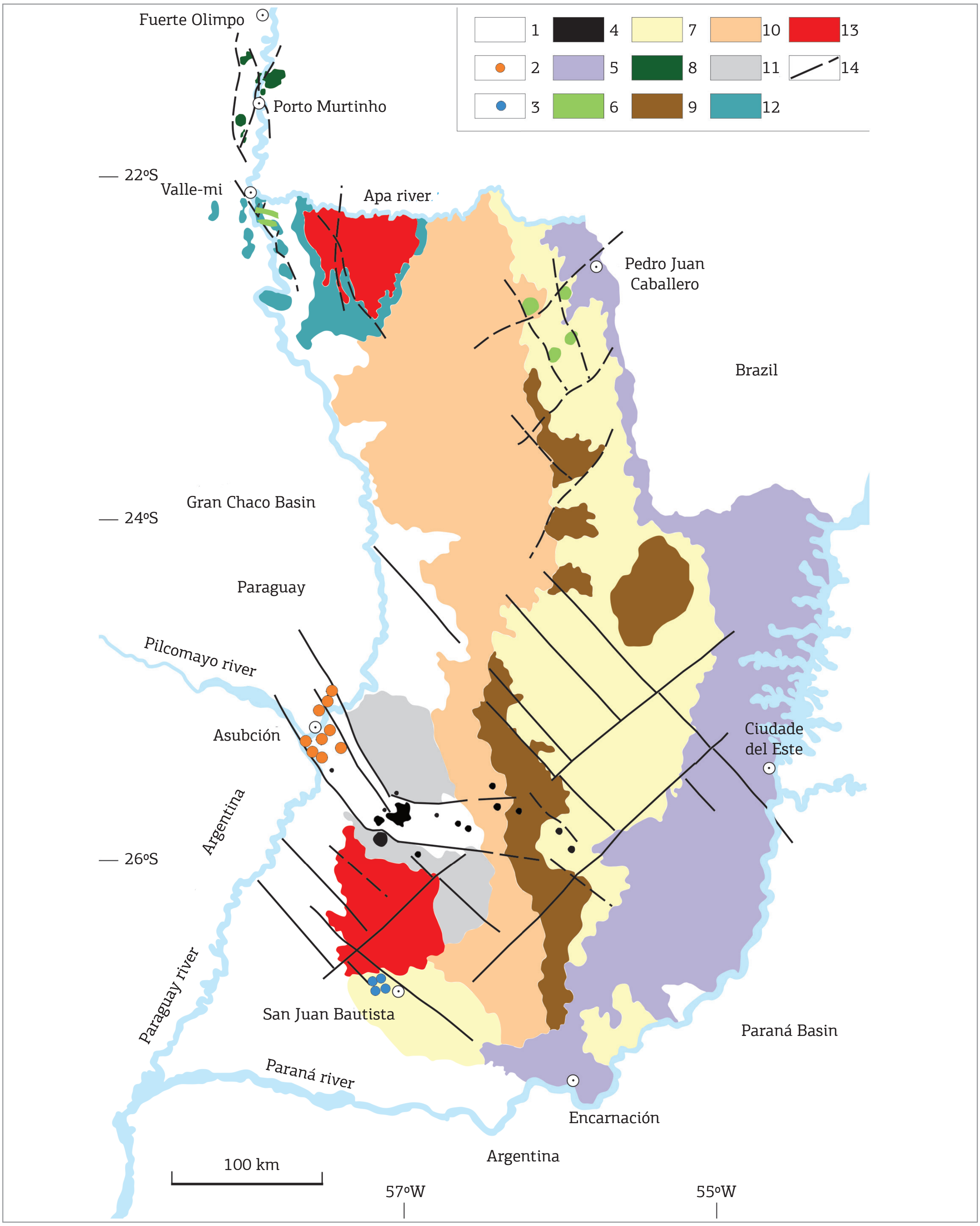


Figure 1. Geological sketch map showing the alkaline magmatism distribution in Paraguay (after Comin-Chiaramonti *et al.* 1997, 1999 and unpublished geological maps). 1. Quaternary sedimentary cover; 2. Tertiary alkaline rocks (Asunción Province); 3. Late Early Cretaceous alkaline rocks (Misiones Province, San Juan Bautista); 4. Early Cretaceous alkaline rocks (post-tholeiites, Central Province); 5. Early Cretaceous tholeiites in the Paraná Basin; 6. Early Cretaceous alkaline rocks (pre-tholeiites, 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-Carboniferous sedimentary rocks (Coronel Oviedo Group); 11. Ordovician-Silurian sedimentary rocks (Caacupé and Itacurubí Groups); 12. Cambro-Ordovician platform carbonates (Itacupumí Group); 13. Archean and Neoproterozoic crystalline basement; 14. Major tectonic lineaments and faults.

faults (more than 60 km deep), within an E-W-trending right-lateral wrenching tectonic regime, identical to those active during rift installation, in the Early Cretaceous.

## RADIOMETRIC AGES

Radiometric age determinations of the Paraguayan alkaline rocks were generally performed using the K/Ar method in the past, mostly by Amaral *et al.* (1967), Comte and Hasui (1971), Palmieri and Arribas (1975), Bitschene (1987), Velázquez (1992) and Velázquez *et al.* (1992). Eby and Mariano (1992) reported the fission-track results for minerals (titanite and apatite) from samples of the Amambay area, whereas Green *et al.* (1991) and Hegarty *et al.* (1996) listed values for apatite from rocks from the Cerro Santo Tomás and Cerro Acahay massifs in the central-eastern region. Because of the large set of non-precise K/Ar data (Tables 1 of Gomes *et al.* 1996a and of Comin-Chiaramonti *et al.* 2007c), which also includes a number of Rb/Sr whole-rock analyses by Velázquez *et al.* 1992), the ages of the magmatic alkaline events remained open until a great number of reliable Ar/Ar determinations became available recently (Milan 2003; Gomes *et al.* 2003; Velázquez *et al.* 2003; Comin-Chiaramonti *et al.* 2007c), allowing the different episodes of that important activity to be better defined. Based on geological evidences and both previous and new radiometric ages, it is concluded that Eastern Paraguay, an undeformed basin along western Gondwana, in and around the Paraná Basin, was characterized by five main alkaline magmatic events lasting from the end of the Paleozoic to the Cenozoic (Fig. 2).

The oldest alkaline rocks in Paraguay are the occurrences lying in the northern sector along the Paraguay river with age span from 255 to 210 Ma, as suggested by various geochronological studies (Amaral *et al.* 1967; Comte & Hasui 1971; Velázquez *et al.* 1992, 1996b; Velázquez 1996; Gomes *et al.* 1996a, 1996b). The large range of measured ages for minerals (amphiboles and alkali feldspars) and whole-rock samples indicates that the K/Ar and Rb/Sr data were affected by different geological processes (subsolidus reactions, exsolutions, hydrothermal alterations, weathering; cf. Velázquez *et al.* 1992, 1996b). The smallest analytical errors (age range from 248 to 242 Ma) were yielded by the K/Ar and Ar/Ar (non-plateau) analyses of biotite separates (Comin-Chiaramonti *et al*. 2007c). New Ar/Ar plateau ages were reported by these authors for biotite from three different massifs, which places the Alto Paraguay alkaline event in the Middle Triassic (241.5 ± 1.3 Ma).

The next alkaline event predates the flood of tholeiites of the Serra Geral Formation (main peak at 133 ± 1 Ma: Renne *et al.* 1992, 1996; Thiede & Vasconcelos 2008), based on the radiometric ages and geological evidences in the Cerro Chiriguelo carbonatite area (Haggerty & Mariano 1983). Alkaline rocks form small dikes near the locality of Valle-mí, close to the mouth of the Apa river in the northern sector (Comin-Chiaramonti *et al.* 1999), and carbonatitic complexes, stocks, plugs and dikes in the Amambay area in the northeastern sector (Gomes *et al.* 2011). Previous geochronological documentation including K/Ar analyses of both biotite and whole rocks and fission track data for both titanite and apatite is poor; however, newer Ar/Ar age spectra (Comin-Chiaramonti *et al.* 2007c) consistently place this event in the late Early Cretaceous (138.9 ± 0.7 Ma).

The most important alkaline episode in Eastern Paraguay came next and includes a great number of occurrences that form intrusions with various shapes and dimensions spread over the central-eastern sector, the largest being the Sapucai and Cerro Acahay. Despite the considerable data available (see Table 1 of Comin-Chiaramonti *et al.* 2007c), only a few reliable K/Ar analyses involving biotite separates and a new set of Ar/Ar determinations (Milan 2003; Gomes *et al.* 2003; Comin-Chiaramonti *et al.* 2007c) are employed to define the alkaline magmatism during the interval from 128 to 126 Ma for the area. Comin-Chiaramonti *et al.* (2007c) used the highly concordant plateau ages to propose an activity peaked in the Early Cretaceous at 126.4 ± 0.4 Ma. This age is similar to the weighted mean Ar/Ar age of 127.56 ± 0.45 reported by Gibson *et al.* (2006) for Cerro Santo Tomás dike and Cerro Cañada stock. Younger ages from 117 to 110 Ma (Milan 2003) are also reported for a few volcanic rocks and data from 120 to 119 Ma (Comin-Chiaramonti *et al.* 2007c, unpublished analyses) were suggested for many of the sodic alkaline dikes cutting the potassic analogues.

The fourth alkaline event is represented by volcanic rocks near the city of San Juan Bautista in southwestern Eastern Paraguay. Three lava flows and one dike were analyzed by Ar/Ar to obtain plateau and miniplateau values indicating a late Early Cretaceous age (118.3 ± 1.6) Ma for the Misiones rocks (Velázquez *et al.* 2003, 2006; Comin-Chiaramonti *et al.* 2007c).

The alkaline magmatism in Eastern Paraguay ended during a Tertiary event consisting of lava flows, plugs and dikes near Asunción. The K/Ar ages determined by various authors (Comte & Hasui 1971; Bitschene 1987; Comin-Chiaramonti *et al.* 1991) for whole rocks from these occurrences vary significantly and cover an interval from 60.9 ± 4.4 to 38.8 ± 2.3 Ma. However, the more recent Ar/Ar miniplateau results obtained by Milan(2003), Gomes *et al.* (2003) and Comin-Chiaramonti *et al.* (2007c) limit this interval from 61 to 56 Ma, which suggests a Paleocene age (58.7 ± 2.4 Ma, average of the plateau and miniplateau ages) for the Asunción rocks.

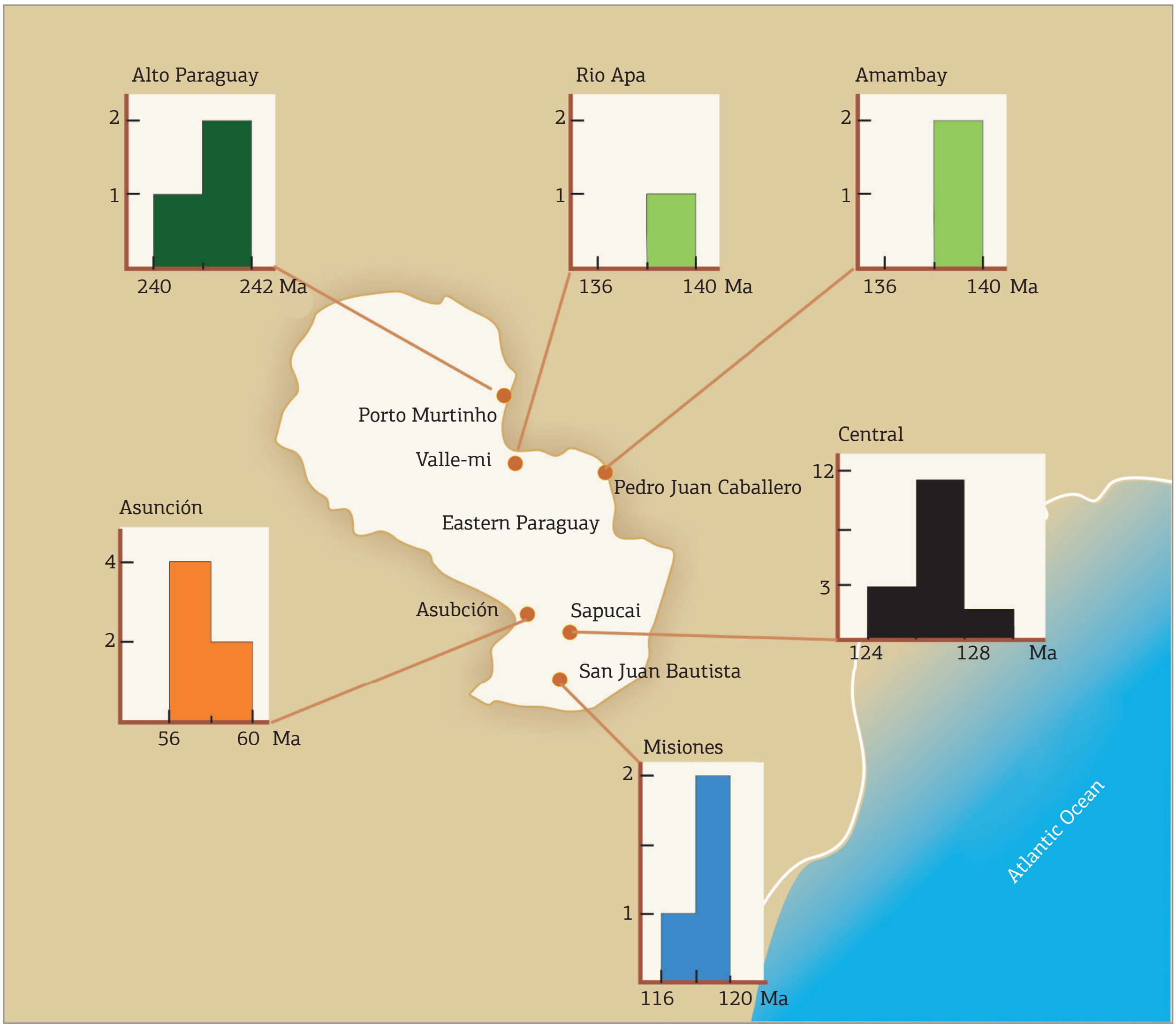


Figure 2. Alkaline provinces in Paraguay: 1. Alto Paraguay; 2. Rio Apa; 3. Amambay; 4. Central; 5. Misiones; 6. Asunción (Velázquez *et al.* 1996a; Comin-Chiaramonti *et al.* 2007c). Their Ar/Ar radiometric ages are shown in histograms.

## ROCK ASSOCIATIONS

Because the Paraguayan alkaline rocks have highly variable textures and compositions, an attempt has been made to assemble the most common rock types to facilitate correlating them to several occurrences.

### Undersaturated to oversaturated syenites and equivalent fine-grained rock types

Syenites and fine-grained rocks are the most abundant petrographic associations that are present in all of the occurrences throughout the Alto Paraguay region (Comin-Chiaramonti *et al.* 2005). Therefore, fine-grained varieties such as phonolites and trachytes dikes in addition to trachyphonolites, rhyolites and ignimbrites lava flows are linked to the Pão de Açúcar volcanic field. However, in the central-eastern region of Eastern Paraguay, intrusive suites occur less commonly and are only found in a few places in association with syenodioritic and gabbroic rocks. In this area, fine-grained types (phonolites and subordinate trachyphonolites) usually form dikes, whereas individual lava domes (*e.g.* Cerro Medina, Cerro Capiitindy, cf. Comin-Chiaramonti *et al.* 1996b) consist of peralkaline phonolites and trachyphonolites, respectively.

### Gabbroic rocks with alkaline affinity and equivalent fine-grained types

Alkaline gabbroic and fine-grained rocks include those ranging in composition from theralites to essexites and alkali gabbros to nepheline syenodiorites (nomenclature after De La Roche *et al.* 1980). This class groups several intrusions from the central-eastern area (e.g., Cerro Acahay, Cerro San

José, Mbocayaty, cf. Comin-Chiaramonti *et al.* 1996b) and is found in association with fine-grained rocks of variable composition (tephrites, alkali basalts, trachyphonolites, phonolites, trachytes) from lava flows and dikes.

### Mafic-ultramafic rocks associated with carbonatites

Mafic-ultramafic rocks associated with carbonatites are described in the Amambay area in the northeastern part of Eastern Paraguay. The intrusive carbonatite complexes of Cerro Chiriguelo and Cerro Sarambí are the most outstanding expression of the alkaline magmatic activity in the region. Silicate rocks such as pyroxenites and shonkinites in addition to a volcanic suite comprise dikes of variable composition and texture (Gomes *et al.* 2011). Rocks showing a more mafic composition are represented by tephrites and phonotephrites. Phonolites and trachyphonolites other than trachytes form satellite plugs (*e.g.* Cerro Apuá).

Carbonatitic rocks in association with small dikes of basanite are found in the northern sector near the city of Valle-mí, not far from the mouth of the Apa river. They are also described in the central-eastern region forming a lava flow genetically related to the Sapucai alkaline complex (Comin-Chiaramonti *et al.* 1992a).

### Mafic-ultramafic and lamprophyric rocks

Although present in some occurrences bearing alkaline gabbros, mafic-ultramafic and lamprophyric rocks are here emphasized due to their extensive fields that form dikes and dike swarms in the central segment of the Asunción Rift near the village of Sapucai. Over 200 ultramafic, mafic, intermediate and potassic felsic dikes are known to be randomly distributed in that area and have been the subject of petrological, geochemical and geotectonical investigations by various authors (Druecker & Gay 1987; Gomes *et al.* 1989; Comin-Chiaramonti *et al.* 1990a, 1992b, 1995a, 2013a; Presser 1998; Velázquez *et al.* 2011).

### Ultramafic lavas with mantle xenoliths

Ultramafic lavas with mantle xenoliths are typical of several plugs and dikes tectonically controlled by the Asunción Arch that outcrop near the capital Asunción in the central-eastern area. These rocks are also related to the Santa Rosa graben in southern Eastern Paraguay with the intrusions found in the nearby city of San Juan Bautista. In both occurrences nephelinites and ankaratrites carrying mantle xenoliths composed of spinel lherzolites and dunites are the main lithotype in addition to peralkaline phonolite dikes.

## ALKALINE PROVINCES

Paraguayan alkaline rocks can be grouped into six distinct provinces based on their geological evidences, tectonic controls, radiometric ages and petrographic associations (Fig. 2), in agreement with the suggestions made by Velázquez *et al.* (1996a). The distribution of alkaline occurrences within each province is shown in Figure 3.

### Alto Paraguay (241 Ma)

Alto Paraguay is a broad province located on the southernmost side of the Amazonian craton along the Paraguay river that encompasses the oldest recognized alkaline magmatic events in the Paraná Basin. Alkaline centers form ring-like complexes and stocks of nepheline syenites and syenites both south and north of the city Porto Murtinho, on the boundary zone between Paraguay and the state of Mato Grosso do Sul in Brazil. Fine-grained rocks occur as lava flows and dikes and are represented by phonolites, trachyphonolites, trachytes, rhyolites and ignimbrites. Notably, near the village of Fuerte Olimpo some outcroppings defined as alkaline rocks by Gibson *et al.* (2006) are actually rhyolites that have an age of 1341 ± 53 Ma (Gomes *et al.* 2000).

### Rio Apa (139 Ma)

Alkaline magmatism is poorly represented in Rio Apa, which only contains recognizable outcroppings from small NE-trending dikes of basanite bearing carbonatic material and cutting through Cambro-Ordovician limestones at the edge of the Paraguay river near the city of Valle-mí.

### Amambay (139 Ma)

The alkaline magmatic activity in Amambay is mainly represented by ring-like complexes in Cerro Chiriguelo and Cerro Sarambí, where the carbonatites are associated with pyroxenites, syenites and fenites as well as dikes of phonolites, trachytes and lamprophyres. Thin veins and dikes containing different generations of carbonatites with variable compositions are also reported by Censi *et al.* (1989) and Eby and Mariano (1992). Additional alkaline centers in the area include the satellite plug in Cerro Apuá, in the Cerro Sarambí surroundings, which is made up of trachytes (Gomes *et al.* 2011); the stock in Cerro Guazú, a shonkinite body cut by lamprophyric dike (Mariano 1978); and other small intrusions poorly geologically known, such as the plugs in Cerro Jhú (trachyphonolites and phonolites) and in Cerro Teyú (trachyphonolites) and the trachytic dikes in Arroyo Gasory.

A comprehensive geochemical investigation of carbonatites, particularly those from the Cerro Chiriguelo complex,

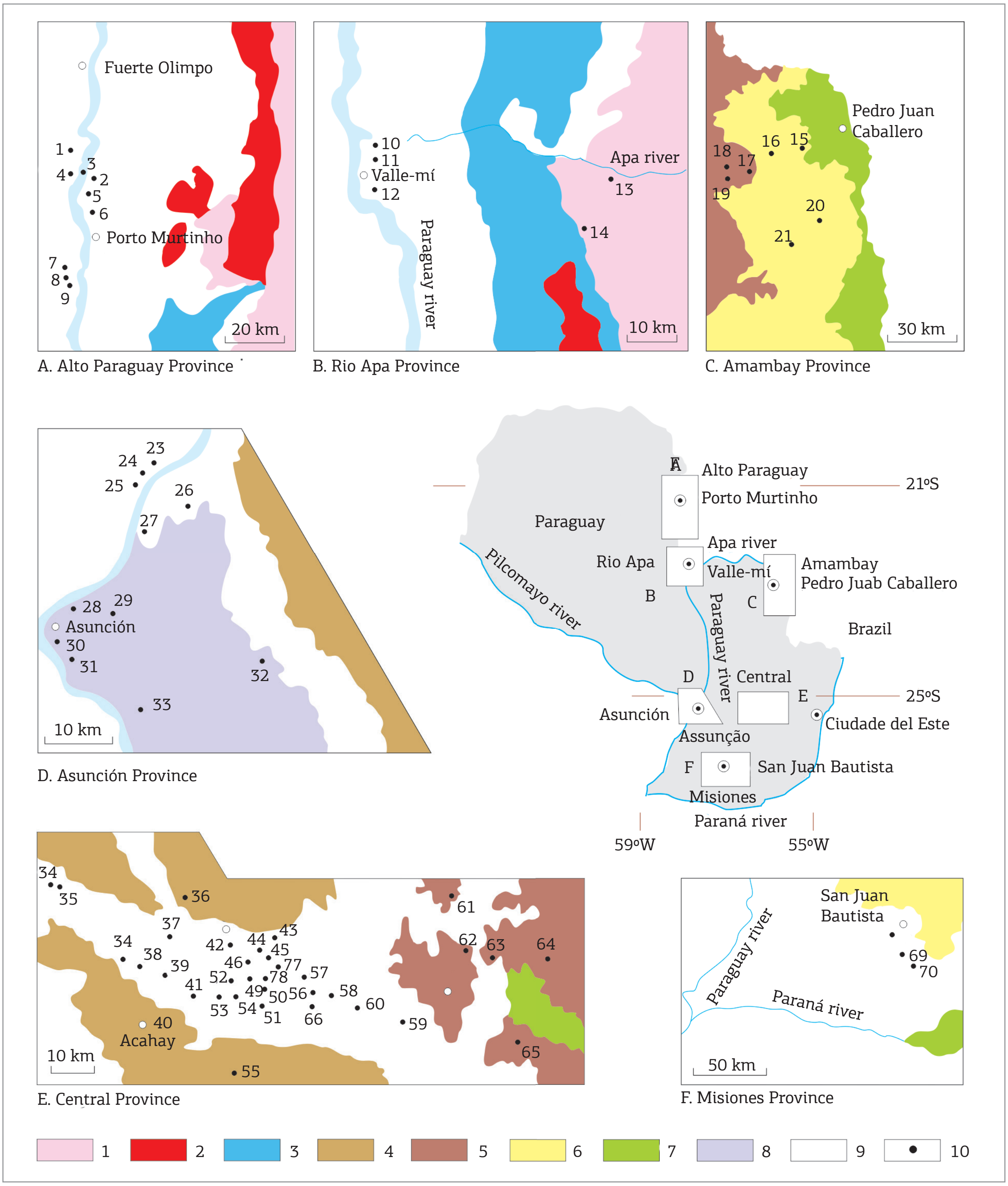


Figure 3. General distribution of alkaline occurrences in the six Paraguayan provinces with numbers and names of localities according to Fig. 1 and Table 1 from Velázquez *et al.* (1996). Alkaline centers cited in the text are the followings: (A) Alto Paraguay, 1. Cerro Boggiani; 2. Pão de Açúcar; 7. Cerro Siete Cabezas; (B) Rio Apa, 12. Valle-mí; (C) Amambay, 15. Cerro Chiriguelo; 16. Arroyo Gasory; 17. Cerro Sarambí; 18. Cerro Apuá; 21. Cerro Guazú (Cerro Teyú and Cerro Jhú are not indicated); (E) Central, 36. Cerro Santo Tomás; 40. Cerro Acahay; 41. Cerro Gimenez; 42. Sapucai; 53. Cerro Medina; 55. Cerro San José; 57. Cerro Cañada; 62. Mbocayaty; 63. Cerro Capiitindy; (F) Misiones, 68. Cerro Caá Jhovy; 69. Estancia Ramirez; Estancia Guavira-y (Cerro Guayacán is not indicated).

was performed by Castorina *et al.* (1996, 1997), Comin-Chiramonti *et al.* (2007a) and Antonini *et al.* (2005).

## Central (126 Ma)

The Central Province clusters alkaline occurrences related to the evolution of the central and eastern parts of the Asunción Rift (DeGraff 1985), which was installed during the Early Cretaceous. This province contains the largest number of alkaline centers occurring as stocks, plugs, lavas and especially dikes and dike swarms in Eastern Paraguay. The great ring-like intrusion in Cerro Acahay is also noteworthy (Comin-Chiaramonti *et al.* 1990b). The rocks are grouped into two distinct sets, one from basanites to phonolites and the other from alkali basalts to trachytes. In these sets are included the corresponding intrusive types. A small occurrence of carbonatite is found near the village of Sapucai (Comin-Chiaramonti *et al.* 1992a).

## Misiones (118 Ma)

Alkaline rocks form small plugs (Cerro Caá Jhovy, Cerro Guayacán and Estancia Guavira-y) and dikes (Estancia Ramirez) in the southernmost sector of Eastern Paraguay, near the city of San Juan Bautista. They include ankaratrites-melanephelinites that carry mantle xenoliths, basanites-tephrites and peralkaline phonolites, being all the occurrences distributed and oriented along the NW-SE structure referred to as the Santa Rosa graben (DeGraff 1985). These rocks were first described by Comin-Chiaramonti *et al.* (1992c) and their petrology and geochemistry have been recently investigated in detail by Velázquez *et al.* (2006).

## Asunción (59 Ma)

Asunción comprises ultra-alkaline rocks from the western segment of the Asunción Rift in Eastern Paraguay. These rocks occur as plugs, necks, lavas and dikes near the capital Asunción and consist primarily of nephelinites and ankaratrites bearing mantle nodules, which range from dunites to lherzolites (Stormer *et al.* 1975; Comin-Chiaramonti *et al.* 1991, 2001, 2010), and subordinate peralkaline phonolites.

# GEOCHEMISTRY

## Major and trace elements

Based on 523 chemical analyses of silicate rocks (intrusives, effusives and dikes) from the ASU graben in the central-eastern region, Comin-Chiaramonti *et al.* (1996c) proposed dividing these rocks into two major groups, potassic or sodic, following their variation in $K_2O$ and $Na_2O$ contents (Fig. 4A). Applying the chemical screens to rocks from other areas, the Paraguayan alkaline magmatism can be classified as being, in general, of potassic affinity in the Rio Apa, Amambay and Central provinces, whereas shows sodic affinity in the Alto Paraguay, Misiones and Asunción provinces (Comin-Chiaramonti *et al.* 2007b). However, it should be noted that alkaline sodic rocks are also found in the Central Province as dikes or plugs (*e.g.* Cerro Medina, Cerro Gimenez) of peralkaline phonolitic composition. On the other hand, the Paraguayan alkaline rocks are predominantly miaskitic (cf. Sørensen 1960) with agpaitic types restricted to a few occurrences mostly from the Alto Paraguay region (*e.g.* Cerro Siete Cabezas, Cerro Boggiani).

Potassic and sodic rocks fields for the ASU alkaline rocks are easily distinguished in the $R_1$-$R_2$ diagram proposed by De La Roche *et al.* (1980). Intrusive rocks and the equivalent lava and dike variants plot to the same regions of the diagram, which suggests a similar composition for the different magma types (Fig. 4B). An analogue behavior was noted in the chondrite normalized rare earth elements (REE) and primordial mantle normalized diagrams (Comin-Chiaramonti *et al.* 1996a). The $R_1$-$R_2$ diagram also allows the recognition of two suites of potassic rocks that conform the general trends of basanite to phonolite (B-P) and alkaline basalt to trachyphonolite/trachyte (AB-T) indicated by fractional crystallization. However, the sodic rocks follow a different evolutive trend (Fig. 4C).

The mantle-normalized incompatible element (IE) patterns for pre- and post-tholeiites potassic alkaline rocks are quite similar and are generally characterized by an large ion lithophile element enrichment and high field strength elemento depletion (Fig. 5A). They are distinguished from sodic rocks in the Alto Paraguay, Misiones and Asunción provinces by their Ta-Nb-Ti negative anomalies (Comin-Chiaramonti *et al.* 1997), whereas rocks from those provinces show slightly positive Ta and Nb anomalies (Comin-Chiaramonti *et al.* 1991, 1997). In particular, the Misiones and Asunción sodic alkaline rocks display nearly identical IE patterns and generally only differ by a marked negative K spike and positive HFSE spikes comparatively to the potassic rocks (Comin-Chiaramonti *et al.* 2007c). Additionally, the associated Paraná tholeiites behave similarly to potassic rocks (Fig. 5B).

## Isotopes

The studied Paraguayan rocks cover a wide range of Sr-Nd isotopic compositions and define a trend similar to the low-Nd array of Hart & Zindler (1989), which is called the "Paraguay array" by Comin-Chiaramonti *et al.* (1995a, 1995b). The initial $^{87}Sr/^{86}Sr$ ($Sr_i$) and $^{143}Nd/^{144}Nd$ ($Nd_i$) ratios range from the depleted to the enriched quadrant with both pre- and post-tholeiites potassic rocks having the highest initial $Sr_i$ and lowest $Nd_i$. Carbonatites (Cerro Chiriguelo and Cerro Sarambí), associated with the


Figure 4. (A) Diagram of $K_2O$ *versus* $Na_2O$ for the fields of highly potassic, potassic and sodic rocks (Middlemost 1975). (B) $R_1$-$R_2$ diagram (De La Roche *et al.* 1980) for potassic and sodic rocks (intrusives, volcanics and dikes) from ASU. (C) $R_1$-$R_2$ diagram showing fields of potassic (in red, trends for both suites, B-P and AB-T), sodic (in yellow) and tholeiitic rocks in Serra Geral (in blue) of Eastern Paraguay (*cf*. Comin-Chiaramonti *et al.* 1996a). Noted that petrochemical evidence points to fractional crystallization as potentially important in the evolution of the potassic suites.

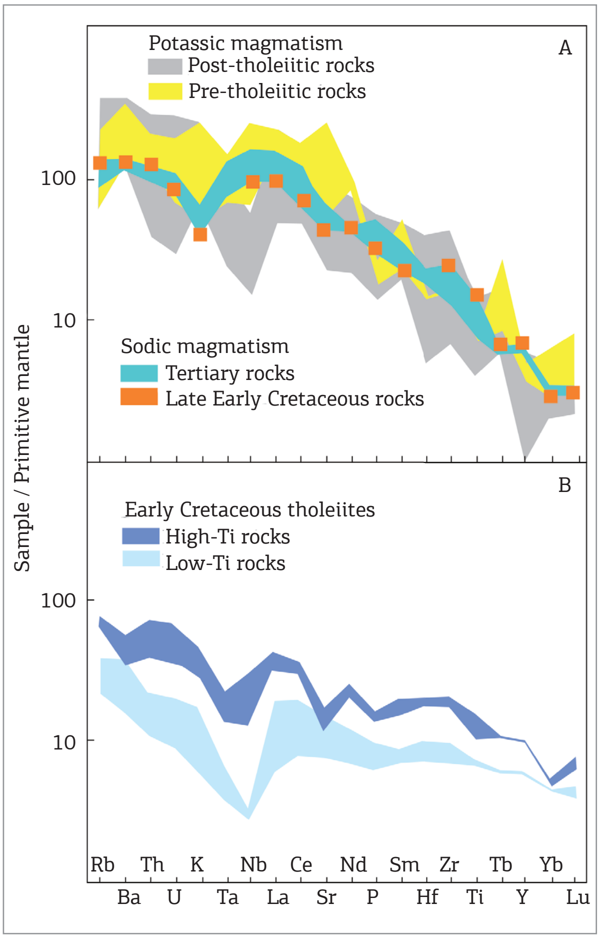


**Figure 5. Primordial mantle normalized to the incompatible element of Early Cretaceous to Tertiary alkaline rocks in Eastern Paraguay (Comin-Chiaramonti *et al.* 1997; Antonini *et al.* 2005). (A) Pre- and post-tholeiitic potassic rocks and Cretaceous and Tertiary sodic rocks; (B) Low- and high-Ti Early Cretaceous tholeiites from the Serra Geral Formation.**

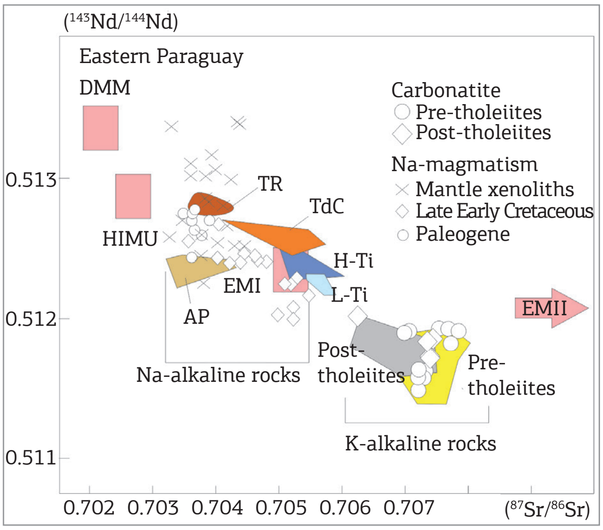


**Figure 6. Initial $^{87}Sr/^{86}Sr$ ($Sr_i$) *versus* $^{143}Nd/^{144}Nd$ ($Nd_i$) diagram for Early Cretaceous to Tertiary alkaline rocks in Eastern Paraguay (Comin-Chiaramonti *et al.* 2007c). AP, Alto Paraguay; TR, Trindade; TdC, Tristan da Cunha; H-Ti, high-Ti tholeiites; L-Ti, low-Ti tholeiites. depleted MORB mantle, high $^{238}U/^{204}Pb$ ou high U/Pb and enriched mantle I fields after Hart and Zindler (1989). Paraguay array after Comin-Chiaramonti *et al.* (1995a, 1995b).**

pre-tholeiitic potassic rocks in northeastern Paraguay also have high $Sr_i$ values (Fig. 6). The $Sr_i$ and $Nd_i$ content of silicate and carbonatite rocks ranges from 0.70636 to 0.70721 and from 0.51194 to 0.51165, respectively. These values are quite distinctive compared to those presented by sodic rocks (Alto Paraguay: $Sr_i$ = 0.70350-0.70570, $Nd_i$ = 0.51207-0.5123; 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, cf. Comin-Chiaramonti *et al.* 1997, 2007c), which plot within the depleted quadrant towards the high U/Pb mantle (HIMU) and depleted MORB mantle compositional fields as indicated by Fig. 6 (Antonini *et al.* 2005).

A few Pb isotopes were available in some pre- and post-tholeiite alkaline potassic rocks and tholeiites from Eastern Paraguay (Antonini *et al.* 2005). According to these authors, the initial Pb isotope composition of both pre- and post-tholeiitic K-magmatism for the most "primitive" rock types show $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values ranging from 16.888 – 17.702, 15.433 – 15.620 and 37.156 – 37.915, respectively. In contrast, the sodic alkaline rocks (Misiones and Asunción) have different Pb isotopic compositions. Late Early Cretaceous sodic rocks are characterized by their initial Pb compositions ($^{206}Pb/^{204}Pb$ = 18.211, $^{207}Pb/^{204}Pb$ = 15.628 and $^{208}Pb/^{204}Pb$ = 37.963), which approach those of the Cretaceous low-Ti tholeiites in southern Paraná (Hauri 1997), whereas the composition of the Tertiary sodic rocks ($^{206}Pb/^{204}Pb$ = 18.964, $^{207}Pb/^{204}Pb$ = 15.678, $^{208}Pb/^{204}Pb$ = 38.484) is shifted towards the HIMU field (Fig. 7). As shown in the diagram, the data available for Paraguayan alkaline and tholeiitic rocks plot between the HIMU and EMI end-members, and subordinately between the DMM and EMI. The Sr-Nd-Pb isotopic data indicate that two main mantle components could have been responsible for generating the Cretaceous to Tertiary alkaline magmatism in Eastern Paraguay: an extreme and heterogeneous EMI, which was prevalent in Cretaceous potassic events, and an HIMU component, which was more important to Cretaceous and Tertiary sodic events (Antonini *et al.* 2005). The initial isotope ratios for the Paraguayan tholeiitic rocks generally agree with the Brazilian equivalents reported by Marques *et al.* (1999).

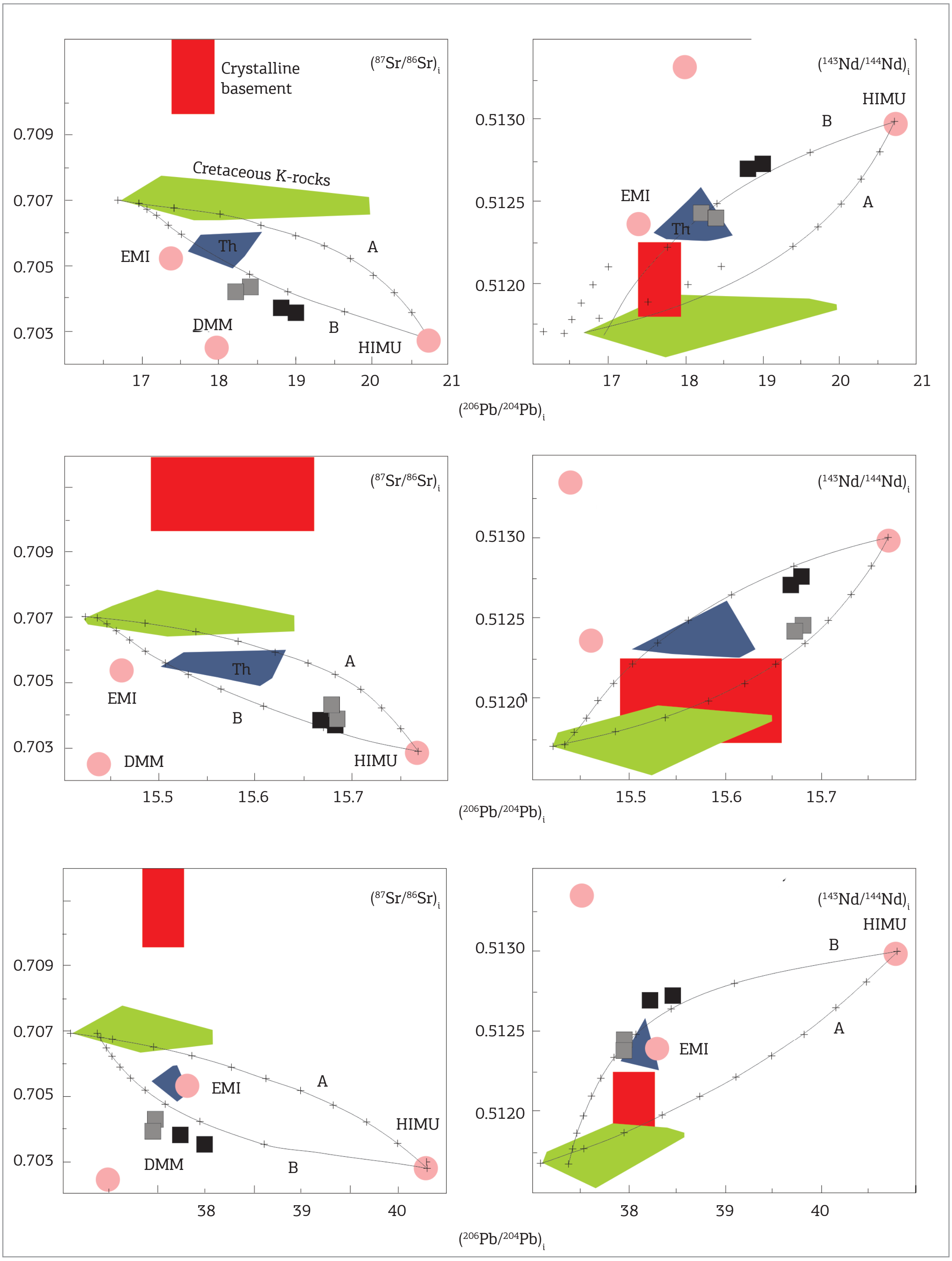


Figure 7. Isotopic mixing curves (A and B) between HIMU and potassic magmas from the Asunción-Sapucai-Villarrica (ASU) graben (Antonini *et al.* 2005; Comin-Chiaramonti *et al.* 2007b). Symbols: black and gray squares are Asunción and Misiones Na-mafic rocks, respectively. depleted MORB mantle, high $^{238}U/^{204}Pb$ ou high U/Pb and enriched mantle I are components from Hart and Zindler (1989).

## GEODYNAMIC IMPLICATIONS

Other considerations on this topic can be found in Comin-Chiaramonti *et al.* (2007c). The geodynamic evolution of Western Gondwana during the Early Cretaceous reflects the amalgamation processes affecting at least the Brasiliano cycle of the region for both the Atlantic and Pacific systems (Trompette 1994). The Brasiliano cycle (890 to 480 Ma) was developed in a diacronic fashion until the framework basement of the South American Platform was arranged (Brito Neves *et al*. 1999). During the Early Ordovician, a mosaic of lithospheric fragments linked by several (accretionary, collisional) Neoproterozoic mobile belts amalgamated to form the Gondwana supercontinent (Unrug 1996). After this amalgamation, Gondwana accumulated Paleozoic and Mesozoic sediments while it was continuously and laterally accreted at its western borders by successive orogenic belts during the Early Paleozoic and Permo-Triassic until Pangea formed (Cordani *et al.* 2000, 2003). The main cratonic fragments (like the Amazonian, Rio Apa and Rio de La Plata) are descended from Pangea's ancestors and were reworked along with smaller ancient crustal blocks in the present-day Paraguay's boundaries (Kröner & Cordani 2003). In this context, the magmatism was driven by extensional regimes derived from the relative movements of ancient blocks. For example, the Permo-Triassic Alto Paraguay alkaline magmatism is located at the boundary of the Rio Apa and Arequipa-Antofalla blocks, which indicates an extensional event occurred at approximately 241 Ma, that was likely induced by counterclockwise and clockwise movements (north and south, respectively) hinged at about 20° in latitude S (Prezzi & Alonso 2002).

The general geodynamic of Paraguay and neighboring countries can be pictured using present-day earthquakes typology combined with paleomagnetic and geological evidence. The earthquake mechanisms (Berrocal & Fernandes 1996) highlight the distribution of earthquakes with hypocenters > 500 km and < 70 km (Figure 13 of Comin-Chiaramonti *et al*. 2007c). The distribution of such deep earthquakes coincides with the inferred location of the subducting Nazca plate under Paraguay. In particular, the depth of lithospheric earthquakes combined with the paleomagnetic results suggests that different rotational paths occurred at approximately 18 – 20° in latitude S, which roughly corresponds to the Chaco-Pantanal basin and indicates the extensional subplate tectonics of the Andean system (Randall 1998). The genesis of the Paraná-Angola-Etendeka (PAE) magma types is also linked to the geodynamic processes promoting the opening of the South Atlantic. According to Chang *et al*. (1988) and Nürberg and Müller (1991), the spreading sea-floor in the South Atlantic at the PAE latitude started at ~ 125 – 127 Ma (Chron M4). North of the Walvis-Rio Grande ridges (< 28° latitude S), the onset of the oceanic crust would be younger (~ 113 Ma; Chang *et al.* 1988). The Early Cretaceous alkaline and alkaline-carbonatitic complexes are sub-coeval to the main flood tholeiites in the Paraná Basin and, therefore, occurred during the early stages of rifting before continental separation. However, the Late Cretaceous analogues formed during advanced stages of the Africa-South America continental separation.

The origin of alkaline-carbonatitic magmatism in terms of plate tectonics is a subject of controversy with various models that have been proposed in the literature (*e.g.* deep mantle plumes or hotspots, cf. Stefanick & Jurdy, 1984; shallow thermal anomalies, cf. Holbrook & Kelemen 1993). Regardless the temperature, size, depth of origin and number of hotspots, the plume model cannot account for the worldwide occurrence of alkaline-carbonatitic magmatism. Interpreting remote sensing data from South American second-order boundaries, Unternehr *et al.* (1988) suggested that important dextral displacement between the two South American domains occurred. Smith and Lewis (1999) demonstrated that the forces acting on plates moving with differential angular velocity in the presence of volatile-rich mantle sources (wet spots) cause rifting parallel to the pre-existing (*e.g.* N-S) sutures, *i.e.*, the Adamastor Ocean. Intraplate alkaline and alkaline-carbonatitic magmatism occurs when second-order plate boundaries (*e.g.* Alto Paranaíba, Ponta Grossa-Moçâmedes Archs, *cf.* Molina & Ussami 1999) intersect the axis of a major rifting, which may be related to the erosion and cycling of the continental mantle along the ridge axis.

Alkaline and alkaline-carbonatitic magmatism in southern Brazil is concentrated in regions containing positive geoid anomalies (Molina & Ussami 1999) related to dense, deep materials. Moreover, both the differing westward angular velocities of lithospheric fragments from the South American plate as defined by second order plate boundaries and the different rotational trends at 19 – 20° in latitude S may favor decompression and melting at different times for various metasomatized (wet spots) portions of the lithospheric mantle presenting variable isotopic signatures (Turner *et al*. 1994; Comin-Chiaramonti *et al*. 2002). It should be stressed that the presence of even a small amount of water and carbon dioxide in the upper mantle may lower the melting temperature by several hundred degrees (Thybo 2006).

This scenario could explain the presence of Late Cretaceous to Tertiary sodic magmatism in the PAE system, even in Eastern Paraguay, where there is evidence of active rifting structures (Comin-Chiaramonti *et al.* 1999). In this case, thermal perturbations follow the second-order plate boundaries and stress earthquake hypocenters in South America (Berrocal & Fernandes 1996).

## Mantle plume

The simplistic mantle plume model cannot explain most of continental flood basalts and recurrent intraplate alkaline magmatism (Ernesto 2005). Following Ernesto *et al.* (2002), alternative thermal sources should be found in the mantle without requiring a material transfer from the lower mantle to the lithosphere. In addition to the indications of geoid anomalies, the existence of long-living thermal anomalies or compositional differences in the mantle has already been demonstrated via a velocity distribution model based on seismic tomography techniques using both P- and S-waves (*e.g.* Zhang & Tanimoto, 1993; Van der Hilst *et al.* 1997). Based on paleomagnetic and gravimetric studies, Ernesto *et al.* (2002) stated the following:

- 1) Paleogeographic reconstructions of the Paraná-Tristan da Cunha (TC) system, assuming this hotspot is a fixed point in the mantle, indicate the TC plume was located ~ 800 – 1.000 km south of the Paraná Magmatic Province (PMP), which requires plume mobility to maintain the PMP-TC relationship.
- 2) Assuming the TC was located in the northern portion of the PMP (~ 20° from its present position), the plume migrated southward from 134 – 130 Ma to 80 Ma at a rate of approximately 40 mm/yr. From 80 Ma to the present, the plume remained virtually fixed, leaving a track compatible with the movement of the Africa plate. Notably, the southward migration of the plume opposes the northward migration of the main Paraná magmatic phases (133 Ma in the south, and 132 Ma in the north).
- 3) Regional thermal anomalies in the deep mantle, which were mapped using geoid and seismic tomography data, offer an alternative, non-plume heat source for generating intracontinental magmatic provinces.
- 4) Both the "hotspot tracks" along the Walvis Ridge and Rio Grande Rise and the Vitória-Trindade chain might reflect the release of lithospheric stresses during rifting rather than a continuous activity induced by mantle plumes beneath the moving lithosphere plates.

Paleomagnetic constraints necessarily provide paleogeographic reconstructions with a more realistic presumed position for the Tristan da Cunha (TC) plume in relation to the Paraná flood basalts and surrounding alkaline rocks. The available paleomagnetic data (Ernesto *et al.* 1996, 1999, 2002; Ernesto 2005) derived from igneous rocks in the PMP are sufficient to delineate the apparent Mesozoic polar wandering in the South America plate and indicate that this continent rotated in a clockwise direction from the Late Jurassic to Early Cretaceous with a slight north-south movement. In contrast, Gibson *et al.* (2006) suggested a northwest displacement based on the concept of anchored mantle plume. They supported their position with the work by O'Connor and Duncan (1990), which assumes the hotspot formed a fixed frame. Therefore, no independent evidence was presented, and the lithosphere path designed to match the Rio Grande Rise-Walvis Ridge hotspot tracks is questioned by various authors based on geodynamics (*e.g.* Ernesto *et al.* 2002 and therein references). However, according to Gibson *et al.* (2006), the plate velocity required to move the TC plume between two consecutive positions (at 139 and 133 Ma, respectively) is nearly three times the 3.5 cm per year estimated by O'Connor and Duncan (1990).

## CONCLUDING REMARKS

Based on the combined geochemical and geophysical results using new radiometric ages for magmatic events in Eastern Paraguay, Comin-Chiaramonti *et al.* (2007c) concluded that any evolutionary model describing the PAE system in terms of HIMU and EM end-members must adhere to the following constraints: a) HIMU and EMI-II are not restricted to oceanic environments; b) end-members are associated in space as a function of the various protoliths; c) mantle regions with HIMU and EMI isotopic characteristics are capable of generating melts that can form a wide variety of silicate rocks, including melts enriched in $CO_2$; d) Paraguayan sodic alkaline rocks appear to be grouped in better defined fields relative to the potassic varieties. However, tend to occupy the same fields as potassic alkaline-carbonatite rocks in Angola-Namibia.

Ernesto *et al.* (2002) emphasized that any hypotheses involving mantle plume activity (TC plume) at the margin of the Paraná Basin are constrained by the distinct lithospheric mantle characteristics and paleomagnetic results. Therefore, alternative thermal sources may be present in the mantle without a transfer of materials from the core or lower mantle to the lithosphere.

Both the geochemistry and Sr-Nd-Pb isotope system point to a lithospheric mantle enriched in incompatible elements by metasomatic processes as the origin of the Paraguayan alkaline rocks. Significant amounts of $H_2O$, $CO_2$ and F were also expected in the mantle source based on the occurrence of related carbonatites. The Nd ages suggest these events occurred during Meso- and/or Neoproterozoic times (2.0 – 1.4 and 1.0 – 0.5 Ga, respectively, according to Comin-Chiaramonti *et al.* 1997) and may be regarded as precursors to both alkaline and tholeiitic magmas in Eastern Paraguay (Velázquez *et al.* 2006).

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