A synthesis on the alkaline magmatism of Eastern Paraguay

Uma síntese sobre o magmatismo alcalino do Paraguai Oriental

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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 238U/204Pb or 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 grábenos 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-toléiítos. Isótopos de Sr-Nd-Pb sugerem que dois componentes man-têlicos 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 suites 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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INVITED REVIEW

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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 (Caacupé 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 activity in the Brazilian Platform.

TECTORIC 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 (Usami 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 genetic relationship between the convergence in southwestern Gondwana and the Alto Paraguai 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 Porá 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 nepheline 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
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 Arribus (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 geo-chronological 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-mi, close to the mouth of the Apa river in the northern sector (Comin-Chiaramonti et al. 1999), and carbonatic 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 Sapucaí 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 miniplat eau 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 alkali 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 miniplat eau ages) for the Asunción rocks.

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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...
Ultramafic lavas with mantle xenoliths

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 Chiriguélo and Cerro Sarambi 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 southeastern 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 Chiriguélo and Cerro Sarambi, 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 Sarambi 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 Chiriguélo 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-mi; (C) Amambay, 15. Cerro Chiriguelo; 16. Arroyo Gasory; 17. Cerro Sarambi; 18. Cerro Apua; 21. Cerro Guazu (Cerro Teyu 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 Capituindy; (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-Chiaramonti 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 occurrences 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. 1999b). The rocks are grouped into two distinct sets, one from basanites to phonolites and the other from alkali basalt 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-melane-ephelinites 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 ankara-phonolites 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 K2O and Na2O 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 Boggiaini).

Potassic and sodic rocks fields for the ASU alkaline rocks are easily distinguished in the R1-R2 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 primitive mantle normalized diagrams (Comin-Chiaramonti et al. 1996a). The R1-R2 diagram also allows the recognition of two suites of potassic rocks that conform the general trends of basanite to phonolite (B-P) and alkali 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 a large iron lithophile element enrichment and high field strength element 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 87Sr/86Sr (Sr) and 143Nd/144Nd (Nd) ratios range from the depleted to the enriched quadrant with both pre- and post-tholeiites potassic rocks having the highest initial Sr and lowest Nd, Carbonatites (Cerro Chiriguelo and Cerro Sarambi), 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.
pre-tholeiitic potassic rocks in northeastern Paraguay also have high Sr values (Fig. 6). The Sr and Nd content of silicate and carbonate 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 = 0.70350-0.70570, Nd = 0.51207-0.5123; Misiones: ca. 118 Ma, Sr = 0.70435-0.70524, Nd = 0.51225-0.51242; Asunción: ca. 60 Ma, Sr = 0.70362-0.70392, Nd = 0.51259-0.51277, cf. Comin-Chiaramonti et al. 1997; Antonini et al. 2005), which approach those of the Cretaceous low-Ti tholeiites in southern Paraná (Hauri 1997), whereas the composition of the Tertiary sodic rocks (206Pb/204Pb = 18.964, 207Pb/204Pb = 15.678, 208Pb/204Pb = 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 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 87Sr/86Sr (Sr) versus 143Nd/144Nd (Nd) 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 238U/204Pb ou high U/Pb and enriched mantle 1 fields after Hart and Zindler (1989). Paraguay array after Comin-Chiaramonti et al. (1995a, 1995b).
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 $^{238}\text{U}/^{204}\text{Pb}$ ou high U/Pb and enriched mantle I are components from Hart and Zindler (1989).
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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 diachronic 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 rerecorded 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 caused by a counter-clockwise movement (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 theoleitites 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 volcano-rich mantle sources (hotspots) 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 Paranaiba, Ponta Grossa-Moçâmades 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 metamorphosed (hot 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 lithospheric 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 CO2; 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 H2O, CO2, 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 alkali and tholeiitic magmas in Eastern Paraguay (Vélázquez et al. 2006).
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