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EASTERN PARAGUAY: POST-PALEOZOIC MAGMATISM

Comin-Chiaramonti P.[1*], Gomes C. B. [2], Ernesto M. [3], Marzoli A. [4] and Riccomini C. [2]

[1] Earth Science Departement, Trieste University: Via Weiss 8. I-34127 Trieste, Italy.

[2] Instituto de Geociências, USP, Rua do Lago 562, CEP 05508-080, São Paulo-Brazil.

[3] Instituto de Astronomia, Geofísica e Ciências Atmósferica, USP, Rua do Matão 1226, CEP 05508-900, São Paulo-Brazil.

[4] Earth Science Departement, Padova University. Corso Garibaldi, 37. I-35137, Padova.

[*] Corresponding author; e-mail: comin@univ.trieste.it

ABSTRACT

Eastern Paraguay is at the westernmost part of the Paraná Basin and was the site of intense magmatic activity in the Mesozoic and Paleocene times. In the Anisian, Triassic, sodic alkaline magmatism occurred along the Paraguay River, at the boundaries between Brazil and the Chaco basin. During the Early Cretaceous, potassic alkaline magmatism pre- and postdates the Paraná flood tholeiites of the Serra Geral Formation. Further alkaline sodic magmatism occurred in Eastern Paraguay during late Early Cretaceous and Paleocene. Geological, petrological, mineralogical and geochemical results suggest that two main mantle components have been involved in the genesis of the Cretaceous to Tertiary magmatism in Eastern Paraguay: an extreme and heterogeneous EMI and a HIMU component. The EMI component dominated the Early Cretaceous potassic alkaline magmatism, whereas the HIMU was important in the late Early Cretaceous and Paleocene sodic magmatism. Different contributions of EMI and HIMU components could also explain the Sr-Nd-Pb isotopic heterogeneity of the Early Cretaceous flood tholeiites in Eastern Paraguay. In the light of these facts, the mantle plume/hotspot hypothesis for the origin of the alkaline lavas must be reviewed, at least regarding which plumes are most likely to have been active at the right place and right time when a specific province is considered. Moreover, the geochemical signatures of the magmatic rocks are distinct from those of the commonly advocated plume. For example, this is the case for Tristan da Cunha and the Paraná Magmatic Province but even for Trindade and the Walvis Ridge and Rio Grande Rise rocks, the alleged hotspot traces. In addition, the geochemical and Sr-Nd-Pb isotope data are different from those of Walvis Ridge basalts. All the geochemical data point to an origin of the Paraná Magmatic Province tholeiites in melting of heterogeneous lithospheric mantle reservoirs. Furthermore, the geochemical and isotope signatures of Walvis Ridge and Rio Grande basalts may be explained by detached continental lithospheric mantle left behind during the continental break-up processes. It is important to stress that the mantle heterogeneity involved in Paraná magmatism is not confined to the tholeiites, but also characterizes the Early and Late Cretaceous alkaline magmatism. Even the carbonatites have on the whole Sr-Nd-Pb isotope characteristics close to those of the related alkaline rocks and the spatially associated tholeiites, indicating similar mantle components in their genesis. Moreover, in order to explain the widespread distribution of South American Early Cretaceous tholeiitic and alkaline magmatism, it is not necessary to invoke an active role for an hypothetical mantle plume head. We support an "EDGE drive convection" model, where the rifting processes resulted in different lithospheric thickness beneath the edge of cratonic shields, inducing small-scale convection cells. The simplistic mantle plume model is unsatisfactory for explaining most continental flood basalts and recurrent intraplate magmatism: alternative thermal sources that do not involve material transfer from the lower mantle to the lithosphere explain the observations better. In addition to indications from geoid anomalies, the presence of long-lived thermal anomalies in the mantle has already been demonstrated by seismic velocity distribution models based on tomographic techniques using both *P*- and *S*-waves. On the whole, the geochemical results combined with $^{40}Ar/^{39}Ar$ ages for the magmatic events in Eastern Paraguay indicate that any model proposed for the evolution of the PAE in terms of HIMU and EM end-members must be consistent with the following constraints: (a) HIMU and EMI-II are not restricted to the oceanic environment; (b) end-members are variously associated in space as a function of the various protoliths; (c) mantle regions with HIMU and EMI isotope characteristics are capable of generating melts that can lead to the formation of a wide variety of silicate rocks, including melts enriched in CO_2; d) systematically the sodic alkaline rock-types are grouped together, in fields well distinct in comparison with the potassic alkaline

fields in Paraguay, but fitting the fields of potassic alkaline-carbonatite fields of the Angola-Namibia; e) even the Na-alkaline rock-types from the "Central Rift" of sub-Andean system fit the Triassic to Paleocene analogues from Eastern Paraguay. Finally, from the paleomagmetic results, it should be stressed that any mantle plume hypothesis is in disagrement with the fixed and mobile models.

INTRODUCTION

Eastern Paraguay represents the westernmost fringe of Early Cretaceous Paraná flood tholeiites (Serra Geral Formation, SGF). In addition it has been the site of alkaline magmatism since Triassic: sodic in the Anisian, late Early Cretaceous and Paleocene times, and potassic at the Early Cretaceous times, the latter both pre-dating and post-dating the tholeiitic flood magmatism of the Serra Geral Formation, SGF (Comin-Chiaramonti & Gomes, 1995, 2005; Comin-Chiaramonti et al., 1997, 1999).

These magmatic rocks, closely related in time and space, offer the opportunity to investigate the petrogenetic significance of the potassic and sodic continental alkaline magmatism and their relationships with the SGF basalts. Due to the high Sr and Nd concentrations of the alkaline rocks, it is reasonable to assume that their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ compositions have not been significantly affected by crustal contamination processes and, therefore, reflect the isotopic signature of the mantle source. This paper aims to discuss, through the review of the available data and new Pb isotopic data, the most important geochemical and isotopic features of the alkaline and tholeiitic magmatism of Eastern Paraguay in order to constrain the spatial and temporal evolution of the subcontinental mantle source(s). The geodynamic implications will be also discussed.

PARAGUAY GEOLOGY

Eastern Paraguay lies in an intercratonic region which includes the westernmost side of the Paraná Basin of Brazil. It is bounded by an anticlinal structure established since Early Paleozoic, the Asunción Arch, separating the Paraná Basin (East) from the Gran Chaco Basin (West) (Fig. 1; Almeida, 1983; Comin-Chiaramonti *et al.*, 1997).

The basement rocks are mainly Precambrian to Early Paleozoic granitic intrusions and high to low-grade metamorphic sediments, considered to be the northernmost occurrence of the Rio de la Plata craton and the southernmost tip of the Amazon craton (Fúlfaro, 1995), at the southern and northern region of Eastern Paraguay, respectively.

Eastern Paraguay was subjected to NE-SW-trending crustal extension during Late Mesozoic, probably related to the western Gondwana breakup. NW-SE fault trends, paralleling the dominant orientation of Mesozoic alkaline and tholeiitic dykes, reflect this type of structure (Comin-Chiaramonti *et al.*, 1992a; Riccomini *et al.*, 2001). The resulting structural pattern controlled the development of the grabens or semigrabens as a response to NE-SW-directed extension and continued evolving into Upper Tertiary times (Comin-Chiaramonti & Gomes, 1995; Comin-Chiaramonti *et al.*, 1999).

From the beginning of Mesozoic times, six main magmatic events have occurred in Eastern Paraguay (Fig. 1):

A. Sodic-alkaline Provinces

1) Alto Paraguay Province

Early Triassic sodic magmatism of the Alto Paraguay Province (Gomes *et al.*, 1995; Comin-Chiaramonti *et al.*, 2005), widespread at the southernmost side of the Amazon craton (Fúlfaro, 1996). This Province encompasses the alkaline centers located north and south of Porto Murtinho, at the boundary zone between the Paraguay and the state of Mato Grosso do Sul, Brazil (Fig. 1). These rocks are related to the oldest recognized alkaline magmatic event around the Paraná Basin, of Triassic age (241 Ma) (Amaral *et al.*, 1967; Velázquez *et al.*, 1992, 1996a; Comin-Chiaramonti et al., 2007). They consist mainly of nepheline syenites and syenites occurring as ring-like complexes and stocks, with fine-grained equivalents, such as lavas and dykes. Notably, in the northern area, near Fuerte Olimpo townships, some outcrops interpreted as alkaline complexes (Gibson et al., 2006), are rhyolites showing an age of 1341 ± 53 Ma (Gomes *et al.*, 2000).

Livieres & Quade (1987) related the magmatism of the Alto Paraguay Province to the Rio Apa Arch, whereas Velázquez *et al.* (1996a) to a cratonic margin. Because of the restricted area of occurrence, with bodies aligned in a narrow belt along the Paraguay river, and the presence of structural lineaments, Velázquez *et al.* (1998) pointed out the possibility of a control by N-S-trending faults. Taking into account that stresses related to the Cabo-La Ventana orogeny (Tankard *et al.*, 1995; Milani, 1997) have propagated to the inner parts of the Brazilian Platform in the general N-S-trending, it is here put forward the hypothesis of a genetical relationship between the convergence in southwestern Gondwana and the Permian-Triassic alkaline magmatism in the Alto Paraguay Province.

2) *Misiones Province*

The Misiones Province includes the sodic alkaline rocks of the region of San Juan Bautista in the southern part of Eastern Paraguay (Comin-Chiaramonti *et al.*, 1992b). It is related to a late Early Cre-taceous magmatic event, with Ar-Ar age-data of ca. 118 Ma (Velázquez *et al.*, 2003), and consists of small plugs and dykes of nephelinite, peralkaline phonolite and tephrite (Comin-Chiaramonti *et al.*, 1992b; Velázquez *et al.*, 2003; 2006). Magnetometric and gravimetric data indicate a conspicuous set of NW-SE-striking structural lineaments, over 150 km long, about 100 km south of the Asunción Rift (Velázquez *et al.*, 1998). This feature was considered as a result of crustal fracturing, being named as Santa Rosa Graben (DeGraff & Orué, 1984; DeGraff, 1985). Recent investigations confirmed that the alkaline bodies of this province are distributed and oriented along NW-SE structures, and were emplaced under a NE-trending extension (Velázquez *et al.*, 2002).

3) *Asunción Province*

The Asunción Province comprises the ultra-alkaline rocks of the western segment of the Asunción Rift in Eastern Paraguay. It marks an important tectono-magmatic activity during the Paleogene, with Ar-Ar ages ranging between 68 and 52 Ma, but with a clear predominance in the 58-56 Ma (Eocene) interval (Velázquez *et al.*, 1996b; Gomes *et al.*, 2003; Comin-Chiaramonti et al., 2007). Its rocks present a markedly sodic composition, mainly nephelinites and ankaratrites, bearing mantle nodules which range from dunites to lherzolites (Comin-Chiaramonti *et al.*, 1991, 2001). Isotopic ratios ($^{87}Sr/^{86}Sr$=0.70362-0.70392 and $^{143}Nd/^{144}Nd$=0.51225-051242; Comin-Chiaramonti *et al.*, 1991, 1995b, 1997) indicate a lithospheric mantle provenance for the ultra-alkaline magmatism of this region. The occurrences are related to NW-SE-striking magnetic lineaments and to a gravimetric low situated beneath the region of Asunción. This gravimetric low corresponds to a graben filled with fanglomeratic sediments containing nephelinite volcanic fragments and bombs (Riccomini *et al.*, 2002). Systematic studies of faults and fracture patterns of the Ñemby, Lambaré and Benjamin Aceval ultra-alkaline bodies and 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 the rift installation, at the Early Cretaceous. Cooling and fracturing of the nephelinitic and ankaratritic bodies in relatively restricted areas indicate that the activity of deep faults caused great energy loss in the asthenosphere, leading to subsequent melting of the lithospheric mantle by decompression during a relatively short-time interval (Riccomini *et al.*, 2001).

B. Potassic-alkaline Provinces

4) *Amambay Province*

In the Amambay Province, located in northeastern Paraguay, along the boundary with Brazil, the alkaline magmatic activity is represented by the ring-like complexes of Cerro Chiriguelo and Cerro Sarambí (both with occurrence of carbonatite facies). Pyroxenites, shonkinites, fenites and dykes of trachytes and phonolites also occur in the region (Comin-Chiaramonti et al., 1999). The ages of this alkaline magmatism range between 140 and 135 Ma (Velázquez *et al.*, 1996b), indicating the presence of a prior event with respect to the tholeiitic basaltic magmatism. Recent Ar-Ar ages fit 139 Ma, an age similar to that of the Velasco alkaline complexes in Bolivia (Comin-Chiaramonti & Gomes, 2005). The Amambay Province is located within the domain of the NE-SW-trending Ponta Porã Arch (Thomas & Associates, 1976) and between two outstanding depressions, one to NW and the other to SE of Pedro Juan Caballero, as indicated by the Bouguer anomaly map (Velázquez *et al.*, 1998; Vidotti *et al.*, 1998; Comin-Chiaramonti *et al.*, 1999). These depressions are probably sedimentary basins and the uplifted block of the Ponta Porã Arch hosts the alkaline intrusions of Cerro Chiriguelo and Cerro Sarambí. The tectonic control of alkaline intrusions of Amambay Province by the Ponta Porã Arch was originally proposed by Livieres & Quade (1987). The presence of magnetic anomalies with higher intensity at the southwestern end of the arch seems to support this hypothesis (Velázquez *et al.*, 1998).

5) Rio Apa Province

The magmatism in the Rio Apa Province is not expressive and consists only of small occurrences of alkaline rocks near Puerto Valle-mí and San Lázaro, at the margins of the Paraguay river, northern part of Eastern Paraguay. It includes thin dykes of carbonatitic basanite afilliation (Comin-Chiaramonti *et al.*, 1997) cutting Cambro-Ordovician limestones, along NE-SW-trending faults (Velázquez *et al.*, 1998). These faults were deep enough to allow the migration of primitive magmatic liquids from mantle to the surface across the entire block of Neoproterozoic carbonatic rocks (Velázquez *et al.*, 1998). As in the Amambay Province, the ages around 139 Ma (Velázquez *et al.* 1996b) show that this magmatic event preceded the tholeiitic magmatism of the Alto Paraná Formation, indicating an older Early Cretaceous magmatic pulse around the Paraná Basin.

6) Central Paraguay Province

The Central Paraguay Province encompasses the occurrences of alkaline rocks related to the evolution of the central and eastern portions of the Asunción Rift (DeGraff, 1985), installed in the Early Cretaceous. This tectonic depression (Fig. 2), a striking feature either in magnetometric or gravimetric maps (Velázquez *et al.*, 1998; Comin-Chiaramonti *et al.*, 1999), is about 200 km long and has a variable width between 25 and 40 km. It is composed of three well-defined segments: the western segment, NW-SE oriented, between Benjamin Aceval (north of Asunción) and Paraguarí, with a length of about 90 km; the central segment, E-W oriented, from Paraguarí to Villarrica, with around 70 km in length; and the less well-defined eastern segment, NW-SE oriented, from Villarrica to the region of the Ybytyruzú

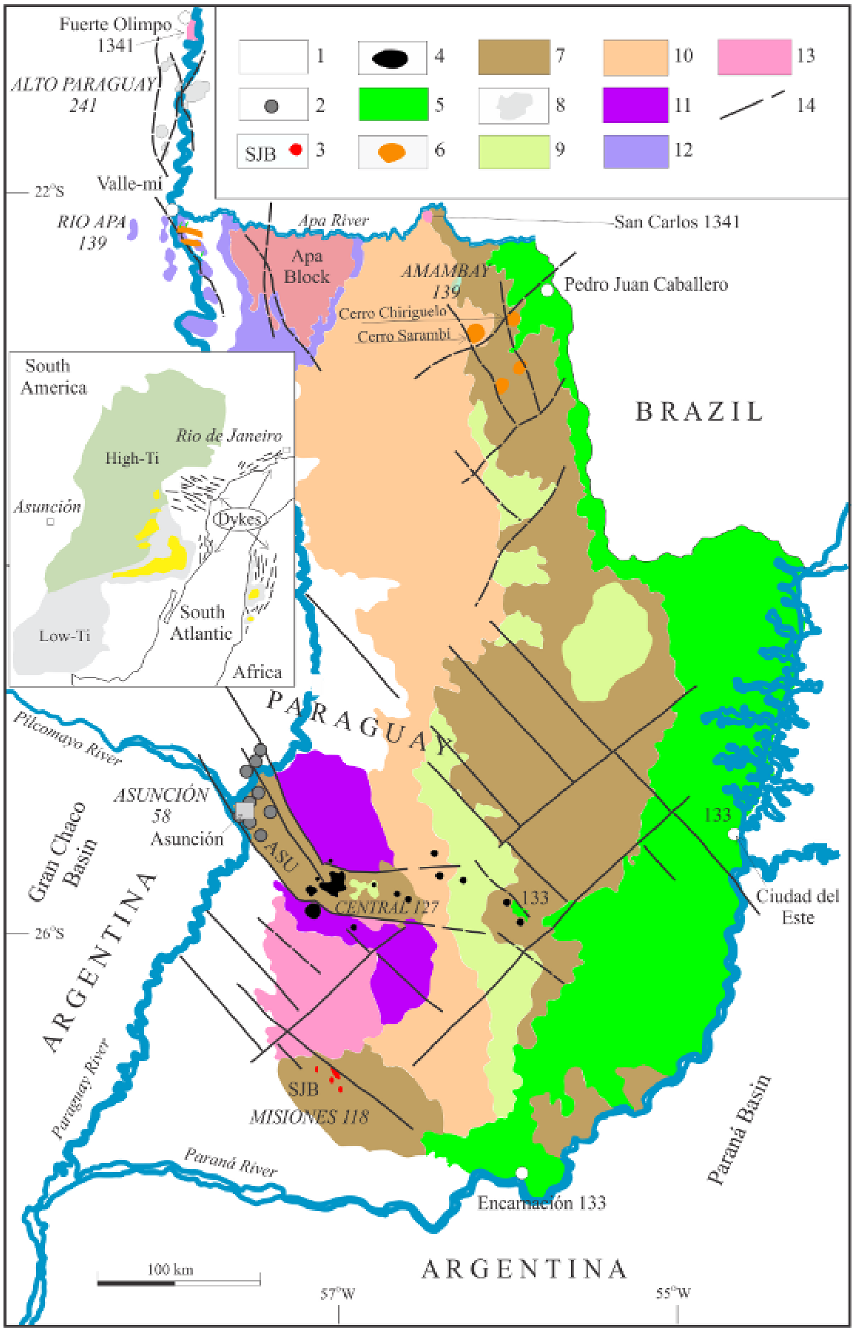

Figure 1: *Geological map of the Eastern Paraguay (after Comin-Chiaramonti, 1997; 1999) showing the main alkaline provinces in Eastern Paraguay. 1: Neogene and Paleogene sedimentary cover (Gran Chaco; Argentina, Partim; Eastern Paraguay); 2: Paleogene sodic alkaline rocks,* ***Asunción Province****; 3: Late Early Cretaceous sodic alkaline rocks (****Misiones Province****, San Juan Bautista, SJB); 4: Early Cretaceous potassic alkaline rocks (post-tholeiites; ASU: Asunción-Sapucai-Villarica graben,* ***Central Province****); 5: Early Cretaceous tholeiites of the Paraná Basin; 6: Early Cretaceous potassic 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 Neo-Proterozoic crystalline basement: high- to low-grade metasedimentary rocks, metarhyolites and granitic intrusions; 14: major tectonic lineaments and faults. 133 (Ma) are referred to* $^{40}Ar/^{39}Ar$ *plateau ages for the tholeiitic magmatism (Renne et al., 1992, 1993. 1996).* ***Inset****: sketch map of the Paraná-Angola-Etendeka system (cf. Piccirillo & Melfi, 1988), where the arrows indicate the occurrences of the main dyke-swarms. The basaltic lavas are subdivided into broad high- and low-Ti groups, and late-stage rhyolites (yellow fields).*

mountains, with an approximate length of 40 km. The study of dyke swarms, faults and joints allowed Velázquez *et al.* (1998) to conclude that the rift was generated under a right-lateral wrenching tectonic regime, associated with an E-W-trending oriented binary. The Ar-Ar ages of alkaline rocks of the Central Paraguay Province range between 126 and 128 Ma (Gomes *et al.* 2003; Comin-Chiaramonti et al., 2007), characterizing an Early Cretaceous magmatic pulse, younger than the tholeiitic magmatism of Alto Paraná Formation (Serra Geral Formation in Brazil). The alkaline bodies occur as stocks, plugs, lavas and specially dykes and dyke swarms (Gomes *et al.*, 1989; Comin-Chiaramonti *et al.*, 1992a,b, 1995a,b) and also includes the great, ring-like intrusion of Cerro Acahay (Comin-Chiaramonti *et al.*, 1990; Velázquez *et al.* 1992). The province consists of highly potassic rocks with a wide petrographic diversity (Velázquez, 1992; Comin-Chiaramonti *et al.,* 1997). These rocks are grouped in two distinct sets, one with basanites to phonolites and other with alkaline basalts to trachytes, both including its corresponding intrusive terms (Comin-Chiaramonti *et al.*, 1993, 1996; Gomes *et al.*, 1996b). In addition, a small occurrence of carbonatite rock has been identified in the surroundings of the locality of Sapucai (Comin-Chiaramonti *et al.*, 1992c).

Notably, on the basis of Drueker and Gay's (1987) interpretation for some NW-trending aeromagnetic anomalies detected in the Eastern Paraguay, some authors (e.g. Gibson et al., 2006) represent a giant mafic dyke swarm, located mainly in the northwestern part of the area. We have been intensively working in the country since 1982 and up to now we did not find any field evidence of the presumed dyke swarm. Thus, it is quite possible that most magnetic anomalies correspond to Precambrian tectonic lineaments at it has been shown by Comin-Chiaramonti et al. (1999).

Resuming, at the westernmost side of the Paraná-Angola-Etendeka system, the Eastern Paraguay represents a region in and around the Paraná basin where six main magmatic events have occurred in a relatively restricted area (i.e. less than 120,000 km^2; cf. Fig. 1) from the end of the Paleozoic to the Cenozoic, as shown by geological evidences and by previous regional and geochronological studies (cf. Comin-Chiaramonti & Gomes 1995, 2005; Comin-Chiaramonti *et al.*, 1992a, 1997, 1999, 2007; Velázquez *et al.*, 2006 and references therein):

1) Permo-Triassic sodic magmatism of the **Alto Paraguay Province** (241 Ma), widespread at the southernmost side of the Amazon Craton.

2) Potassic alkaline-carbonatitic complexes and dykes from North Eastern Paraguay, from the **Rio Apa** (139 Ma) and **Amambay Provinces**, which predates the tholeiitic flood basalts (Paraná, **Serra Geral Formation**, **SGF**).

3) The Paraná **SGF** flood tholeiites and dykes (133 ± 1 Ma according to Renne *et al.* (1992, 1993, 1996); 137-127 Ma, according to Turner *et al.* (1994), Stewart *et al.* (1996) and Peate et al. (1999), both represented by high-Ti and low-Ti basalts and andesi basalts (cf. Bellieni *et al.*, 1986; Piccirillo & Melfi, 1988).

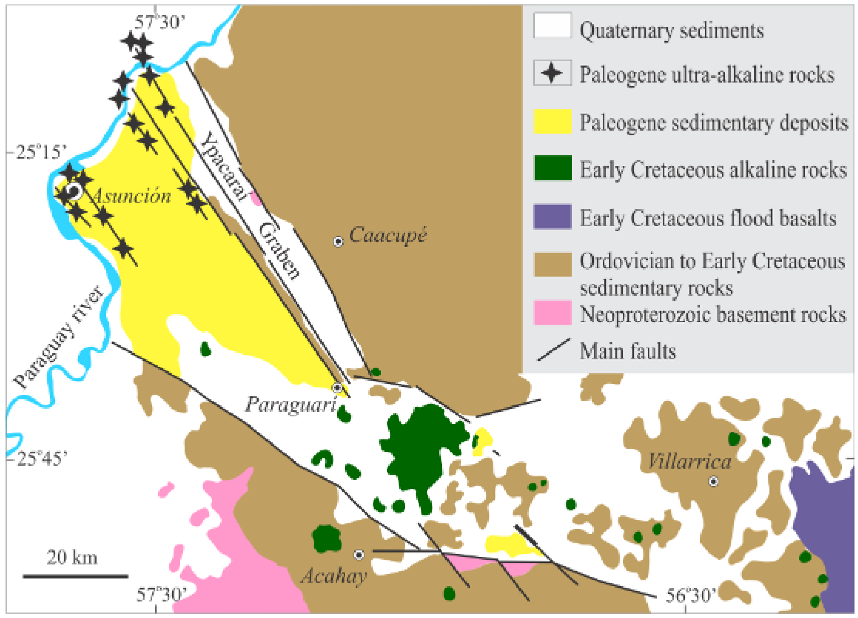

Figure 2: *Geologic map of the Asunción-Sapucai-Villarrica Rift with location of Early Cretaceous (Central Paraguay Province) and Paleogene (Asunción Province) alkaline rock occurrences (after Velázquez et al., 1998, modified).*

4) Potassic alkaline complexes and dykes (129-126 Ma) with subordinate silico-carbonatite flows and dykes, widespread mainly in the Asunción-Sapucai-Villarrica graben, **Central potassic Province**. A lot of sodic alkaline dykes is also present, cutting the potassic analogues: $^{39}Ar/^{40}Ar$ data (whole rock, unpublished data) indicate a probable age around 119-120 Ma, similar to that of the sodic alkaline rocks from Misiones Province.

5) Sodic alkaline complexes, plugs and dykes (118 Ma), occurring mainly at the **Misiones Province** (San Juan Bautista Region), southwestern Paraguay (Velazquez *et al.*, 2006, and therein refences).

6) Paleogene sodic alkaline complexes, plugs and dykes (61-56 Ma) cropping out at the western side of the Asunción-Sapucai-Villarrica graben (**Asunción Province**; cf. Comin-Chiaramonti *et al.*, 1991).

PETROCHEMISTRY AND NOMENCLATURE

Alkaline rocks may be distinguished into sodic or potassic. Conventionally, potassic rocks are those in which K_2O (wt %) exceeds Na_2O (wt %). However, Le Maitre and IUGS (1989) suggested to apply the terms "sodic" and "potassic" to rocks with (Na_2O - 2) ≥ K_2O and (Na_2O - 2) ≤ K_2O, respectively. Middlemost (1986) proposed $0.5<K_2O/Na_2O<2$ and >2 for "potassic" and "high-potassic" groups, respectively, at $SiO_2 \leq 53.5$ wt %.

The chemical screens adopted (Comin-Chiaramonti & Gomes, 1995; Comin-Chiaramonti *et al.*, 1997) are:

1) $Na_2O - 2 \geq K_2O$: sodic (N);

2) $Na_2O - 2 < K_2O$ to $K_2O/Na_2O \leq 1$: transitional (tK);

3) $1 < K_2O/Na_2O \leq 2$: potassic (K);

4) $K_2O/Na_2O > 2$: highly potassic (HK).

Notably, the petrochemical classification is consistent with the mineral chemistry of Comin-Chiaramonti *et al.*, 1990, 1992a; Cundari *et al.*, 1995).

Asunción-Sapucai-Villarrica (ASU) graben

A total of 523 of specimens (intrusives, effusives and dykes), from ASU (Comin-Chiaramonti 6 Gomes, 1995), analyzed for the field, age, petrography, mineral chemistry and petrochemistry, were classified following the above criteria and following nomenclature after de La Roche (1980) adopting the chemical classification after Le Maitre (1986). 18% of the analized specimens from ASU are N, 18% tK, 57% K and

7% HK. (cf. Fig. 3). The combined (intrusive+effusive) rock-types gave 19% N, 14% tK, 59% K, 8% HK. Likewise, for dykes: 17% N, 22%tK, 55% K, 6% HK (Comin-Chiaramonti & Gomes, 1995).

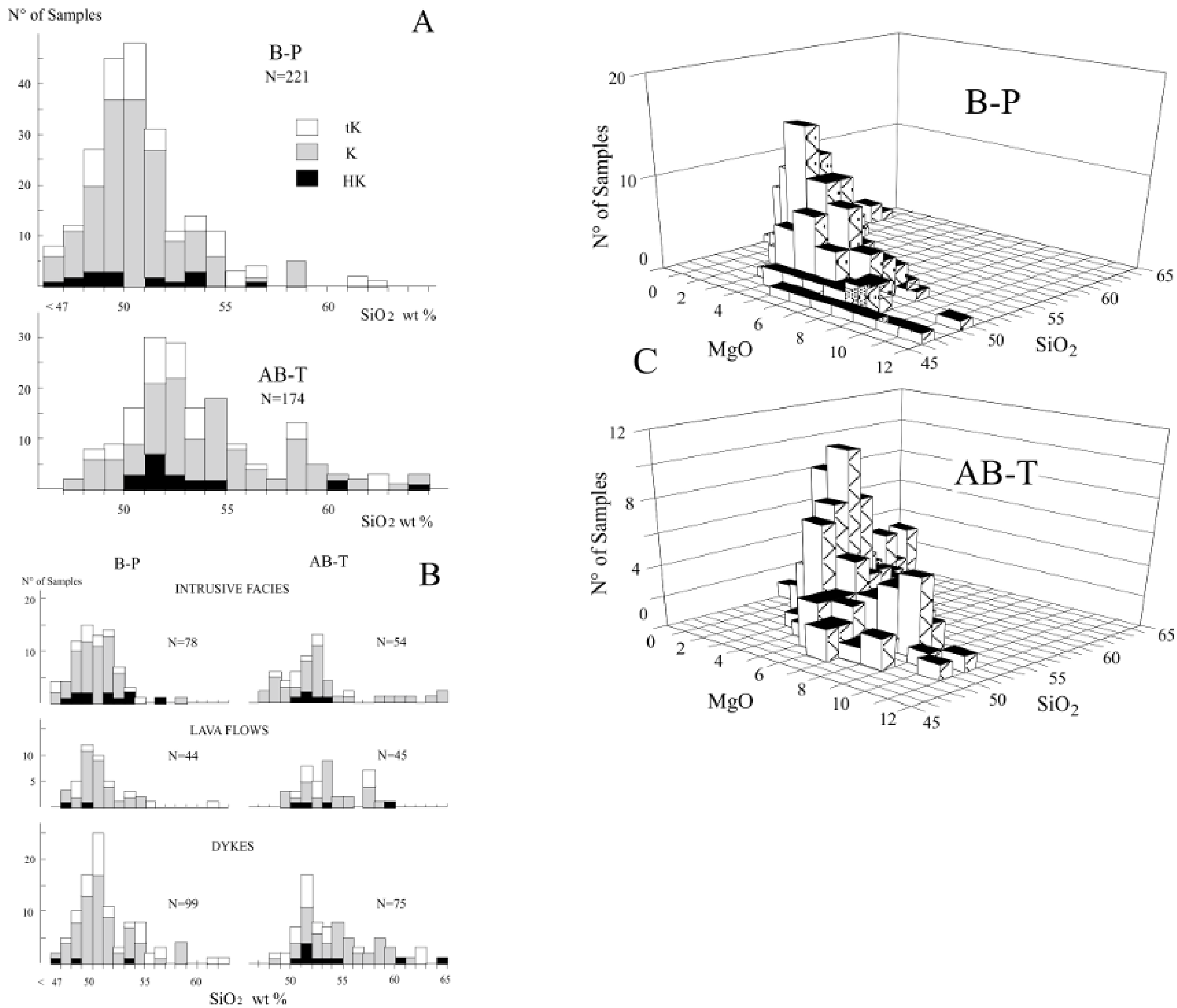

Figure 3: *Alkaline potassic specimens. A. SiO_2 (wt%) histograms for basanite / tephrite / phonotephrite / phonolite (B-P) and alkali basalt / trachybasalt / trachyandesite / trachyte (AB-T) suites, HK: $K_2O \geq 2$, K: $2 < K_2O/Na_2O < 1$, tK: $K_2O/Na_2O < 1$. B. Histograms subdivided into intrusives, lavas and dykes. C. 3D histograms showing frequency distribution for SiO_2 vs MgO, wt% for the B-P and AB-T suite, respectively. Data source: Comin-Chiaramonti & Gomes, 1995.*

Potassic rocks

The potassic magmatic rocks are rare in the **Amambay** and in the **Apa Provinces**. In the former they are rapresented mainly by evolved rock-types as trachytes associated with glimmeritic dykes and carbonatitic bodies (Chiriguelo and Sarambí; Censi *et al.*, 1989; Castorina *et al.*, 1997). Notably, the Chiriguelo complex is partially covered by tholeiitic flood basalts of the Paraná Basin (Censi *et al.*, 1989; Cundari *et al.*, 1995). In the Apa province, scarce basanitic dykes are present (Castorina *et al.*, 1997; Comin-Chiaramonti *et al.*, 1999). The potassic rocks, concentrated mainly in the **Central Province** of ASU**,** are represented by two main suites, i.e. basanite-tephrite-phonotephrite-phonolite (**B-P**) and alkali basalt-trachybasalt-trachyandesite-trachyphonolite/trachyte (**AB-T**), respectively: The results are diagrammatically represented in Fig. 4 (cf. Figs. 4, 5, 6 and 11 of Comin-Chiaramonti *et al.*, 1995a and Figs 1, 2, 3 of Comin-Chiaramonti *et al.*, 1995b). Some of these potassic rocks intrude the flood tholeiites of the Paranà Basin (Bellieni *et al.*, 1986).

Sodic rocks

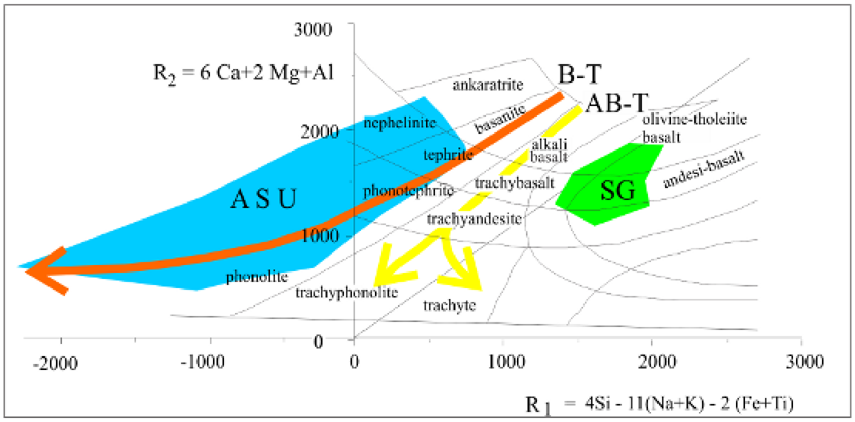

Figure 4: *R_1- R_2 plot, in terms of de la Roche's 81980) diagram (cf. Comin-Chiaramonti & Gomes, 1995; Comin-Chiaramonti et al., 1997). R_1 = 4Si - 11 (Na+K) - 2 (Fe+Ti), R_2 = 6Ca + 2Mg + Al, with the fields of the tholeiitic (SG) and alkaline (sodic) rocks (ASU) from Eastern Paraguay and the general trends of the **B-P** and **AB-T** potassic suites (nomenclature of lavas only is shown). Data sources: (Bellieni et al., 1986; Piccrillo & Melfi, 1988; De Marchi et al., 1988; Comin-Chiaramonti et al., 1991, 1992, 1995a, b, 1997; Cundari et al., 1995; Comin-Chiaramonti & Gomes, 1995). Note that textural, mineralogical and petrochemical evidence points to fractional crystallization as potentially important in the evolution of the ASU (**Central Province**) suites. The variable rock textures, the widespread occurrence of megacrysts/xenocrysts and the compositional scatter prompted a detailed investigation of this process to test its viability:*

*Fractionation models based on major oxides (Comin-Chiaramonti et al., 1995b, 1997) yielded SR^2 < 2wt% of early-formed phases, i.e. olivine + clinopyroxene + magnetite ± plagioclase ± mica ± leucite ± apatite (Table 3 of Comin-Chiaramonti et al., 1997). Assuming a mean basanite composition (mg# = 0.65; Cr =399, Ni = 140 ppm) as parental magma to the **B-P suite**, 16-21 wt% fractionation of the above phases yielded a mean tephrite (mg# = 0.57); 28 wt% fractionation from the latter a mean phonotephrite (mg# = 0.51), and 58 wt% a mean phonolite (mg# = 0.37). The corresponding Rayleigh's trace element fractionation yielded observed/calculated ratios within the range 0.8-1.4, Ni and Ba in phonolite excepted. Likewise for the **AB-T suite**, 20 wt% fractionation of the above phases from a mean parental alkali basalt (mg# = 0.66) yielded a mean trachybasalt (mg# = 0.59); 22-25 wt% fractionation from the latter a mean trachyandesite (mg# = 0.50) and 27-33 wt% fractionation a mean trachyphonolite (mg# = 0.36). The best fit for a mean trachyte (mg# = 0.39) was obtained by 57 wt% fractionation from trachyandesite. Trace elements modelling yielded observed/calculated ratios = 0.8-1.2, except for Ni, Ba, Zr and Nb in the more evolved compositions. This may be attributed to a combination of factors, including variation in crystal/liquid distribution coefficients, crystal-liquid disequilibria and the influence of processes other than crystal fractionation. Olivine-liquid equilibria often failed to satisfy the $mg\#_{ol\text{-}liq}$ relationships predicted by Roeder & Emslie (1970; see also mineral chemistry, Fig. 7A of Comin-Chiaramonti et al., 1997) and suggest that olivine accumulation (mg# Ol > $mg\#_{liq}$), olivine fractionation ($mg\#liq_1$>mg#Ol>$mg\#liq_2$) and magma mixing ($mg\#Ol_1$> mg#liq>$mg\#Ol_2$) may have been important in ASU.*

In an attempt to evaluate the role of fractionation in the B-P and AB-T suites, the variation of Th, Zr, Ni and Cr in the basanite to tephrite and alkali basalt to trachybasalt transitions, respectively, were investigated by means of a model elemental distribution, predicted for open-system fractionation in a periodically replenished magma reservoir, PRF (cf. O'Hara & Mathews, 1981). Convergence of X and Y values was obtained (Fig. 16 of Comin-Chiaramonti et al., 1995b), particularly for B-P (Comin-Chiaramonti et al., 1995a,b,c). Similar results were obtained for the proposed tephrite to phonotephrite and trachybasalt to trachyandesite transitions, respectively. The general tendency for X+Y values to approach unity suggests that the PRF model is roughly equivalent to a succession of closed-system fractionation events. The phonotephrite to phonolite and trachyandesite to trachyte model fractionation, respectively, yielded negative values for Cr and Ni. Therefore, the extreme rock compositions are inconsistent with Rayleigh-type fractionation processes, probably reflecting, at least in part, their distinct fO_2 and its influence on partition coefficients.

Other than in the **Alto Paraguay Province**, they are concentrated mainly in the **Asunción Province** and represented by ankaratrites+nephelinites (45%) and phonolites (42%). Very subordinate, and widespread in the **Central Province** are tephrites, alkali basalts, hawaiites and mugearites (cf. Fig. 4). Mantle xenoliths are abundant in the ankaratrite and nephelinites of the Asunción Province. They are spinel lherzolites, hartzburgites and dunites up to 45 cm in diameter with protogranular texture and variably amounts of glassy pathes, similar to the "blebs" of Maaløe & Prinzlau (1979). These mantle xenoliths, indicative of a depleted, variously metasomatized mantle, were described in detail elsewhere (Comin-Chiaramonti *et al.*, 1986, 1991, 2001; DeMarchi *et al.*, 1988; see also later).

In the **Misiones Province**, four localities are characterized by sodic alkaline rocks (Velázquez *et al.*, 2006): Estancia Guavirá-y (ankaratrites and melanephelinites carrying mantle xenolith and clinopyroxene megacrysts), Estancia Ramirez (tephrites), Cerro Guayacán (basanites) and Cerro Caá Jhovy (peralkaline phonolites). The compositional variations are reported in Fig. 5 and compared with the alogues from Asunción Province.

AGE DETERMINATION

A summary of old available radiometric age determination is reported in Table 1. Here the mean results of recent measures are reported: over a lot of 76 "high quality" Ar-Ar ages, only 33 samples have been considered as representative of the ages of the post-Paleozoic various magmatic events in Eastern Paraguay (s. Comin-Chiaramonti *et al.*, 2007, for a discussion). The following results are apparent:

1. **Alto Paraguay Province**: 241 ± 1 Ma

2. **Apa Province**: 138.9 ± 0.2

3. **Amambay Province**: 138.5 ± 0.8

4. **Central Province**: 126.8 ± 1.3

5. **Misiones Province**: 118.3 ± 0.9

6. **Asunción Province**: 58.4 ± 2.1

Notably an age of 133±1 Ma was assumed for the **Serra Geral flood tholeiites** from Paraguary (cf. Fig. 1), based on the "high quality" Ar-Ar ages from the "very fresh" (not altered) samples following Renne *et al.* (1992, 1993, 1996).

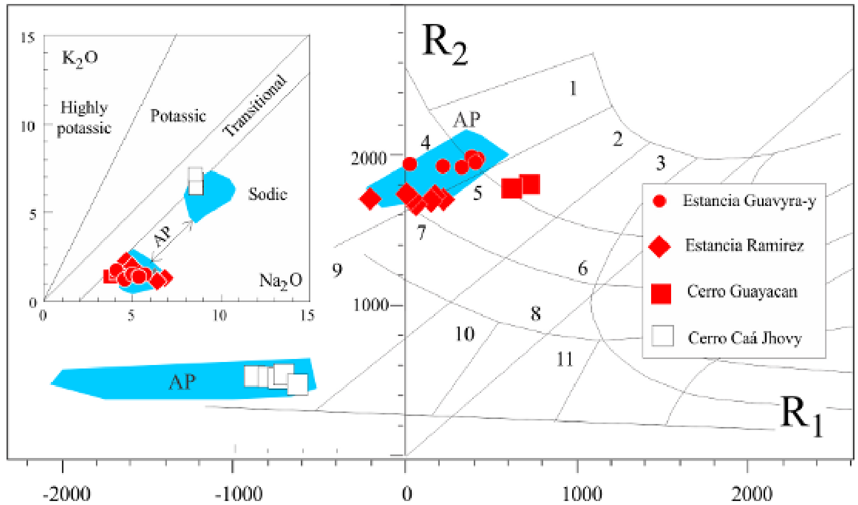

Figure 5: *Compositional variation for the Misiones rocks in terms of de la Roche's diagram (1980); cf. Fig. 4.* ***Inset****: Na_2O vs K_2O (wt%) diagram. The fields from Asunción Province are also represented (AP). Data sources (Velázquez et al., 2006 and therein references).*

Table 1: *Previous radiometric ages for magmatic rocks from Alto Paraguay and Eastern Paraguay. Abbreviations: WR, whole rock; Am, amphibole; Bi, biotite; FC, felsic concentrates; AF, alkali feldspar; Tit, titanite; Ap, apatite. Data source: 1. Velazquez et al., 1996b; 2. Gomes et al., 1995; 3. Comte & Hasui, 1971; 4. Amaral et al., 1967; 5. Gibson et al., 1995a; 6. Eby & Mariano, 1992; 6a. Sonoki & Garda, 1988; 7. Bitschene, 1987; 8. Velazquez et al., 1992; 9. Palmieri & Arribas, 1975; 10. Comin-Chiaramonti et al., 1997.*

REGION/LOCALITY	Occurrence	Rock-type	Material	Method	Age(Ma)	Re.
ALTO PARAGUAY:						
Sodic magmatism						
Cerro Siete Cabezas	Stock	Nepheline syenite	Am	K/Ar	227.9±7.8	1
Cerro Siete Cabezas	Stock	Nepheline syenite	Bi	K/Ar	249.0±3.0	1
Cerro Siete Cabezas	Stock	Syenite	Am	K/Ar	229.8±8.3	1
Cerro Siete Cabezas	Stock	Syenite	Bi	K/Ar	244.4±10.4	1
Cerro Siete Cabezas	Stock	Syenite - Quartz syenite	AF - WR	Rb/Sr erorchron	255±11	1
Cerro Siete Cabezas	Stock	Nepheline syenite	Am	Ar/Ar	236.0±1.6	2
Cerrito	Stock	Nepheline syenite	Bi	K/Ar	253.2± 9.2	1
Fecho dos Morros	Stock	Nepheline syenite	Am	K/Ar	212.8±14.8	1
Pão de Açucar	Stock	Nepheline syenite	Am	K/Ar	233.2±7.2	1
Pão de Açucar	Stock	Nepheline syenite	Bi	K/Ar	248.3±5.3	1
Pão de Açucar	Lava flow	Phonolite	WR	K/Ar	219.1±13.3	3
Pão de Açucar	Lava flow	Trachyphonolite	Bi	Ar/Ar	242± 1.6	2
Pão de Açucar	Stock	Nepheline syenite	Bi	K/Ar	244.6	4
Pão de Açucar	Stock	Nepheline syenite	Bi	K/Ar	241.7	4
Pão de Açucar	Stock	Nepheline syenite	AF	K/Ar	211.3	4

Pão de Açucar	*Stock*	*Nepheline syenite*	*Am*	*K/Ar*	*209.6*	*4*
Cerro Boggiani	*Stock*	*Nephelinic syenite*	*Am*	*K/Ar*	*234.6±13.7*	*1*
Cerro Boggiani	*Stock*	*Nepheline syenite*	*Am*	*K/Ar*	*234.0±9.0*	*1*
Cerro Boggiani	*Lava flow*	*Peralkaline phonolite*	*WR*	*K/Ar*	*236.7±10.9*	*1*
Cerro Boggiani, *Fecho dos Morros, Cerrito*		*Nepheline syenite* *Nepheline syenite, Peralkaline phonolite*	*WR, Bi, Am, AF*	*Rb/Sr*	*255±11*	*1*
RIO APA: Potassic magmatism						
Valle-mì	*Dyke*	*Basanite*	*WR*	*K/Ar*	*142±2*	*5*
AMAMBAY						
Cerro Chiriguelo	*Stock*	*Ca-carbonatite*	*Bi*	*K/Ar*	*128±5*	*6*
Cerro Chiriguelo	*Lava flow*	*Trachyte*	*Bi*	*K/Ar*	*146.7±9.2*	*6a*
Cerro Chiriguelo	*Lava flow*	*Trachyte*	*WR*	*K/Ar*	*138.9±9.2*	*6a*
Cerro Sarambi	*Dyke*	*Syenite*	*WR*	*K/Ar*	*140±1*	*5*
Arroyo Gasory	*Dyke*	*Trachyte*	*Tit*	*Fission-track*	*137±7*	*6*
Arroyo Gasory	*Dyke*	*Trachyte*	*Ap*	*Fission-track*	*145±8*	*6*
CENTRAL PROVINCES (ASU): *Potassic magmatism*						
Cerro Km 23	*Stock*	*Theralite*	*Bi*	*K/Ar*	*131.9±5.0*	*7*
Cerro Km 23	*Dyke*	*Basanite*	*WR*	*K/Ar*	*115.8±4.2*	*7*
Ybytyruzù (Cerro Acatí)	*Lava flow*	*Trachyphonolite*	*Bi*	*K/Ar*	*125.9±4.6*	*7*
Ybytyruzù (Cerro Boni)	*Lava flow*	*Latite*	*Bi*	*K/Ar*	*124.6±4.2*	*7*
Ybytyruzù (Cerro Itatí)	*Lava flow*	*Phonotephrite*	*Bi*	*K/Ar*	*128.8±4.6*	*7*
Mbocayaty	*Stock*	*Nepheline syenodiorite*	*AF*	*K/Ar*	*130.0±3.4*	*8*
Mbocayaty	*Stock*	*Nepheline syenodiorite*	*Bi*	*K/Ar*	*129.2± 6.8*	*8*
Mbocayaty	*Stock*	*Essexite*	*Bi*	*K/Ar*	*128.2±4.5*	*7*
Mbocayaty	*Stock*	*Essexite, Nedpheline syenodiorite*	*WR, Bi, AF*	*Rb/Sr isochron*	*126.5±7.6*	*8*
CENTRAL PROVINCES (ASU): *Potassic magmatism*						
Cerro Km 23	*Stock*	*Theralite*	*Bi*	*K/Ar*	*131.9±5.0*	*7*
Cerro Km 23	*Dyke*	*Basanite*	*WR*	*K/Ar*	*115.8±4.2*	*7*
Ybytyruzù (Cerro Acatí)	*Lava flow*	*Trachyphonolite*	*Bi*	*K/Ar*	*125.9±4.6*	*7*

Ybytyruzù (Cerro Boni)	*Lava flow*	*Latite*	*Bi*	*K/Ar*	*124.6±4.2*	*7*
Ybytyruzù (Cerro Itatí)	*Lava flow*	*Phonotephrite*	*Bi*	*K/Ar*	*128.8±4.6*	*7*
Mbocayaty	*Stock*	*Nepheline syenodiorite*	*AF*	*K/Ar*	*130.0±3.4*	*8*
Mbocayaty	*Stock*	*Nepheline syenodiorite*	*Bi*	*K/Ar*	*129.2± 6.8*	*8*
Mbocayaty	*Stock*	*Essexite*	*Bi*	*K/Ar*	*128.2±4.5*	*7*
Mbocayaty	*Stock*	*Essexite, Nedpheline syenodiorite*	*WR, Bi, AF*	*Rb/Sr isochron*	*126.5±7.6*	*8*
Cerro Km 23	*Stock*	*Theralite*	*Bi*	*K/Ar*	*131.9±5.0*	*7*
Cerro Km 23	*Dyke*	*Basanite*	*WR*	*K/Ar*	*115.8±4.2*	*7*
Ybytyruzù (Cerro Acatí)	*Lava flow*	*Trachyphonolite*	*Bi*	*K/Ar*	*125.9±4.6*	*7*
Ybytyruzù (Cerro Boni)	*Lava flow*	*Latite*	*Bi*	*K/Ar*	*124.6±4.2*	*7*
Ybytyruzù (Cerro Itatí)	*Lava flow*	*Phonotephrite*	*Bi*	*K/Ar*	*128.8±4.6*	*7*
Cerro Santo Tomás	*Stock*	*Syenogabbro*	*Bi*	*K/Ar*	*126.0±4.5*	*7*
Cerro Santo Tomás	*Stock*	*Syenogabbro*	*FC*	*K/Ar*	*136.8±5.0*	*7*
Cerro Santo Tomás	*Stock*	*Essexite*	*WR*	*K/Ar*	*136.5±10.2*	*9*
Cerro Santo Tomás	*Dyke*	*Basanite*	*Bi*	*K/Ar*	*130.1±4.8*	*7*
Cerro Santo Tomás	*Dyke*	*Basanite*	*Bi*	*K/Ar*	*127.9±4.8*	*7*
Cerro Santo Tomás	*Stock*	*Nepheline syenodiorite*	*Bi*	*K/Ar*	*132.0±11.5*	*3*
Cerro Santo Tomás	*Stock*	*Syenogabbro*	*WR, Bi, AF*	*Rb/Sr isochron*	*128.0±8.0*	*7*
Cerro Santo Tomás	*Stock*	*Syenodiorite*	*WR, Bi, AF*	*Rb/Sr isochron*	*126.5±7.6*	*8*
CENTRAL PROVINCES (ASU):						
Potassic magmatism						
Cerro Acahay	*Dyke*	*Trachybasalt*	*WR*	*K/Ar*	*118.0±4.0*	*2*
Cerro Arrúa-í	*Stock*	*Nepheline syenodiorite*	*Bi*	*K/Ar*	*132.3±8.4*	*8*
Cerro Arrúa-í	*Stock*	*Nepheline syenodiorite*	*WR, Bi, AF*	*Rb/Sr isochron*	*126.5±7.6*	*8*
Sodic magmatism						
Sapucai	*Dyke*	*Na-Tephrite*	*WR*	*K/Ar*	*66.0±2.0*	*2*
Sapucai	*Dyke*	*Na-Tephrite*	*WR*	*K/Ar*	*32.8±0.9*	*2*
Cerro Gimenez	*Plug*	*Na-Phonolite*	*WR*	*K/Ar*	*66.0±4.6*	*8*
MISIONES: Sodic magmatism						
Estancia Guavira-y	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*120±5*	*10*

ASUNCIÓN: Sodic magmatism						
Cerro Patiño	*Plug*	*Ankaratrite*	*WR*	*K/Ar*	*38.8±2.3*	*7*
Limpio	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*50.2±1.9*	*7*
Cerro Verde	*Plug*	*Ankaratrite*	*WR*	*K/Ar*	*57.0±2.3*	*7*
Villa Hayes	*Plug*	*Ankaratrite*	*WR*	*K/Ar*	*58.4±2.2*	*7*
Cerro Ñemby	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*45.7±1.8*	*7*
Remanso Castillo	*Dyke*	*Melanephelinite*	*WR*	*K/Ar*	*40.6±1.7*	*7*
Cerro Confuso	*Plug*	*Phonolite*	*WR*	*K/Ar*	*55.3±2.1*	*7*
Cerro Confuso	*Plug*	*Phonolite*	*WR*	*K/Ar*	*60.9±4.4*	*7*
Cerro Confuso	*Plug*	*Phonolite*	*WR*	*K/Ar*	*59.3±2.4*	*7*
Nueva Teblada	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*46.3±2.0*	*7*
Nueva Teblada	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*56.7±2.3*	*7*
Cerro Lambaré	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*48.9±2.0*	*7*
Cerro Lambaré	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*48.9±2.2*	*7*
Cerro Tacumbú	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*46.0±7.0*	*3*
Cerro Tacumbú	*Plug*	*Melanephelinite*	*WR*	*K/Ar*	*41.3±1.8*	*7*

GEOCHEMISTRY

IE (Incompatible Elements) patterns, LILE (Large Ion Lithophile Element) vs HFSE (High Field Strenght Element) ratios, and Sr-Nd-Pb isotopic compositions indicate that the magmatic events which occurred in Eastern Paraguay were generated from geochemically distinct (enriched vs. depleted) mantle sources (Comin-Chiaramonti & Gomes, 1995, 2005; Comin.Chiaramonti *et al*, 1997).

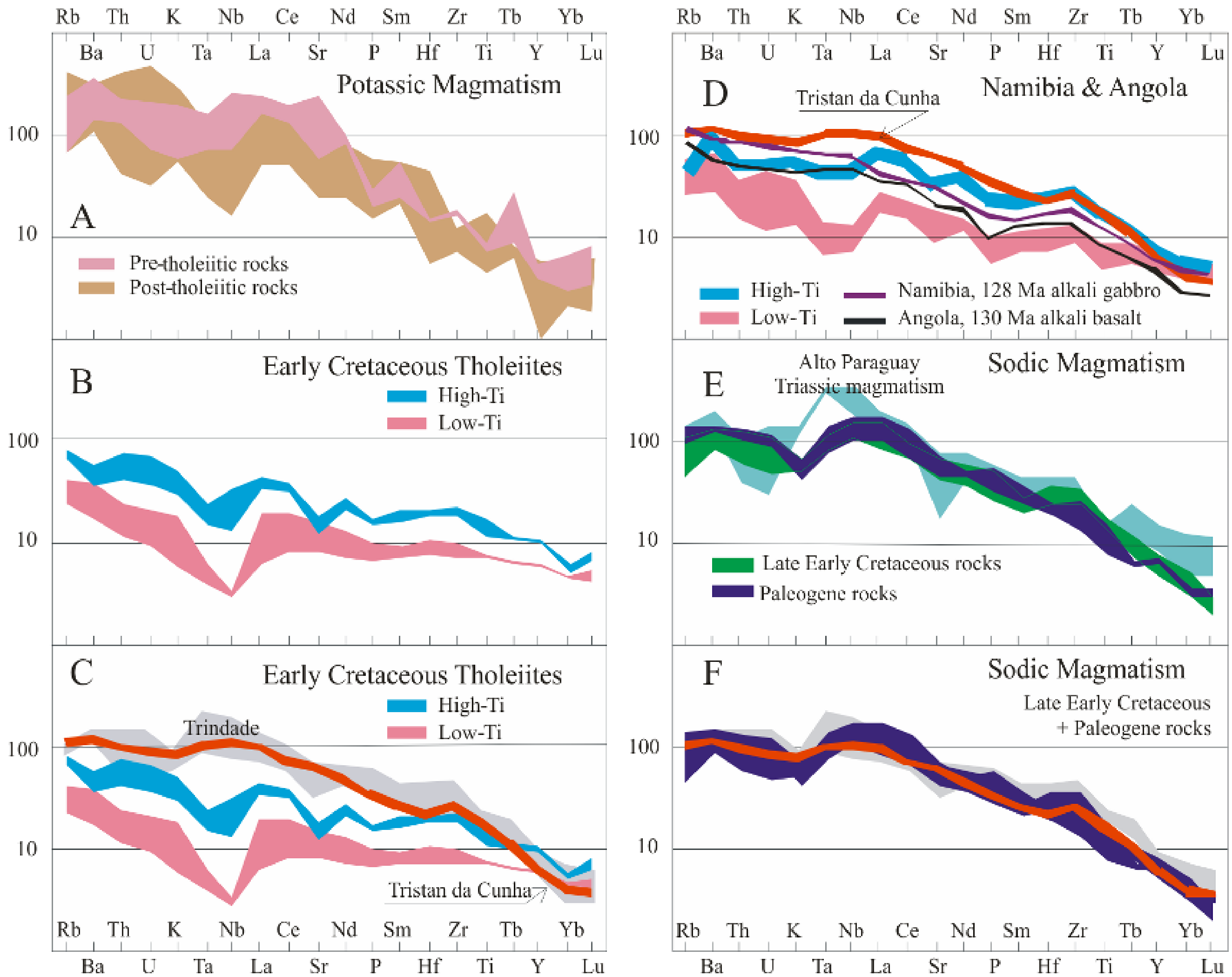

Figure 6: *Eastern Paraguay: incompatible elements (data sources: Comin-Chiaramonti & Gomes, 1995, 2005; Comin-Chiaramonti et al., 1997, 1999) normalized to the primitive mantle (Sun & McDonough, 1989) representative of the compositions of the mafic K-alkaline rocks (A) and tholeiites (B), compared with Trindade and Tristan da Cunha basanites (C: Le Roex et al., 1998; Marques et al:, 1999a; Siebel et al:, 2000). D: high- and low-Ti "uncontaminated" tholeiitic basalts from Angola and Namibia compared with Namibia alkaline gabbros and Angola alkali basalts (Comin-Chiaramonti et al., 1999; Alberti et al., 1999). E: Triassic sodic rocks (Alto Paraguay: nepheline syenites with SiO_2 = 55 wt% and MgO = 2.5 wt %), compared with sodic alkaline mafic rock-types of late Upper Cretaceous and Paleogene ages from Paraguay (Comin-Chiaramonti et al., 1999; Velázquez et al., 2006). F: sodic mafic magmatism (late Lower Cretaceous+Paleogene) compared with the field of the Tridade and Tristan da Cunha basanites.*

Incompatible elements

The IE patterns of the Alto Paraguay sodic magmatic rocks (considering the less evolved rocks, i.e. nepheline syenites, SiO_2 = 55 wt% and MgO = 2.5 wt%) largely reflects their differentiated composition (e.g. negative Sr and Ti spikes), yet features like positive Nb-Ta anomalies are most probably primary, i.e. related to the mantle source of the parent magmas (Fig. 6).

The pre- and post-tholeiites potassic alkaline rocks (from Rio Apa-Amambay and ASU, respectively, are low-Ti variant (cf. Gibson *et al.*, 1995a, b, 1997, 1999, Comin-Chiaramonti *et al.*, 2004, 2007) and display quite similar IE patterns, in general characterized by LILE enrichment and HFSE depletion (Fig. 6). The latter geochemical features suggest that the enrichment processes were related to small-volume melts in a lithospheric mantle (Comin-Chiaramonti *et al.*, 1997, 2004, 2007; Castorina et al., 1997). On the other hand, high-titanium potassic rocks are typical of the Late Cretaceous potassic magmatism in the APIP and Namibia suites which, on the contrary, are characterizd by HFSE enrichments (Milner *et al.*, 1995, 1996; Le Roex *et al.*, 1998; Ewart *et al.*, 2004).

The Cretaceous low- and high-Ti Paraná flood tholeiites are distinct in terms of their relatively low elemental abundances and high LILE/HFSE ratios (Fig. 6). In general, the marked Ta-Nb negative spike of the Paraná tholeiitic basalts is similar to that of the potassic alkaline magmas from Eastern Paraguay, but marks a clear difference with the Mesozoic to Cenozoic sodic alkaline rocks from Paraguay and with the hot-spot Ocean Island basalts (OIB) of the southern Atlantic islands of Tristan da Cunha and Trindade (Fig. 6 and D).

The late Early Cretaceous (Misiones, SJB) and Paleocene (Asunción) sodic alkaline rocks display almost identical IE patterns (Comin-Chiaramonti et al., 1991; Velázquez et al., 2006). With respect to the potassic alkaline magmatism, the Early Cretaceous and Paleocene sodic events differ, in general, by a marked negative K spike and positive HFSE spikes (Fig. 6, F), with a general pattern similar to the Tristan da Cunha and Trindade ocean islands magmas, and, to some extent, also to the Early Cretaceous potassic alkaline mafic rocks from Angola and Namibia (Fig. 6D)

Sr-Nd isotopes

The investigated rocks from Eastern Paraguay cover a wide range of Sr-Nd isotopic compositions (Fig. 7A) defining on the whole a trend similar to the low Nd array of Hart & Zindler (1989; cf. “Paraguay array” of Comin-Chiaramonti *et al.*, 1995c). Due to the high Sr and Nd content of the most "primitive" alkaline rocks (and associated carbonatites) from Eastern Paraguay, Comin-Chiaramonti *et al.* (1999) suggest that initial Sr-Nd isotopic ratios of such rocks can be considered crustally uncontaminated and, as a result, representative of the isotopic composition of the mantle source(s). Initial $^{87}Sr/^{86}Sr$ (Sr_i) and $^{143}Nd/^{144}Nd$ (Nd_i) ratios range from the depleted quadrant to the enriched one.

The potassic alkaline rocks, both pre- and post-tholeiites, have the highest initial Sr_i and the lowest Nd_i. Including the Cerro Chiriguelo and Sarambí carbonatites (Comin-Chiaramonti & Gomes, 1995, 2005), which occur associated with the pre-tholeiitic potassic rocks in northeastern Paraguay, the Sr_i and Nd_i range from 0.70636 to 0.70721 and from 0.51194 to 0.51165, respectively. These values are quite distinct from those of the late Early Cretaceous sodic rocks (Misiones: ca. 118 Ma; Sr_i = 0.70486 ± 0.00043, Nd_i = 0.51226 ± 0.00015), and by the Paleocene sodic rocks (ASU: ca. 60 Ma), which plots within the depleted quadrant (Sr_i = 0.70369 ± 0.00011, Nd_i = 0.51268 ± 0.00006) towards the HIMU-DMM mantle components (Velázquez *et al.*, 2006). Notably, Sri and Ndi of the "uncontaminated" tholeiites (both high- and low-Ti) are intermediate between the potassic and sodic rocks.

The Sr_i (0.70425 to 0.70595; av. 0.70527 ± 0.00034) and Nd_i (0.51213 to 0.51280; av. 0.51224 ± 0.00011) of the Early Cretaceous Brazilian rocks (Fig. 7C) are generally higher and lower, respectively, than those of the coeval rocks (both sodic and potassic) from Angola and Namibia (Comin-Chiaramonti et al., 2005, 2007). Late Cretaceous potassic alkaline-carbonatitic complexes have the following Sr_i and Nd_i mean values, respectively: Alto Paranaíba (APIP), Sr_i = 0.70527 ± 0.00036 and Nd_i = 0.51224 ± 0.00006 (Gibson *et al.* 1995a, b, 1997, 1999; Comin-Chiaramonti *et al:*, 2002, 2004, 2007); Taiúva-Cabo Frio and Serra do Mar, Sr_i = 0.70447 ± 0.00034 and Nd_i = 0.51252 ± 0.00008 (Gibson et al., 1995b, 1997); Lages, Sr_i = 0.70485 ± 0.00053 and Nd_i = 0.51218 ± 0.00022 (Comin-Chiaramonti et al., 2002).

Note that the alkaline-carbonatite magmatism trends towards the Sr_i and Nd_i field delineated by the Late Cretaceous tholeiites from Walvis Ridge and Rio Grande Rise (Richardson et al., 1982; Gamboa & Rabinowitz, 1984).

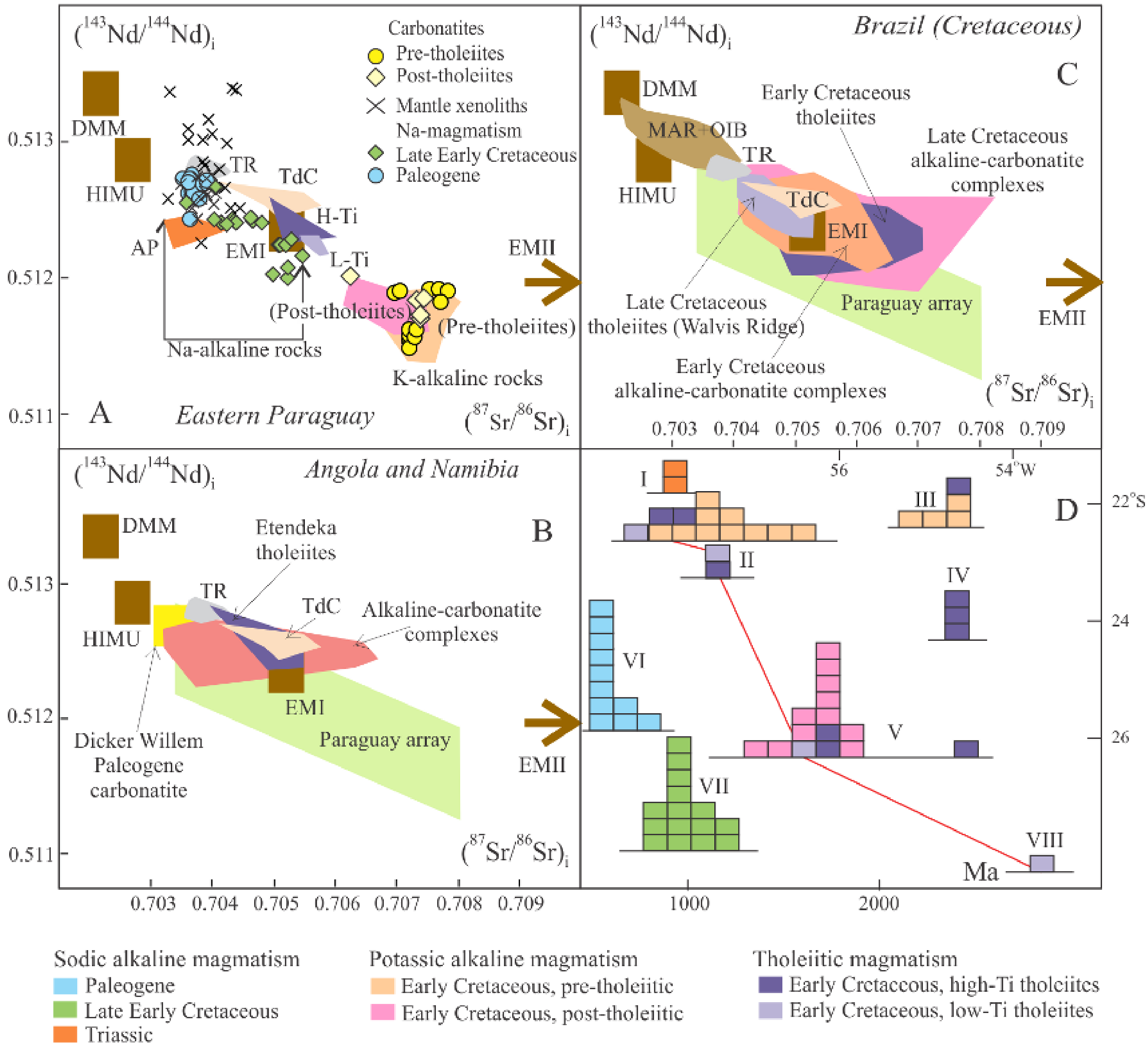

Figure 7: *Initial $^{87}Sr/^{86}Sr$ (Sr_i) vs. $^{143}Nd/^{144}Nd$ (Nd_i) diagram for the magmatic rocks from Eastern Paraguay (A) compared with Angola and Namibia (B) and Brazil (C). AP, Alto Paraguay; TR: Trindade; TdC, Tristan da Cunha; H-Ti and L-Ti, high-Ti and low-Ti tholeiites, respectively. Data source and other symbols as in Fig. 6. DMM, HIMU, EMI and EMII fields after (Zindler & Hart, 1986; Sracke et al., 2005). D: distribution of TDM ages (Ma) in Eastern Paraguay: I, Alto Paraguay; II, Rio Apa; III; Amambay; IV Carayó; V, Sapucai; VI, Asunción; VII, Misiones; VIII, Encarnación. Colours as in D. Red line joins "L-Ti" tholeiites. Data sources: Comin-Chiaramonti & Gomes, 1995, 2005.*

Mantle xenoliths

Mantle xenoliths, protogranular spinel facies, are widespread in two alkaline provinces from Eastern Paraguay, Asunción and Misiones Provinces, respectively. The mantle xenoliths are distinguished into two main suites, LK (relatively low in K and incompatible elements, IE) and HK (high in K and IE), both ranging from lherzolite to dunite and showing trends of "melt extraction", as shown by the chemistry of the major elements (Comin-Chiaramonti et al., 1986, 1991, 2001; De Marchi et al., 1988).

The IE contents ofr clinopyroxenes encompass world-wide occurrences. This suggest that processes, other than depletion, occurred. K is mostly partioned into blebs in the xenoliths and glassy drops in clinopyroxenes. The blebs have been interpreted as derived from breakdown of volatile-bearing phases, such as amphibole and/or phlogopite, which melted during the ascent to the surface. Sometimes the glassy drops contain primary carbonates ($\delta^{18}O‰ = + 8$; $\delta^{13}C‰ = - 9.5$).On the other hand, the glassy drops may represent the products of incongruent partial melting induced by the decompression. Both probably are the remnants of hydrous phases and/or products induced by the influx of small-volume, volatile-rich melts.

The clinopyroxenes display variable REE enrichments, more apparent in those crystals characterized by spongy texture and abundance of glassy drops: a possible explanation for the progressive enrichment of samples characterized by similar HREE, but different LREE abundances, is different ion-exchange processes, due to the passage of a LREE-rich chemical front on depleted compositions, in both LK and HK suites. It is believed that "residual" pyroxenes incorporated REE during later metasomatic events. The above observation is consistent with the Nd isotopic ratios measured on clinopyroxenes, indicating a LREE-depleted source for some samples and supporting the hypothesis that clinopyroxenes from some lherzolites did not crystallize from an original LREE enriched component. On the other hand, some samples approache enriched or undifferentiated compositions.

Alkaline basaltic magmas from deeper, garnet-bearing mantle may be suitable enriching agents. Moreover, the Paraguay xenoliths were probably involved in carbonatitic metasomatism, as indicated by IE patterns of some clinopyroxenes. The latter are characterized by high LREE and Sr abundances coupled with depletion in Nb, Ti, Zr. Notably, similar behaviour has already been described for clinopyroxenes from peridotite xenoliths hosted in ocean island basalts from Samoa and Tubai, which show clear evidence of carbonatitic metasomatism (Hauri *et al.*, 1993, 1997).

Systematic isotope differences between LK and HK xenoliths were not observed, except those related to $\Delta^{18}O$‰ (*cpx-ol*). This suggests buffering dominated by olivine in the upper mantle, where the equilibration was supported by coherence between observed O-isotopic fractionation and clinopyroxene temperatures.

The observed radiogenic isotope trend (Bulk Earth vs Depleted Mantle) is not consistent with major element refractory parameters, suggesting that mixing with enriched components is also recorded on a whole-rock scale: the enriched components were mostly trapped in some clinopyroxenes that have previously crystallized from depleted to quasi-chondritic mantle sources.

On the whole, the isotopic data indicate that the lithospheric mantle prior to the enrichment was dominated by a depleted component, isotopically resembling MORB sources or even more depleted, probably related to the occurrence of residua which differentiated from ancient events of partial melting.

Considering that magmatism in the Asunción-Sapucai-Villarrica graben (Early Cretaceous: tholeiitic and potassic alkaline-carbonatitic rocks; late Early Cretaceous to Paleogene: sodic alkaline rocks) and in the Misiones province (Early Cretaceous: tholeiitic; late Early Cretaceous: sodic alkaline rocks) requires their parental magmas to have derived from a heterogeneous subcontinental mantle (garnet peridotite), significant fluids are expected to modify the isotope ratios of the overlaying spinel peridotite.

On this respect, the Sm-Nd and Rb-Sr systematics may reflect to some extent the main melting episodes occurring in the mantle regions during the various phases of lithospheric thinning and repeated interactions between fluids and overlaying peridotites.

Lead isotopes

Pb isotopes are believed to discriminate between DMM and HIMU components (cf. "Mantle components" review of Zindler & Hart (1986) and Sracke et al. (2005). For this purpose lead isotopic compositions have been carried out on four selected late Early Cretaceous and Eocene rocks from South Eastern Paraguay (Table 3 of Velázquez *et al.*, 2006) and compared with the whole magmatism from the Eastern Paraguay, following (Antonini *et al.*, 2005).

The initial Pb isotope compositions of both pre- and post-tholeiitic K-magmatism for the most "primitive" rock-types, show $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ = 16.888-17.702, 15.433-15.620 and 37.156-37.915, respectively. The initial lead isotope ratios of the tholeiitic Paraguayan rocks generally agree with the Brazilian equivalents reported by Marques *et al.* (1999b); the Palaeozoic basement rocks (Brasiliano cycle; ~ 500 Ma; cf. Table 3 of Antonini *et al.*, 2005) overlap the field of the Eastern Paraguay tholeiites, and then the latter might partly reflect interaction with crustal material. The sodic alkaline rocks (Misiones and ASU) have different Pb isotopic compositions and differ from the potassic rock-types: the Cretaceous potassic rock-types are characterized by initial Pb compositions ($^{206}Pb/^{204}Pb$ = 18.211, $^{207}Pb/^{204}Pb$ = 15.628 and $^{208}Pb/^{204}Pb$ = 37.963) approaching those of the Cretaceous low-Ti tholeiites of southern Paraná (Hauri, 1997), whereas the Eocene sodic rock-types ($^{206}Pb/^{204}Pb$ = 18.964, $^{207}Pb/^{204}Pb$ = 15.678, $^{208}Pb/^{204}Pb$ = 38.484) appear shifted towards the HIMU field (Fig. 8).

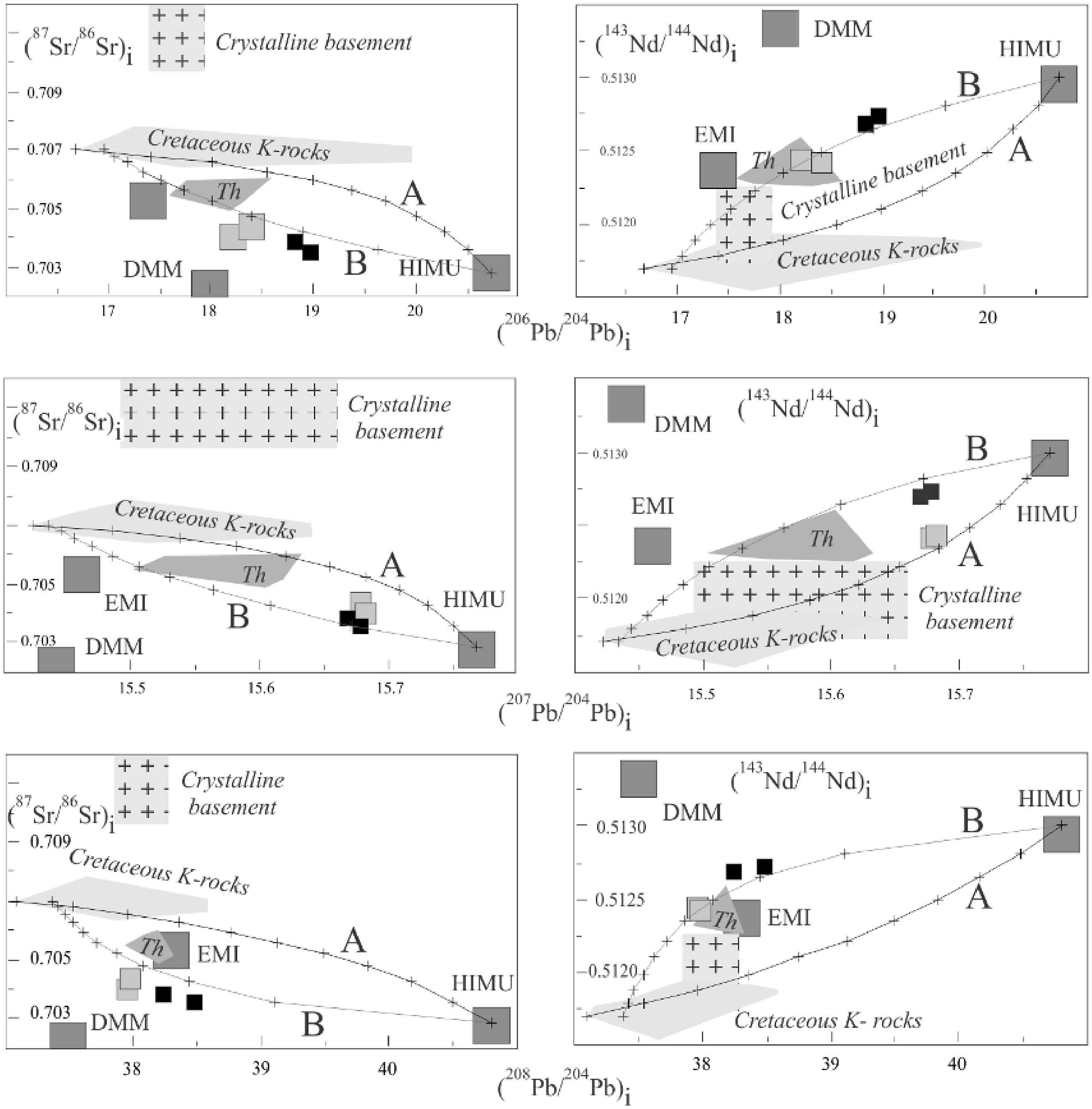

Figure 8: *Isotopic mixing curves (A and B) between HIMU and potassic magmas from Lower Cretaceous Potassic rocks (LCK, Eastern Paraguay), computed using the following isotopic composition: HIMU (St. Helena; Chaffey et al., 1989); $^{87}Sr/^{86}Sr$ = 0.70282, Sr = 650, $^{143}Nd/^{144}Nd$ = 0.5130, Nd = 40, $^{206}Pb/^{204}Pb$ = 20.73, $^{207}Pb/^{204}Pb$ = 15.77 and $^{208}Pb/^{204}Pb$ = 40.80, U = 1.44, Th = 3.88, Pb = 4, μ = 24.4, κ = 2.78; LCK,* ***A:*** *$^{87}Sr/^{86}Sr$ = 0.7070, Sr = 1300, $^{143}Nd/^{144}Nd$ = 0.5117, Nd = 60, $^{206}Pb/^{204}Pb$ = 16.672, $^{207}Pb/^{204}Pb$ = 15.422, $^{208}Pb/^{204}Pb$ = 37.10, U = 1.47, Th = 6.38, Pb = 2, μ = 23.09, κ = 4.80;* ***B****: A: $^{87}Sr/^{86}Sr$ = 0.7070, Sr = 1300, $^{143}Nd/^{144}Nd$ = 0.5117, Nd = 60, $^{206}Pb/^{204}Pb$ = 16.945, $^{207}Pb/^{204}Pb$ = 15.434, $^{208}Pb/^{204}Pb$ = 37.369, U = 2.40, Th = 9.10, Pb = 15, μ = 9.8, κ = 3.8. Symbols: black and gray squares: Asunción and Estancia Guavira-y Na-mafic rocks. Crosses: 10% step of mixing. DMM, HIMU and EMI components after Hart & Zindler (1989). Crossed areas represent the crystalline basement at 119 Ma (Antonini et al., 2005).*

On the whole, the available data for the alkaline-carbonatite complexes and tholeiites from the Paraná-Angola-Etendeka system (PAE) plot between HIMU and EMI end-members, and subordinately DMM and EMI, as well crustal l.s. components (e.g. EMII; Figs. 11 and 12 of Velázquez *et a*l., 2006). To be noted that the tholeiitic flood basalts from Eastern Paraguay and from Angola-Namibia, at the westernmost and easternmost sides of the PAE, respectively, delineate well different fields (cf. Fig. 12 Velázquez *et a*l., 2006).

MAR and OIB delineate trends between the DMM and HIMU mantle components. In comparison, the PAE carbonatites plot close to the EMI/DMM - HIMU mixing lines for both Pb-Sr and Pb-Nd (Comin-Chiaramonti & Gomes, 2005). This observation seems to confirm the advantages in using carbonatite over silicate rocks, as indicators of mantle sources, because of their rapid ascent to the surface conditions, and buffering against crustal assimilation due to their high Sr, Nd and Pb concentrations in the liquids.

PETROGENESIS

General Considerations

These considerations are the logic consequence of the previously presented data.

Similarly to the whole Paraná basin, in Paraguay the high-Ti tholeiites have IE abundances higher than the coeval low-Ti analogues and negative Sr anomaly (Comin-Chiaramonti *et al.*, 1995c, 1997, 1999, 2002, 2004; Comin-Chiaramonti & Gomes, 1995, 2005). These differences have been ascribed to different melting degrees (up to 5 % and 20 % for high- and low-Ti basalts, respectively) of a large-scale heterogeneous mantle source (Cundari *et al.*, 1995), possibly a veined garnet peridotite where the distribution and the frequency of the "metasomatizing" channels determine the different chemical signatures (Comin-Chiaramonti & Gomes, 1995, 2005).

In summary, IE suggest a common signature for potassic alkaline magmatism from Central Province, both B-P and AB-T suites, of Paraguay and PAE tholeiitic magmas, whereas Paraguay sodic alkaline rocks display similar IE patterns as Atlantic OIBs and African potassic alkaline basalts. Strongly LREE-enrichment patterns suggest that Paraguayan potassic and sodic alkaline magmas issued from a garnet-bearing peridotite, yet their mantle source compositions were clearly distinct both in terms of IE composition and mineralogy: as proposed by Comin-Chiaramonti *et al.* (1997), the relative K enrichment of the Eastern Paraguay potassic rocks suggests that a K-bearing phase (e.g. phlogopite) was not a residual phase during the partial melting of the mantle. Phlogopite, instead, was probably a residual phase in the mantle source for the sodic alkaline rocks, as is consistent with the Early melting degree inferred for the sodic magmatism in relation to the potassic one (e.g. 4-6% and 6-11% melting, of a garnet mantle, respectively (Comin-Chiaramonti *et al.*, 1997; Velázquez et al., 2006).

The Sr-Nd isotopic variations of the alkaline rocks from Eastern Paraguay (Fig. 7A) may be explained: a) by generation from distinct portions of a large- and small-scale heterogeneous lithospheric mantle source, where the small-scale heterogeneity is required by the variations in the Sr_i and Nd_i ratios in each magmatic event; or b) in terms of mixing of magmas generated from an enriched mantle component (with extreme EMI signature) and from a depleted mantle component (DMM- or HIMU-like components), respectively. In any case, on the basis of the isotopic compositions, it is possible to infer a time related (Early Cretaceous to Paleogene) progressive increase of the role of the depleted mantle domain(s) in the genesis of alkaline magmatism in Eastern Paraguay (Comin-Chiaramonti & Gomes, 1995, 2005). On the other hand, the sodic magmatism, including the Alto Paraguay sodic magmatism (Triassic), tends to plot near to the depleted quadrant. Notably, Sr_i and Nd_i of the "uncontaminated" tholeiites (both high- and low-Ti) are intermediate between the potassic and sodic rocks.

The Sr-Nd isotopic variation of the Paraguayan alkaline rocks is larger than at of all other PAE alkaline magmatism. In Angola and Namibia, at the easternmost fringe of the Paraná-Etendeka system, Sr_i and Nd_i values for most Early Cretaceous Angolan K-alkaline-carbonatite complexes (Fig. 7B) vary between 0.70321 and 0.70466, and between 0.51273 and 0.51237, respectively, showing on the whole depleted characteristics relative to the Bulk Earth (cf. Hart & Zindler, 1989). On the other hand, the Early Cretaceous alkaline-carbonatite complexes from Namibia have a similar Sr_i range (0.70351-0.70466), but almost constant Nd_i (0.51250 to 0.51244; Milner & Le Roex, 1996; Le Roex & Lanyon, 1998).

Model Ages

Despite uncertainties related to the Sm/Nd fractionation (*f*) during the melting and magma differentiation (Arndt & Goldstein, 1987), Nd model ages (depleted mantle, T^{DM}; De Paolo, 1988) may give a broad indication of the age of the main enrichment processes which may affected the mantle source(s) of the Paraguayan magmas. In general, the Paraguayn potassic magmas display T^{DM} comparable to those of the PAE tholeiites and higher than those of sodic magmas (cf. Fig. 7D). T^{DM} of the potassic alkaline rocks increases from the pre-toleiitic rocks of North Eastern Paraguay (peaks at 1.1-1.4 Ga, for $f \approx -0.5$ to -0.7; Valle-mí in Apa Block, and Amambay), to the post-tholeiitic ASU potasssic alkaline complexes and dykes (1.7 Ga, $f \approx -0.4$ to - 0.5). The sodic alkaline rocks display Late Proterozoic T^{DM} (0.9 Ga, Alto Paraguay; 0.6 Ga, Na-ASU; 1.0 Ga, Misiones, for $f \approx -0.4$ to -0.5). To be noted that the younger model ages parallel the Rio Paraguay lineament and characterize the sodic magmatism (Antonini *et al.*, 2005).

The different geochemical behaviour in the different sectors of the PAE imply also different sources. Utilizing the T^{DM}(Nd) model ages on the whole Paraná-Angola-Etendeka system (cf. Comin-Chiaramonti & Gomes, 2005; Gastal *et al.*, 2005), we observe that (1) the H-Ti flood tholeiites and dyke swarms (cf. inset of Fig. 1) from the Paraná basin, and the Early Cretaceous potassic rocks and carbonatites from Eastern Paraguay mainly range from 0.9 to 1.7 Ga, whereas in Angola and Namibia the Early Cretaceous K-alkaline rocks range from 0.4 to 0.9 Ga;

(2) the low-Ti tholeiites display a major T^{DM} variation, from 0.7 to 2.4 Ga (mean 1.6 ± 0.3) with an increase of the model ages from North to South; (3) Late Cretaceous alkaline rocks and associated carbonatites show model ages ranging from 0.6 to 1 Ga, similar to the age shown by the Triassic to Paleogene sodic alkaline rock-types along the Paraguay river. These model ages indicate that some notional distinct "metasomatic events" may have occurred during Paleoproterozoic to Neoproterozoic times as precursor to the alkaline and tholeiitic magmas in the Paraná-Angola-Etendeka system (Comin-Chiaramonti *et al.*, 1991, 1992, 1995c, 1997, 1999, 2005, 2007; Comin-Chiaramonti & Gomes, 1995, 2005; Antonini *et al.*, 2005).

The T^{DM}(Nd) model ages and mantle heterogeneity are supported in the Paraná basin also by the model of Meen *et al.* (1989; s. also Castorina et al., 1997): a veined lithospheric mantle (amphibole/phlogopite-carbonate-lherzolite+CO2-fluid type III and IV veins of Meen *et al.* (1989) of Proterozoic age may well account for the magmatism of the Paraná basin.

Pb isotopes

Some Authors (e. g. Le Roex & Lanyon, 1998; Ewart *et al.*, 2004) postulated that the Early Cretaceous alkaline-carbonatitic and tholeiitic magmatism from northwestern Namibia and the Late Cretaceous alkaline and alkaline-carbonatitic magmatism from Alto Paranaíba-Serra do Mar (southern Brazil) would reflect the variable contributions of the asthenospheric mantle components related to the Tristan da Cunha and Trindade plumes, respectively. On the contrary, other Authors (e.g. Alberti *et al.*, 1999; Ernesto *et al.*, 2002; Antonini *et al.*, 2005) suggested that the alkaline and alkaline-carbonatitic magmatism in the PAE originated from lithospheric mantle sources without appreciable partecipation of plume-derived materials.

On the basis of geochemical and geophysical data, Ernesto (2005) and Ernesto *et al.* (1995, 1999, 2000, 2002) proposed that the genesis of the PAE tholeiites mainly reflects melting of heterogeneous subcontinental mantle reservoirs, and that the geochemical and isotopic signatures of the Walvis Ridge and Rio Grande Rise basalts may be explained by contamination through detached continental lithospheric mantle left behind during the continental break-up processes (cf. also models after Foulger & Anderson, 2005; Lustrino, 2005; Foulger *et al.*, 2005; Anderson, 2006).

In the Pb isotopic diagrams (cf. Figs. 11 and 12 of Comin-Chiaramonti *et al.*, 2007), the Early Cretaceous potassic alkaline and tholeiitic magmatism from the PAE appears to be related to heterogeneous mantle sources spanning from time-integrated HIMU to EM components. According to Tatsumi (2000), for example, relatively low $^{206}Pb/^{204}Pb$ and high $^{207}Pb/^{204}Pb$ compositions could be related to delamination of pyroxenite restites formed by anatexis of the initial basaltic crust in Archean-Proterozoic times. We stress that, in general, the enriched isotopic signatures of the Early Cretaceous alkaline magmatism, decreases from West (Paraguay) to East (Brazil, SE-continental margin, and Angola and Namibia) reflecting the decrease of Nd model ages for potassic rocks from Paraguay towards the East. These results suggest that the PAE magmatism is related both to large- and small-scale heterogeneous mantle sources. Also it should be noted that the the isotopic signature of the Trindade and Abrolhos ocean islands (Figs. 11 and 12 of Comin-Chiaramonti *et al.*, 2007) is similar to that of the alkaline-carbonatitic Early Cretaceous magmatism from Angola and Namibia, but quite different from that (EMI signature) of the Late Cretaceous-Tertiary analogue from the Alto Paranaíba (APIP), Ponta Grossa Arch, and Cabo Frio-Taiúva-Serra do Mar areas (Comin-Chiaramonti & Gomes, 2005). According to Thompson *et al.* (1998), the APIP would be the inland surface expression of the "dogleg" track left by the Trindade Plume, but, in terms of Sr-Nd-Pb isotopes, the contribution, if any, of the asthenospheric components related to the that plume is difficult to account for.

Hawkesworth *et al.* (1986, 1999, 2000) interpreted the Etendeka (Namibia) high-TiO_2 (HTZ) tholeiitic basalts as resulting from melting of a Proterozoic lithospheric mantle, which, in the case of the Walvis Ridge (WR2 basalts, cf. Richardson et al., 1982), was floating inside the oceanic asthenosphere during the opening of the South Atlantic. Alternatively, the elemental and isotopic signature of the HTZ basalts could be related to contamination of oceanic mantle by ancient subcontinental lithospheric mantle. In summary, the isotopic signature of the Early and Late Cretaceous alkaline-carbonatite complexes from the PAE reflects ancient heterogeneities preserved in the subcontinental lithospheric mantle.

All the data indicate that they represent a thermally-eroded metasomatic SCUM (Subcontinental Upper Mantle) and/or delaminated lithospheric materials stored for long time, for example, towards the transition zone or deeper mantle in Archean-Proterozoic times. In this context, for the important differences in terms of patterns of the trace elements and of radiogenic isotopes, the role of the Tristan da Cunha plume claimed by Ewart et al. (2004) is not apparent. Therefore, we believe, as documented by Ernesto (2000, 2002, 2005), that the hypothesis of asthenospheric plumes for the PAE magmatism is not compelling, except that it may represent a thermal perturbation.

GEODYNAMIC IMPLICATIONS

These are largely based on the paper of Comin-Chiaramonti et al. (2007). The geodynamic evolution of Western Gondwana in the Early Cretaceous reflects the amalgamation processes which affected the region at least at the time of the Brasiliano cycle, both at the Atlantic and Pacific systems. The Brasiliano cycle was developed between about 890 to 480 Ma in a diacronic way, until the final arrangement of the framework basement of the South American platform (Brito Neves *et al.*, 1999). During the Early Ordovician a mosaic of lithospheric fragment linked by several (accretionary, collisional) Neo-Proterozoic mobile belts amalgamated to form Gondwana (Unrug, 1996). After the amalgamation, the Gondwana supercontinent accumulated Paleozoic and Mesozoic sediments. Concomitantly, it was continuosly laterally accreted at its western borders by means of successive orogenic belts, in the Early Paleozoic and in the Permian-Triassic, until the formation of Pangea (Cordani et al., 2000, 2003). The main cratonic fragments, descending from ancestors of the Pangea, were reworked, like the Amazonia, Rio Apa, Arequipa-Antofalla and Rio de La Plata cratons and smaller ancient crustal blocks at the present-day Paraguay boundaries, were continuously reworked (Kröner & Cordani, 2003). In this context, the magmatism was driven by the relative extensional regimes derived by the relative movements of the ancient blocks. For example, the Alto Paraguay Late Triassic alkaline magmatism, is located at the boundaries between the Rio Apa and Arequipa-Antofalla blocks and reveals an extensional events at about 241 Ma, probably induced by counterlockwise and clockwise movements (North and South, respectively) hinged at the about 20° South latitude (Prezzi & Alonso, 2002).

The general geodynamic situation of the Paraguay and neighbouring countries can be pictured by the present-day earthquakes typology combined with the paleomagnetic and geological evidences. The earthquakes mechanisms (Berrocal & Fernandes, 1995) highlight the distribution of the earthquakes with hypocentres > 500 km and < 70 km, respectively (Fig. 13 of Comin-Chiaramonti *et al.*, 2007). The distribution of the deep earthquakes coincides with the inferred location under Paraguay of the subducting Nazca plate. In particular, the depth of the lithospheric earthquakes together with the paleomagnetic results, delineates different rotational paths at about 18-20° South Latitude, roughly corresponding to the Chaco-Pantanal basin, indicating extensional subplate tectonics at the Andean system (Randall, 1998). Also crucial to the the genesis of PAE magma types is the link with the geodynamic processes which promoted the opening of the South Atlantic. According to Chang *et al.* (1988) and to Nürberg & Müller (1991), the sea-floor spreading in the South Atlantic at thye PAE latitude started at ~125-127 Ma (Chron M4). North of the Walvis-Rio Grande ridges (latitude >28°), the onset of the oceanic crust would be younger (~113 Ma; Nürberg & Müller, 1991). The Early Cretaceous alkaline and alkaline-carbonatitic complexes are subcoeval with the main flood tholeiites of the Paraná Basin and, therefore, occurred during the early stages of rifting, before the continental separation. On the other hand, the Late Cretaceous analogues emplaced during advanced stages of Africa-South America continental separation.

The origin of alkaline-carbonatitic magmatism in terms of plate tectonics is currently debated. Various models have been proposed involving deep mantle plume/hot spots (up to 16; Stefanick & Jurdy, 1984), or shallow thermal anomalies (Holbrook & Kelemen, 1993). Whatever the temperature, size, depth of origin and number of hotspots, the plume model cannot account for the worldwide occurrence of the alkaline-carbonatitic magmatism. According to the interpretation of remote sensing data along the South American second-order boundaries, Unternehr *et al.* (1988) suggest important dextral desplacement between the two South American domains across this boundary. Smith & Lewis (1999) demonstrate that the forces acting on plates which move at differential angular velocity and the presence of volatile-rich mantle sources ("wetspot") would drive the rifting to occur parallel to the pre-existing (e.g. N-S) sutures, i.e. "Adamastor Ocean" which separated the Rio de la Plata Craton in South America from the Kalahari and Congo Cratons in southern Africa, ~580-550 Ma ago (Frimmel & Fölling, 2004). Intraplate alkaline and alkaline-carbonatitic magmatism occurred where second order "plate boundaries" (e.g. Alto Paranaíba, Ponta Grossa-Moçâmedes Archs, Uruguay lineament, Damara Belt; cf. Molina & Ussami, 1999) intersect the axis of major rifting, possibly related to the erosion and cycling of continental mantle towards the ridge axis.

In southern Brazil, the alkaline and alkaline-carbonatitic magmatism is concentrated in regions showing positive geoid anomalies (Ernesto *et al.*, 2002, 2005; Molina & Ussami, 2004) that may be related to dense very deep materials. Moreover, the different westward angular velocity of the lithospheric fragments in the South American plate, as defined by the "second order plate boundaries", as well as the different rotational trends at 19-20° South-Latitude, may favour the decompression and melting at different times of variously metasomatized (wet spot) portion of the lithospheric mantle with variable isotopic signatures (Turner *et al.*, 1994; Comin-Chiaramonti *et al.*, 1999). It shoud be stressed that the combined presence of even small amount of water and carbon dioxide in the Late mantle may Early the melting temperature even of some hundred degrees (Thybo, 2006). This scenario could explain the presence of Late Cretaceous to Tertiary sodic magmatism in the PAE, even at the Eastern Paraguay longitude, where there is evidence of active rifting structures (Comin-Chiaramonti *et al.*, 1992, 1999). In this case, the thermal perturbations may be channelled along the "second order plate boundaries", as stressed also by the hypocenters of earthquakes in South America (Berrocal & Fernandes, 1995).

Mantle plume

The over-simplified model of mantle plumes is not satisfactory for explaining the most of continental flood basalts and the recurrent intraplate alkaline magmatism, and therefore, following Ernesto *et al.* (2000, 2002, 2005), alternative thermal sources can be found in the mantle with no implication of material transfer from the core or Early mantle to the lithosphere. Besides the indications from geoid anomalies (Ernesto *et al.* 2002) the existence of long-living thermal anomalies or compositional differences in the mantle have already been demonstrated by velocity distribution models based on seismic tomography techniques, using both P- and S-waves (Zhang & Tanimoto, 1993; Li & Romanovicz, 1996, Van der Hilst *et al.*, 1997; Liu *et al.*, 2003). Ernesto et al., in their paleomagnetic and gravimetric studies (2002) stated that:

1) Paleogeographic reconstructions of the Paraná-Tristan da Cunha (TC) system, assuming this hotspot is a fixed point in the mantle, indicates that the TC plume was located ~800-1000 km south of the Paraná Magmatic Province (PMT). Therefore, plume mobility would be required in order to maintain the PMP-TC relationship.

2) Assuming that TC was located in the northern portion of the PMP (~20° from the present TC position), the plume migrated southward from 133-131 Ma (main phase in the area) to 80 Ma at a rate of about 40 mm/yr. From 80 Ma to Present the plume remained virtually fixed, leaving a track compatible with the African plate movement. Notably, the southward migration of the plume is in opposition to the northward migration of the main Paraná magmatic phases (133 Ma in the south, and 132 in the North).

3) Regional thermal anomalies in the deep mantle, mapped by geoid and seismic tomography data, offer an alternative non-plume-related heat source for the generation of intracontinental magmatic provinces.

4) The "hotspot tracks" of Walvis Ridge and Rio Grande Rise, as well the Vitória-Trindade chain, might reflect the accomodation of stresses in the lithosphere during rifting, rather than continuous activity induced by mantle plumes beneath the moving lithosphere plates.

Paleomagnetic constraints are necessary for paleogeographic reconstructions that could provide a more realistic position of the presumed Tristan plume in relation to the Parana flood basalts and surrounding alkaline rocks. There are sufficient good quality paleomagnetic data (Renne *et al.*, 1992, 1993. 1996; Ernesto *et al.*, 1995, 2000, 2005) to delineate the Mesozoic apparent polar wandering in South America, many of these data derived from igneous rocks from the Parana Magmatic Province. All these data indicate that from Late Jurassic to Early Cretaceous South America was describing a clockwise rotation, and a slight north-south movement. On the contrary, Gibson *et al.* (2006) propose a displacement towards northwest in the 133-139 Ma interval, on the basis of mantle anchored plumes.

They found support for this proposition in the work by O'Connor & Duncan (1990) which is completely based on the assumption that the hotspot formed a fixed frame. Therefore no independent evidence is presented, and lithosphere path has been traced to match the Rio Grande Rise-Walvis Ridge hotspot tracks which geodymanic meaning has been questioned by various authors (e.g. Ernesto *et al.*, 2002 and therein references). On the other hand the required plate velocity to place the Tristan da Cunha plume in the two consecutive positions (139 and 133 Ma, respectively) according to Gibson *et al.* (2006), in their model exceeds almost three times the 3.5 cm per year estimated by O'Connor & Duncan (1990).

Concluding Remarks

On the whole, the geochemical and geophysical results together with the ages of the magmatic events in Eastern Paraguay indicate that any model proposed for the evolution of the PAE in terms of HIMU and EM end-members must be consistent with the following constraints: (a) HIMU and EMI-II are not restricted to the oceanic environment; (b) end-members are variously associated in space as a function of the various protoliths; (c) mantle regions with HIMU and EMI isotope characteristics are capable of generating melts that can lead to the formation of a wide variety of silicate rocks, including melts enriched in CO_2; d) systematically the sodic alkaline rock-types are grouped together, in fields well distinct in comparison with the potassic alkaline fields in Paraguay, but fitting the fields of potassic alkaline-carbonatite fields of the Angola-Namibia.

Summarizing:

1. $^{40}Ar/^{39}Ar$ plateau ages highlight that distinct magmatic events took place in Eastern Paraguay since the Middle Triassic in areas strongly characterized by extensional tectonics. The first event occurred during the Anisian (Middle Triassic) and was of sodic affinity. After a magmatic hiatus of about 100 Ma, during the Lower Cretaceous, the potassic alkaline magmatism pre- and post-dated the emission of the Paraná Basin flood tholeiites. Since late Lower Cretaceous to Paleogene, only sodic magmatism occurred in Paraguay. The Sr-Nd-Pb isotopic data indicate that two main mantle components, an extreme and heterogeneous EMI component, which was prevalent in the Cretaceous K-alkaline magmatism, and a depleted component, which appears important for the sodic magmatism at Middle Triassic, late Lower Cretaceous and Paleogene, could have been involved in the genesis of the Cretaceous to Paleogene magmatism in Eastern Paraguay.

2. The potassic rocks form a compositional continuum from moderately to strongly potassic and from alkali basalt/basanite to trachyte/phonolite. The sodic rocks include mainly ankaratrites, nephelinites and phonolites.

3. The potassic suites (pre- and post tholeiitic) are characterized by strongly fractionated REE and negative "Ta-Nb-Ti anomalies". On the contrary, slight positive anomaly for Ta and Nb was observed in the sodic rock.

5. Sr-Nd isotope data confirm the distinction of the potassic rocks, enriched in $^{87}Sr/^{86}Sr$ and low in $^{143}Nd/^{144}Nd$, from the sodic rocks, close to BE and transitional to the Paraná flood tholeiites. Crustal contamination does not appear to have been significant in the generation of the investigated rocks.

6. The Pb-Sr-Nd isotopic systematics show that the Lower Cretaceous alkaline magmatism from the PAE appears to be related to heterogeneous mantle sources spanning from DM-HIMU and to time-integrated enriched mantle components. This alkaline magmatism mimics, in terms of isotopic compositions, the coeval flood tholeiites. The enriched isotopic signatures of the Lower Cretaceous alkaline magmatism, decreases from West (Paraguay) to East (Brazil, SE-continental margin, and Angola and Namibia). A similar decreasing isotopic shift is also observed for the age of the magmatism, in Paraguay and Brazil, i.e. Lower- Upper Cretaceous to Tertiary. These results suggest that the PAE magmatism is related both to large- and small-scale heterogeneous source mantle.

7. The source of potassic rocks is constrained by high LILE, LREE, Th, U and K, relative to the composition of the primitive mantle.

8. The close association of potassic and sodic rock suites in Eastern Paraguay demands that their parental magmas derived from small subcontinental mantle masses, vertically and laterally heterogeneous in composition and variously enriched in incompatible elements. Significant H-O-C and F are also expected in the mantle source from the occurrence of the related carbonatites. These considerations may be extended to the whole Paraná - Angola - Etendeka system.

9. Any hypothesis of mantle plume activity at the margin of the Paraná Basin is constrained by distinct lithospheric mantle characteristics and by paleomagnetic results [81]. This does not preclude that thermal perturbations from the asthenosphere may have triggered magmatic activity in the lithospheric mantle in the Eastern Paraguay.

10. It is proposed that isotopically variously enriched sources, implied by the potassic magmas, derived from a depleted lithospheric mantle, pervasively invaded by IE-C-H rich fluids. These are expected to have promoted crystallization of K-rich phases (e.g. phlogopite) in a pristine peridotite, where they developed a veined network variously enriched in LILE and LREE under various redox conditions. The newly formed veins ("enriched component") and peridotite matrix ("depleted component") underwent a different isotopic evolution with the time, depending on their parent/daughter ratio. This model may be extended to the Paraná flood tholeiites and to high- and low-Ti potassic magmatism from the southeastern Brazil, Angola and Namibia.

11. Isotopically distinct magmas were generated following two main "enrichment" events of the subcontinental upper mantle estimated at 2.0-1.4 Ma and 1.0-0.5 Ga, respectively. This would have preserved isotopic heterogeneities over a long period of time, pointing to a non-convective lithospheric mantle beneath different cratons or intercratonic regions.

12. The occurrence of sodic and potassic magmatism in the Paraná Basin implies appropriate lithospheric sources to generate also the flood tholeiites. Therefore, any hypothesis of an asthenospheric plume origin is not compelling other than a thermal perturbation and/or a decompressional environment, and possible sources of the Precambrian plume melts which contaminated the lithosphere.

13. The over-simplified model of mantle plumes is not satisfactory for explaining the most of continental flood basalts and the recurrent intraplate alkaline magmatism, and therefore, following Ernesto *et al.* (2002) alternative thermal sources can be found in the mantle with no implication of material transfer from the core or lower mantle to the lithosphere. Besides the indications from geoid anomalies, as mentioned before, the existence of long-living thermal anomalies or compositional differences in the mantle have already been demonstrated by velocity distribution models based on seismic tomography techniques, using both P- and S-waves (Zhang & Tanimoto, 1988; Li & Romanovicz, 1996; Van der Hilst *et al.*, 1997; Liu *et al.*, 2003).

On the whole, the geochemical results combined with the new $^{40}Ar/^{39}Ar$ ages for the magmatic events in Eastern Paraguay indicate that any model proposed for the evolution of the PAE in terms of HIMU and EM end-members must be consistent with the following constraints: (a) HIMU and EMI-II are not restricted to the oceanic environment; (b) end-members are variously associated in space as a function of the various protoliths; (c) mantle regions with HIMU and EMI isotope characteristics are capable of generating melts that can lead to the formation of a wide variety of silicate rocks, including melts enriched in CO_2 (Bell, 1998); d) systematically the sodic alkaline rock-types are grouped together, in fields well distinct in comparison with the potassic alkaline fields in Paraguay, but fitting the fields of potassic alkaline-carbonatite fields of the Angola-Namibia; e) even the Na-alkaline rock-types from the "Central Rift" of sub-Andean system (cf. Lucassen et al., 2002) fit the Triassic to Paleocene analogues from Eastern Paraguay.

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