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Petrologia. — *Eastern Paraguay: an overview of the post-Paleozoic magmatism and geodynamic implications*. Nota (*) di PIERO COMIN-CHIARAMONTI, CELSO DE BARROS GOMES, ANGELO DE MIN, MARCIA ERNESTO, ANDREA MARZOLI e CLAUDIO RICCOMINI, presentata dal Socio : Giuliano Panza

ABSTRACT. — Eastern Paraguay, at the westernmost part of the Paraná-Angola-Etendeka (PAE) system, at the westernmost fringe of the Early Cretaceous flood tholeiites (Serra Geral Formation, SGF), was the site of repeated and different magmatic activity from Mesozoic to Paleocene times. In the early Middle Triassic, sodic alkaline magmatism occurred along the belt represented by the Paraguay River, at the boundaries between Brazil and the Chaco-Pantanal basin. During the Early Cretaceous, potassic alkaline magmatism (where are present also alkaline-carbonatitic complexes) pre- and post-dates SGF. Further alkaline sodic magmatism occurred in Eastern Paraguay during late Early Cretaceous and Paleocene. The latter are characterized by the presence of abundant mantle xenoliths (spinel facies) in the ultramafic rock-types in the Misiones and Asunción provinces. Geological, petrological, mineralogical, geochemical and isotopic results suggest that almost two main mantle components have been involved in the genesis of the magmatism in Eastern Paraguay: an extreme and heterogeneous EM and a HIMU component. The EM-like component appear prevalent in the Early Cretaceous potassic alkaline magmatism, whereas the HIMU was important in the late Early Cretaceous and Paleocene sodic magmatism. Different contributions of mantle component similar to EM and HIMU could also explain the geochemical heterogeneity of the Early Cretaceous flood tholeiites in Eastern Paraguay (i.e. high- and low-Ti types, with high and low contents of incompatible elements, respectively). In the light of these facts, the mantle plume/hotspot hypothesis for the origin of the magmatism in Eastern Paraguay must be reviewed, at least regarding which plumes are most likely to have been active at the right place and right time for a specific province. In fact, in order to explain the widespread distribution of South American (Angolan and Namibian) Early Cretaceous tholeiitic and alkaline magmatism, a hypothetical mantle plume head is not compelling. We support rifting processes which resulted in different lithospheric thickness beneath the edge of cratonic shields, inducing small-scale convection cells. In addition, 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 geophysical evidence and geochemical results, combined with new well controlled ages (mainly $^{40}Ar/^{39}Ar$ 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 satisfy 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 compositions are capable of generating melts that can lead to the formation of a wide variety of silicate rocks, including melts enriched in CO_2 (including alkaline-carbonatitic complexes, i.e. mantle metasomatism); d) the geochemical features of the sodic alkaline rock-types cluster together, well distinct in comparison with the potassic alkaline from Paraguay, but consistent with the potassic alkaline-carbonatite rocks from Angola and Namibia; e) the paleomagnetic results indicate that any mantle plume hypothesis is in disagreement with the fixed and mobile plume models. Finally, it is suggested that a more complete fluidodynamic models must be developed for the plate-tectonic models.

(*) Pervenuta in forma definitiva il 6 settembre 2007.

KEY WORDS: Paraguay; Alkaline- and tholeiitic magmatism; Age; Geochemistry; Mantle plumes; Lithospheric mantle.

RIASSUNTO. — *Paraguay Orientale: una sintesi del magmatismo post-Paleozoico e implicazioni geodinamiche.* Il Paraguay Orientale, situato nella parte più occidentale del sistema Paraná-Angola-Etendeka (Namibia: PAE), è una regione interessata da ripetuta e differente attività magmatica in un arco temporale che si estende dal Mesozoico al Paleocene. Durante il Medio Triassico inferiore, un magmatismo alcalino sodico si estende lungo il corso superiore del Rio Paraguay, al confine tra il Brasile (bacino del Paraná) e il bacino Chaco-Pantanal. Durante il Cretacico Inferiore differenti tipi di magmatismo alcalino potassico (dove sono frequenti i complessi alcalino-carbonatitici) precedono e seguono le colate tholeiitiche della Formazione Serra Geral. Successivamente, durante il tardo Cretacico Inferiore e il Paleocene, si verificano altri due episodi di magmatismo alcalino sodico. Questi ultimi sono caratterizzati dalla presenza di abbondanti xenoliti di mantello (facies a spinello) nei tipi di rocce ultramafiche. In generale, le caratteristiche geologiche, petrologiche, mineralogiche, geochimiche e geochimico-isotopiche suggeriscono che nel Paraguay Orientale almeno due componenti di mantello sono state variamente coinvolte nella genesi del magmatismo dal Cretacico al Paleocene: una componente fortemente arricchita (tipo EM) e una componente "impoverita" (tipo HIMU). In particolare la componente tipo EM è assolutamente prevalente nel magmatismo alkalino potassico, mentre la componente tipo HIMU appare importante per il magmatismo sodico del tardo Cretacico Inferiore e del Paleocene. Contributi differenti dei componenti of EM e HIMU sono consistenti anche con la eterogeneità geochimica osservata nelle tholeiiti del Paraguay Orientale (come anche in tutto il bacino del Paraná), cioè varianti ad "alte" e "basse" concentrazioni in Titanio (ed elementi incompatibili). Alla luce di questi fatti deve essere rivista ogni ipotesi di "mantle plume" e "hot spot", relativa all'origine del magmatismo nel Paraguay Orientale, per lo meno in quanto inconsistenti dal punto di vista spazio-temporale. Infatti, per quanto riguarda la diffusione in Sud America (e Angola e Namibia) di magmatismo tholeiitico e alcalino, con caratteristiche geochimiche e petrogenetiche profondamente differenti che chiaramente riflettono eterogeneità di mantello (metasomatismo di mantello), una ipotetica "mantle plume" è difficile da sostenere. Si suggeriscono pertanto processi distensivi diffusi a differenti profondità litosferiche e attivi in particolar modo ai limiti delle differenti aree cratoniche e che inducono celle convettive a piccola scala. Per di più, la presenza di anomalie termiche di lungo periodo è stata messa in evidenza dai modelli di distribuzione delle onde sismiche, basati su tecniche tomografiche sia delle onde P che delle onde S. Nel complesso, le evidenze geofisiche combinate con i dati geochimici e recenti datazioni radiometriche controllate dal punto di vista degli equilibri isotopici (soprattutto datazioni ^{40}Ar/^{39}Ar su rocce e minerali), indicano che nel Paraguay Orientale ogni modello proposto per la evoluzione del PAE, in termini di componenti EM e HIMU, deve soddisfare le seguenti condizioni:
a) i componenti di mantello tipo HIMU e EMI-II non sono ristretti al solo ambiente oceanico; (b) questi componenti risultano variamente associati nello spazio in funzione di differenti protoliti; (c) regioni mantelliche con differenti composizioni isotopiche tipo HIMU and EMI sono in grado di generare fusi che possono portare alla formazione di una grande varietà di rocce silicatiche, inclusi fusi arricchiti in CO_2, e quindi complessi alcalino-carbonatitici; d) le caratteristiche geochimiche del magmatismo sodico, sia Mesozoico che Paleogenico, sono estremamente simili, ma ben differenti rispetto al magmatismo alcalino-potassico del Paraguay, e se mai consistenti col magmatismo potassico dell'Angola e della Namibia; e) le risultanze paleomagnetiche indicano che ogni modello relativo alla presenza di "mantle plume" non si accorda nè con la presenza di una "mantle plume" fissa, nè mobile. Infine si suggerisce che debbano essere sviluppati modelli fluidodinamici che tengano conto di tutte le variabili meccaniche del nostro pianeta per quanto riguarda una migliore definizione della tettonica a placche.

INTRODUCTION

The tectonic development of the South American (Western Gondwana) platform along about Lat. 20-28°S has been characterized by three major events: (a) the Gondwana amalgamation (c. 600 Ma; Trompette, 1994); (b) the development of extensive tholeiitic large igneous provinces, the Central Atlantic Magmatic Province (~ 200 Ma; Marzoli et al., 1999); c) the emplacement of the flood tholeiites of the Paraná Basin (c. 135-130 Ma, according to Rocha-Campos et al., 1988) which slightly preceded the opening of the South Atlantic ocean. Moreover, the formation of Andean orogen along the western margin of South America (c. 185 Ma to present) is also important.

Eastern Paraguay represents the westernmost fringe of Early Cretaceous flood tholeiites of the Paraná Basin (Serra Geral Formation, SGF; cf. Piccirillo and Melfi, 1988 and therein references). In addition, Eastern Paraguay has been the site of alkaline magmatism since Triassic times, i.e., sodic, in the early Middle Triassic, 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 SGF (Comin-Chiaramonti and Gomes, 1996, 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 Mesozoic continental tholeiitic basalts. Due to the high Sr and Nd concentrations of the alkaline rocks, it is reasonable to assume that their Sr and Nd isotope compositions have not been significantly affected by crustal contamination processes (Comin-Chiaramonti et al., 1997). Therefore, they may reflect the isotopic signatures of the mantle source(s), as also indicated by the associated carbonatites. Notably, also in the East Brazilian rift system magmatic activity spanned from Early Cretaceous through Mid-Cenozoic times and peaked between 132 and 120 Ma, 110 and 100 Ma, and 60 and 40 Ma (cf. Chang et al., 1992).

This paper offers a synthetical and crytical review of previous studies (e.g. Comin-Chiaramonti and Gomes, 1996, 2005; Comin-Chiaramonti et al:, 1997, 2007 and therein references) relative to the most important geochemical and isotopic data of the alkaline and tholeiitic magmatism of Eastern Paraguay. In particular, a careful selection of the best radiometric ages (mainly ^{40}Ar/^{39}Ar data on very fresh rock-types and/or unaltered biotite) was performed in order to constrain the spatial and temporal evolution of the involved subcontinental mantle source(s). The geodynamic implications are also reviewed.

PARAGUAY GEOLOGY

Eastern Paraguay lies in an intercratonic region including the westernmost side of the brazilian Paraná Basin (PB). The latter represents an undeformed basin at the western Gondwana part with sedimentation beginning in the Ordovician, tapped by Early Cretaceous tholeiitic flood basalts of the Serra Geral Formation (Zalan et al., 1990; Rogers et al., 1995) and followed by younger sedimentation (Fig. 1).

PB is bounded at its western side by an anticlinal structure established since Early Paleozoic, the Asunción Arch, separating the Paraná Basin (East) from the Gran Chaco (and Pantanal wetland) Basin (West) (Fig. 1; Almeida, 1983; Fulfaro, 1996; Comin-Chiaramonti et al., 1997, 1999).

The two basins have very different characteristics from a geophysical point of view: PB shows a high-velocity upper-mantle lid with a maximum S-wave velocity of

4.7 km/s (Moho 37 km depth), with no resolvable low-velocity zone to at least a depth of 200 km; on the other hand, the distinguished feature of the Chaco Basin consists of a rather shallow Moho 30 km depth (Feng et al., 2007), and low, asthenospheric, upper mantle S-wave velocities of about 4.2 km/s, with velocity increasing only slightly to about 4.3 km/s at about 150 depth (Snoke and James, 1997).

The basement rocks are mainly Precambrian to Early Paleozoic granitic intrusions and high to low-grade metasedimentary rocks, considered to be the northernmost occurrence of the Rio de La Plata craton and the southernmost tip of the Amazon craton (Fúlfaro, 1996; Comin-Chiaramonti et al., 1997; Cordani et al., 2001, 2005; Mantovani et al., 2005) at the southern and northern region of Eastern Paraguay (the Tebicuary block and the Apa block, respectively; cf. Fig. 1). Cordani et al. (2003a,b) suggested that Tebicuary area represent a late Neoproterozoic mobile belt, north of the Rio de La Plata, whereas Apa block corresponds to a Paleoproterozoic-Mesoproterozoic mass at the contact with the Paraguay mobile belt.

Betweeen these two blocks, Eastern Paraguay was subjected to NE-SW-trending crustal extension during Late Jurassic - Early Cretaceous, probably related to the western Gondwana breakup (cf. Comin-Chiaramonti et al., 1997, 1999 and therein references). NW-SE trending faults, paralleling the prevailing 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 grabens or semigrabens as a response to NE-SW-directed extension and continued evolving into Cenozoic times (Comin-Chiaramonti and Gomes, 1996; Comin-Chiaramonti et al., 1999). Notably, structural and geochronological data suggest that many of the alkaline occurrences along the western and eastern borders of the Paraná basin are linked to this extensional tectonics (Riccomini et al:, 2005). According to Tommasi and Vauchez (2001), rift orientations seem to have been controlled by the pre-existing lithospheric mantle fabric, as revealed by deep geophysical data.

The thermal history, using apatite fission track analyses (AFTA), reveals that at least two main episodes have been identified in sedimentary and igneous/metamorphic samples ranging in age from Late Ordovician (443-439 Ma) to Early Cretaceous (128-118 Ma; Hegarty et al., 1996). On the other hand, AFTA data from Asunción-Sapucai-Villarrica graben (ASU) show evidence for rapid cooling beginning some time between 90 and 80 Ma (similar to the results from Brazilian and Uruguayan coasts), followed by a Tertiary heating/cooling episode (about 60 Ma). The time of the Late Cretaceous event is significantly younger than any rifting activity related to the Paraná flood basalts and the opening of the South Atlantic, and the cooling may be involved several kilometers of differential uplift and erosion, playing an important role on the control of the geomorphology and drainage patterns in the region (cf. Fig. 1), especially in the Asunción-Sapucai-Villarrica graben system (see below).

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. Peate, 1997; Gibson et al., 2006) represent a giant tholeiitic dyke swarm, similar to the Brazilian Ponta Grossa dyke swarm (Piccirillo et al., 1990), mainly located in the northwestern part of the area, in particular north of the Asunción-Sapucai-Villarrica graben (ASVG). We have been intensively worked in the country since 1982 and up to now we did not find any field evidence of the dyke swarm, as suggested by Drueker and Gay. Thus, it is quite possible that most magnetic anomalies correspond indeed to Precambrian tectonic lineaments, as shown by Comin-Chiaramonti et al. (1999). On the contrary, in ASVG more than 200 alkaline dykes were sampled and mapped (Comin-Chiaramonti, 1992a, 1996c).

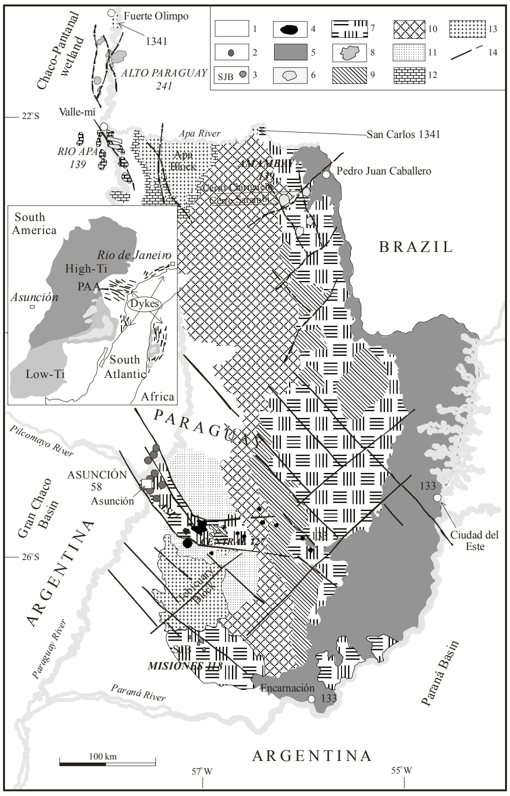

Fig. 1. - Simplified geological map of the Eastern Paraguay (after Comin-Chiaramonti, 1997; 1999 and unpublished geological maps) showing the main alkaline provinces in Eastern Paraguay. 1: Neogene and Paleogene sedimentary cover (Gran Chaco; Argentina, Partim; Eastern Paraguay; Chaco-Pantanal wetland, Paraguay and Brazil); 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 Neoproterozoic crystalline basement: high- to low-grade metasedimentary rocks, metarhyolites and granitic intrusions; 14: major tectonic lineaments and faults. The numbers of the main provinces (see text) are referred to the best geochronological results (this works and Comin-Chiaramonti *et al.*, 2007). 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 and Melfi, 1988), where the arrows indicate the occurrences of the main tholeiitic dyke-swarms. PAA: dyke swarm of the Ponta Grossa Arch. The basaltic lavas are subdivided into broad high- and low-Ti groups, and the late-stage rhyolites, according to Bellieni *et al.* (1984*a, b*), Piccirillo *et al.* (1988; light grey fields).

In summary, from the field stratigraphic control and starting from Mesozoic times, almost six main alkaline magmatic events have occurred in Eastern Paraguay, other than Early Cretaceous tholeiitic magmatism, i.e. three with sodic and three with potassic affinity, respectively (Fig. 1).

A. *Sodic-alkaline magmatism.*

*1) Alto Paraguay Province*Early Middle Triassic sodic magmatism of the Alto Paraguay Province is widespread at the southernmost side of the Amazon craton, along the Paraguay river, in an area corresponding to the eastern margin of the Chaco-Pantanal system (cf. Fúlfaro, 1996; Gomes et al., 1996; Comin Chiaramonti et al., 1999, 2005). This province encompasses the alkaline centers located at north of Valle-mí town, at the boundary zone between the Paraguay and the State of Mato Grosso do Sul in Brazil (Fig. 1).

The magmatic rocks, Triassic in age (241 Ma), are related to the oldest recognized alkaline magmatic event around the Paraná Basin (Amaral et al., 1967; Velázquez et al., 1992, 1996a, 1998a; 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 the village of Fuerte Olimpo, some outcrops, interpreted by Gibson et al. (2006) as alkaline complexes, are indeed metarhyolites showing an age of 1341 ± 53 Ma (Gomes et al., 2000).

Livieres and Quade (1987) related the magmatism of the Alto Paraguay Province to the Rio Apa Arch, whereas Velázquez et al. (1996a) related it to a cratonic margin. Due to the restricted area of the occurrences, with the bodies aligned in a narrow belt along the Paraguay river and the presence of structural lineaments, Velázquez et al. (1998a, b) pointed to the possibility of their tectonic control by N-S-trending faults. Taking into account that the stresses related to the Cabo-La Ventana orogeny (Tankard et al., 1995; Milani, 1997; Jaillard et al., 2002) have propagated into the inner parts of the Brazilian Platform following a general N-S-trend, Riccomini et al. (2005) proposed the hypothesis that a genetic relationship between the convergence in southwestern Gondwana and the Triassic alkaline magmatism in the Alto Paraguay Province may apply. On the basis of magnetotelluric and gravimetric results within the framework of the regional geology, Fisseha et al. (2003) suggested that the Pantanal wetland and the Alto Paraguay represent a collisional boundary between the Apa and Paraná blocks. Also according to the same authors, this boundary may be the evidence of the northward continuation of the Pampean belt (as Paraguay belt) under the Pantanal sedimentary cover.

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; cf. Fig. 1). It is related to a late Early Cretaceous magmatic event, with ^{40}Ar-^{39}Ar age data at ca. 118 Ma (Velázquez et al., 2003), and consists of small plugs and dykes of ankaratrite and melanephelinite bearing mantle xenoliths, tephrites and peralkaline phonolites (Comin-Chiaramonti et al., 1992b, 2007; Velázquez et al., 2003, 2006). On the contrary, Gibson et al. (2006) considered this magmatism as coeval with the Cenozoic Asunción plugs. Magnetometric and gravimetric data indicate a conspicuous set of NW-SE-striking structural lineaments, over 150 km long, at about 100 km south of the Asunción Rift (Velázquez et al., 1998a), suggesting crustal fracturing (Santa Rosa Graben; DeGraff and Orué, 1984; DeGraff, 1985). Recent investigations by Velázquez et al. (2002, 2006) confirmed that the alkaline bodies of this province were emplaced along NW-SE structures, under a NE trending extension.

3) Asunción Province. The Asunción Province comprises the mafic-ultramafic ultra-alkaline and phonolitic rocks of the western segment of the Asunción Rift. It marks an important tectono-magmatic activity during the Paleogene, with ^{40}Ar-^{39}Ar ages ranging between 68 and 52 Ma, but with a clear predominance in the 58-56 Ma span (Eocene; Velázquez et al., 1996b; Gomes et al., 2003; Comin-Chiaramonti et al., 2007), corresponding to the younger thermal peak indicated by the AFTA data (58 Ma; Hegarty et al., 1996). The mafic-ultramafic magmatic rocks are ankaratrites and melanephelinites, containing mantle xenoliths ranging 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, 1996a, 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, corresponding to a graben filled with fanglomeratic sediments with melanephelinite volcanic fragments and bombs (Riccomini et al., 2002). Systematic studies of faults and fracture patterns of various ultra-alkaline bodies (e.g. Ñemby, Lambaré and Benjamin Aceval) 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 melanephelinitic and ankaratritic bodies in relatively restricted areas indicate that the activity of deep faults caused great energy loss in the mantle, leading to subsequent melting of the lithospheric mantle (garnet facies, according to Comin-Chiaramonti et al., 2001) by decompression during a relatively short-time interval (Riccomini et al., 2001).

Notably, scarce sodic plugs and dykes also cut the potassic alkaline complexes of the Central Province (see below).

B. *Potassic-alkaline magmatism.*

4) *Amambay Province.* In the Amambay Province (northeastern Paraguay, along the boundary with Brazil), the magmatic activity formed mainly the ring-like alkaline-carbonatite complexes (e.g. Cerro Chiriguelo and Cerro Sarambí; see below). Pyroxenites, shonkinites, fenites and dykes of trachytes and phonolites also occur in the region (Comin-Chiaramonti et al., 1999). Recent ^{40}Ar-^{39}Ar ages fit 139 Ma, an age similar to that of the Velasco alkaline complexes in Bolivia (139 Ma; cf. Comin-Chiaramonti and Gomes, 2005), indicating the presence of a prior event with respect to the tholeiitic basaltic magmatism.. The Amambay Province is located within the domain of the NE-SW-trending Ponta Porã Arch (Thomas and 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., 1998b; Vidotti et al., 1998; Comin-Chiaramonti et al., 1999). These depressions probably represent sedimentary basins, and the uplifted block of the Ponta Porã Arch (Velázquez et al. 1998b; Comin-Chiaramonti et al., 1999 and therein references) hosts the Cerro Chiriguelo and Cerro Sarambí complexes. The tectonic control of alkaline intrusions of Amambay Province by the Ponta Porã Arch, as proposed by Livieres and Quade (1987), is supported also bby magnetic anomalies (Velázquez et al., 1998b).

5) *Rio Apa Province.* The magmatism in the Rio Apa Province consists only of a few occurrences of alkaline dykes near Puerto Valle-mí neighborood, at the margins of the Paraguay river. It includes thin small dykes (1-2 m thick) of carbonatitic-basanite affiliation (Castorina et al., 1996, 1997) cutting a platform

of limestones, along NE-SW-trending faults (Velázquez et al., 1998b). These faults were deep enough to allow the migration of primitive magmatic liquids from mantle to the surface across the entire block of Cambro-Ordovician carbonatic rocks (Velázquez et al., 1998b). Notably, the carbonates in the basanitic dykes are believed to be primary for their geochemical imprinting in comparison with the intruded sedimentary carbonates [i.e.: basanite carbonate, δ^{18}O‰ (V-SMOW) 8.53, δ^{13}C‰ (PDB-1) -6.8; sedimentary carbonates, δ^{18}O‰ 21÷24 and δ^{13}C‰ -1.7 ÷ +0.6; Castorina et al. (1997)]. As in the Amambay Province, the ^{40}Ar-^{39}Ar ages around 139 Ma (Velázquez et al. 1996b) and the field relationships (Censi et al., 1989) confirm that this magmatic event, coeval to the alkaline rocks of the Amambay province, preceded the tholeiitic magmatism of the Alto Paraná Formation, indicating an older Early Cretaceous magmatic pulse around the Paraná Basin. The alkaline dykes are associated with the tholeiitic dykes of the Alto Paraná Formation, also cutting the Cambro-Ordovician carbonatic platform. The latter are strongly alterated above all by late processes of epidotization, indicating high H_2O activity (cf. Castorina et al., 1996).

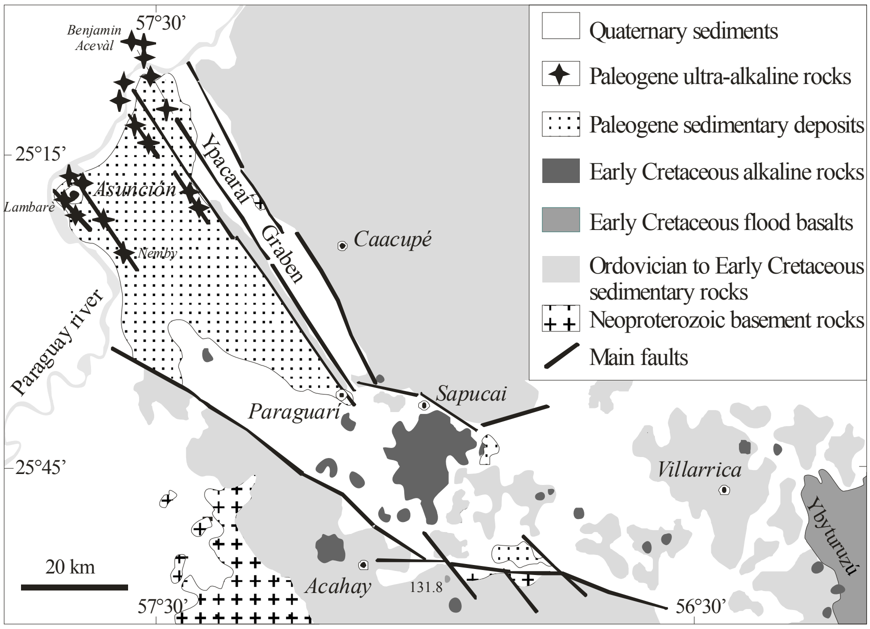

Fig. 2. - Simplified geologic map of the Asunción-Sapucai-Villarrica Rift with location of Early Cretaceous (Central Paraguay Province) and Paleogene (Asunción Province) alkaline rock occurrences (after Velázquez *et al.*, 1998*b*, modified and unpublished 1: 100,000 geological map of Comin-Chiaramonti mainly based on the 1: 100,000 topographic maps of the IGM, Paraguay, 1975). For the dykes, here not represented, see detailed maps of Comin-Chiaramonti *et al.* (1996*c*). The value 131.8±1.9 represent a whole-rock K/Ar age, Ma, of the tholeiitic sill of Cerro Obí (high-Ti andesi-basalt, K% =1.9108, ^{40}Ar Rad (ccSTP/g)10^{-6}=10.143, Atm ^{40}Ar%= 4.139; Comin-Chiaramonti, 1996*c* and Capaldi, unpublished data).

6) *Central Paraguay Province.* The Central Paraguay Province includes 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., 1998b; Comin-Chiaramonti et al., 1999 and therein references), is about 200 km long and 25 to 40 km widt. It is composed of three segments: (a) western, NW-SE oriented, between Benjamin Aceval (north of Asunción) and Paraguarí, about 90 km long; b) central, E-W oriented, from Paraguarí to Villarrica, extending around 70 km; and c) eastern, NW-SE oriented, from Villarrica to the Ybytyruzú highlands, with an approximate length of 40 km (Riccomini et al., 2005).

Dyke swarms, faults and joints distribution allowed Velázquez et al. (1998b) to suppose that the rift was generated under a right-lateral wrenching tectonic regime, associated with an E-W-trending oriented binary.

The potassic rocks are concentrated in the central and eastern segments. The ^{40}Ar-^{39}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 AFTA data indicate cooling commencing between 90 and 80 Ma from temperatures exceeding 110°C, suggesting a kilometre-scale uplift (cf. Fig. 2) at that time.

The alkaline bodies occur as stocks, plugs, lavas and and dyke swarms (Gomes et al., 1989; Comin-Chiaramonti et al., 1992a,b, 1995, 1996a,b) and also includes the great, ring-like intrusion of Cerro Acahay (Comin-Chiaramonti et al., 1990; Velázquez et al. 1992). Alkaline complexes and dykes intrudes also the tholeiitic flows of the Ybyturuzú highlands (Comin-Chiaramonti et al., 1996c).

The province mainly consists of potassic to highly potassic rocks with a wide petrographic variety (Velázquez, 1992; Comin-Chiaramonti et al., 1997). These rocks are grouped into two distinct suites, linked by fractional crystallization processes, one formed by basanites to phonolites and the other by alkaline basalts to trachytes, both including its corresponding intrusive terms (Comin-Chiaramonti et al., 1993; Gomes et al., 1996) In addition, a small occurrence of a silico-carbonatite flow has been identified not far from the Sapucai village (Comin-Chiaramonti et al., 1992c), as well as carbonate-rich “ocelli” characterize the Cañada and Cerro Est of St. Helena complexes. Also it should be noted that some tholeiitic dykes and sills (both high-Ti and low -Ti variants) are present in this area. In particular tholeiitic sills (e.g. Guayaquil and La Rosada, low-Ti; Cerro Obi, high-Ti), show K/Ar ages between 133 and 132 Ma (Capaldi, unpublished data; cf. Fig.2).

Younger Na-rocks of the central and eastern segments, intruding the potassic rocks, probably have an age similar to the alkaline-rocks from Misiones Province (Comin-Chiaramonti and Gomes, 1996), as indicated by previous K/Ar age on the whole-rock (Comin-Chiaramonti and Gomes, 1996).

PETROCHEMISTRY AND NOMENCLATURE OF THE ALKALINE ROCKS

Alkaline rocks may be distinguished into sodic or potassic. Following Middlemost (1986) and Le Maitre and IUGS (1989), the chemical screens adopted for the alkaline rocks from Eastern Paraguay (cf. Comin-Chiaramonti et al., 1997, Comin-Chiaramonti and Gomes, 1996, 2005), consistent also with the mineral chemistry (Comin-Chiaramonti et al., 1990, 1992a; Cundari and Comin-Chiaramonti, 1996) are as follows:

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).

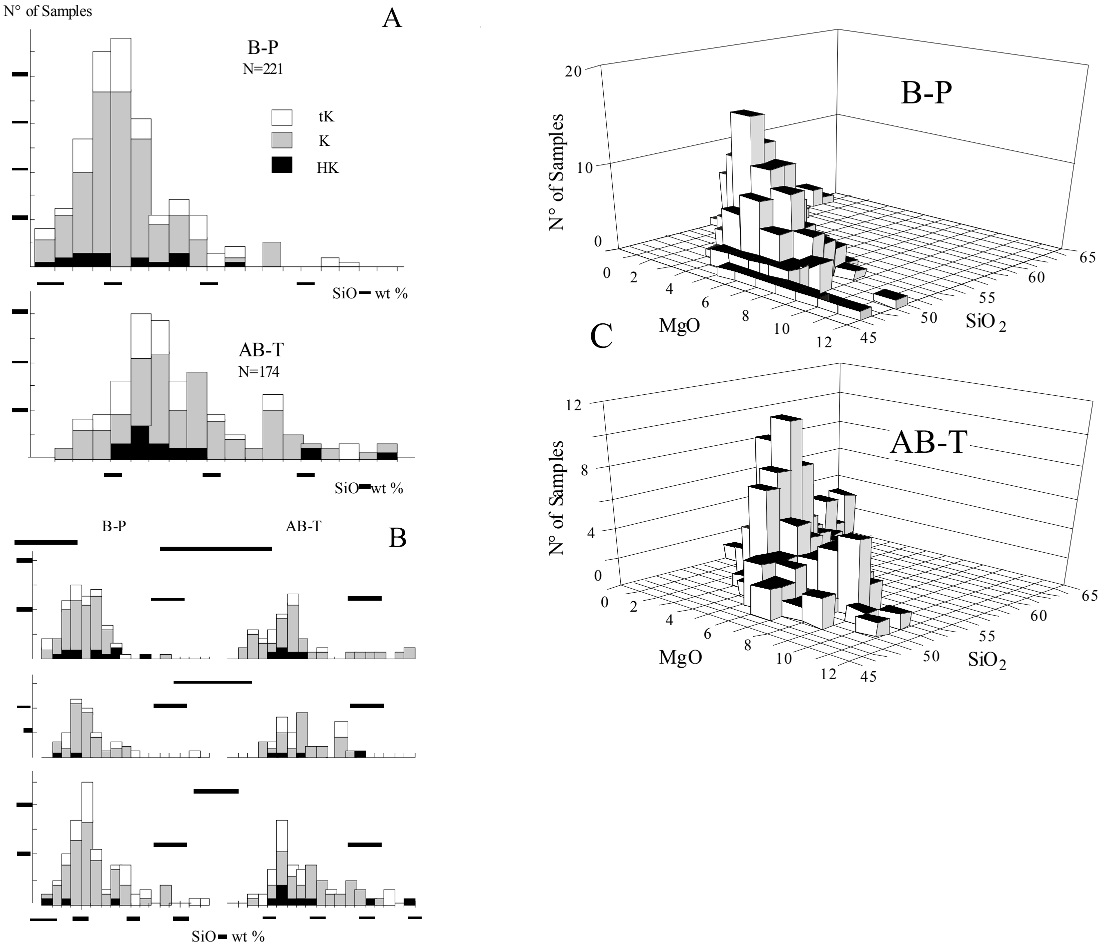

Fig. 3. - Alkaline potassic specimens. A. SiO_2 (wt%) histograms for basanite / tephrite / phonotephrite / phonolite (B-P) and alkali basalt / trachybasalt / trachyandesite / trachyphonolite/trachyte (AB-T) suites, HK: $K_2O \geq 2$, K: $2 < K_2O/Na_2O < 1$, tK: $K_2O/Na_2O < 1$. B. Histograms subdivided into intrusives, lavas and dykes. C. 3Dhistograms showing frequencydistribution for SiO_2 vs. MgO, wt% for the B-P and AB-T suite,respectively. Data source: Comin-Chiaramonti and Gomes (1996).

Asunción-Sapucai-Villarrica (ASU) graben.

A total of 523 specimens (intrusives, effusives and dykes) from ASV (Comin-Chiaramonti and Gomes, 1996), analyzed on the basis of the field, age, petrography, mineral chemistry and petrochemistry, were classified following the above criteria and following nomenclature after De La Roche et al. (1980) and De La Roche (1986), and adopting the chemical classification proposed by Le Maitre (1986). 18% of the analyzed 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 the dykes: 17% N, 22%tK, 55% K, 6% HK (Comin-Chiaramonti and Gomes, 1996).

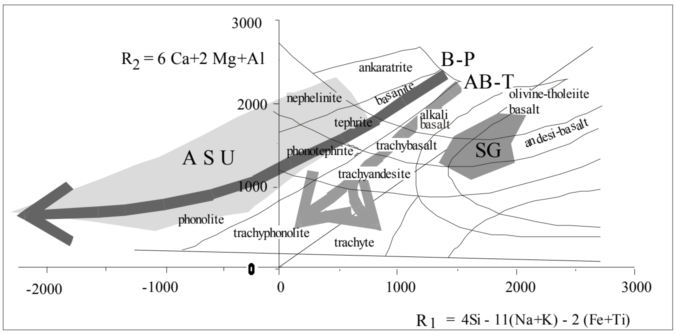

Fig. 4. - R1 - R2 plot, in terms of De la Roche's (1986) diagram (cf. Comin-Chiaramonti and Gomes, 1996; Comin-Chiaramonti *et al.*, 1997). R_1=4Si-11(Na+K)-2(Fe+Ti), R_2=6Ca+2Mg+Al, with the fields of the tholeiitic (SG) and alkaline (sodic) rocks (ASU) from Eastern Paraguay and the general trends of the **B-P** and **AB-T** potassic suites (only the lavas nomenclature is shown). Data sources: Bellieni *et al.* (1986a), Piccirillo and Melfi (1988), Demarchi *et al.* (1988), De Min (1993), Comin-Chiaramonti *et al.* (1991, 1992, 1995*a*, *b*, 1997), Comin-Chiaramonti and Gomes (1996), Cundari *et al.* (1996). It should be noted that textural, mineralogical and petrochemical evidence points to fractional crystallization as a potentially important process 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.*, 1996b, 1997) yielded ΣR^2<2 wt% of early-formed phases, *i.e.* olivine + clinopyroxene + magnetite ± plagioclase ± mica ± leucite ± apatite (Comin-Chiaramonti *et al.*, 1997: tab. 3). 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 originated 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 originated 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 yieldedobserved/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-liq relationships predicted by Roeder and Emslie (1970; see also mineral chemistry, Comin-Chiaramonti *et al.*, 1997: fig. 7A) 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 the ASU rocks. 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 and Mathews, 1981). Convergence of X and Y values was obtained (Fig. 16 of Comin-Chiaramonti *et al.*, 1996*b*), particularly for B-P (Comin-Chiaramonti *et al.*, 1996*a,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.

Potassic rocks.

The potassic rocks from **Amambay** Province are mainly represented by evolved rock-types as trachytes associated with glimmeritic dykes and carbonatitic bodies (Cerro Chiriguelo and Cerro Sarambí; Censi et al., 1989; Castorina et al., 1997). The Cerro Chiriguelo complex is partially covered by tholeiitic flood basalts of the Paraná Basin (Censi et al., 1989; Cundari and Comin-Chiaramonti,1996). In the **Rio Apa** province, scarce basanitic dykes, primary carbonate-rich, are present (Castorina et al., 1997; Comin-Chiaramonti et al., 1999). The potassic rocks, mainly concentrated 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, evolving through fractional crystallization, starting from different parent magmas (De Min, 1993; Comin-Chiaramonti et al., 1997; cf. Fig. 4).

The results are diagrammatically represented in Fig. 4 (cf. Figs. 4, 5, 6 and 11 of Comin-Chiaramonti et al., 1996a and Figs 1, 2, 3 of Comin-Chiaramonti et al., 1996b). Some of these potassic rocks intrude the flood tholeiites of the Paranà Basin, especially at the Ybytyruzú highlands (Bellieni et al., 1986a).

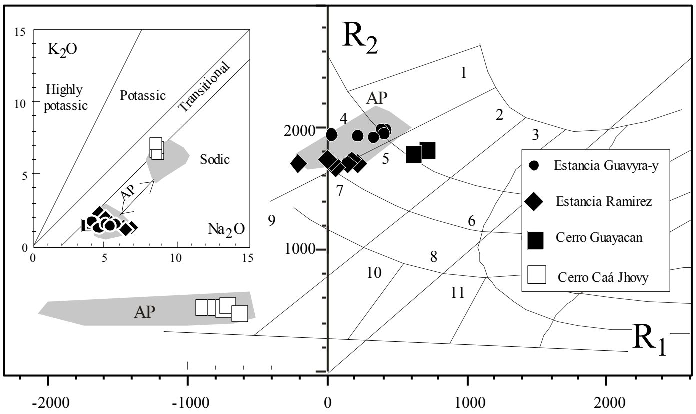

Fig. 5. - Compositional variation for the Misiones rocks in terms of De La Roche's diagram (1986; cf. fig. 4). **Inset**: Na_2O vs K_2O (wt%) diagram. The fields from the Asunción Province are also shown (AP). Data source: Velázquez *et al.* (2006, and therein references).

Sodic rocks.

Other than in the Alto Paraguay Province, they are mainly concentrated in the **Asunción Province** and represented by ankaratrites+melanephelinites (45%) and phonolites (42%). Very subordinate, and widespread in the Central Province are tephrites, alkali basalts, hawaiites and mugearites (cf. Fig. 5).

Mantle xenoliths are abundant in the ankaratrite and melanephelinites of the Asunción Province (see below). They are spinel lherzolites, harzburgites and dunites up to 45 cm in diameter with protogranular texture and variable amount of glassy patches, similar to the "blebs" of Maaløe and Prinzlau (1979). These mantle xenoliths, indicative of a depleted, variously metasomatized upper mantle, were described in detail elsewhere (Comin-Chiaramonti et al., 1986, 1991, 2001; Demarchi et al., 1988; see 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 xenoliths 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 analogues from the Asunción Province. The mantle xenoliths belong to the spinel facies and are very similar to those from the Asunción analogues.

AGES OF THE MAGMATISM

Alkaline magmatism.

Old available radiometric ages, mainly based on Rb/Sr isochrones, K/Ar determinations and on fission track techniques (Amaral et al., 1967; Bitschene, 1987; Comin-Chiaramonti et al., 1997), are available on request to the corresponding author.

The averaged results show a very large spreading in age, i.e., Alto Paraguay (19 samples), 235±14 Ma; Rio Apa and Amambay (9 samples), 140.1±8.8 Ma; Central Province (potassic magmatism, 33 samples), 127.9±5.6 Ma; Misiones (1 sample), 120±5 Ma; Central Province (sodic magmatism, 7 samples), 112±11 Ma; Asunción (18 samples), 51.1±9.6 Ma.

Gibson et al. (2006) show rather different ^{40}Ar-^{39}Ar ages, quoting only 8 lamprophyres (?) and one trachytic rock: Valle-mí, 159 Ma (1 sample); Amambay, 143±2 Ma (3 samples); Central Province, 127.4±1.2 Ma (5 samples). In particular, in their Fig. 4, they distinguished three Early Cretaceous alkaline provinces, i.e. Alto Paraguay Province (143 Ma, including Rio Apa, Triassic sodic complexes from Alto Paraguay and even the Precambrian rhyolitic bodies near Fuerte Olimpo; cf. Fig. 1), Amambay Province (145 Ma), Sapucai-Villarrica Province (127.5 Ma), other than a lot of Cenozoic outcrops widespread in the Asunción and San Juan Bautista regions.

Our recent "high quality" ^{40}Ar-^{39}Ar measurements were performed by argon-ion laser-heating system. Over a lot of 76 ^{40}Ar-^{39}Ar ages, only 33 samples have been considered as representative of the ages of the post-Paleozoic various magmatic events in Eastern Paraguay, i.e. those having plateau and miniplateau ages defined by at least three successive concordant steps and by at least 70% and 50%, respectively, of the total released ^{39}Ar (see Comin-Chiaramonti et al., 2007, for a discussion). These "high quality" data are not only based on the new ^{40}Ar-Ar^{39} techniques, but also taking into consideration the mineralogical equilibria of the analyzed phases as were controlled by microprobe and diffractometrical (i.e. structural) analyses.

According to this criterion, with , as standard deviation;□the exception of the Central Province, the results (1 cf. Tab. 2 of Comin-Chiaramonti et al., 2007) are quite different from Gibson et al. (2006), as below:

1. Alto Paraguay Province: 241 ± 1 Ma (N=3)
2. Apa Province: 138.9 ± 0.2 (N=1)
3. Amambay Province: 138.5 ± 0.8 (N=2)
4. Central Province: 126.8 ± 1.3 (N=17)
5. Misiones Province: 118.3 ± 0.9 (N=4)
6. Asunción Province: 58.4 ± 2.1 (N=6)

Notably, the major differences with respect with the old reported ages, other than the standard deviation, are for the Alto Paraguay, Asunción and Misiones Provinces, for which Triassic, late Early Cretaceous and Paleocene ages, respectively, have been ascertained.

Tholeiitic magmatism.

From the stratigraphical point of view, the age of the tholeiitic magmatism in Eastern Paraguay is well constrained as younger than 138 Ma (Amambay Province, northeastern Paraguay, where tholeiitic flood basalts, high-Ti variants, partially cover the Cerro Chiriguelo alkaline-carbonatitic complex, dated at 138.5 Ma), and older than 126-128 Ma (Central Province, where the S. Helena alkaline complex, dated at 126 Ma, intrudes the tholeiitic flows, low-Ti variants, in the Ybyturuzú highland; Comin-Chiaramonti et al., 2007).

In a review relative to the old radiometric ages available for the Paraná flood basalts, Rocha-Campos et al. (1988) suggested that the main eruptive phase occurred between 135 and 130 Ma. Renne et al. (1992), studying the lavas of southern Brazil (^{40}Ar/^{39}Ar ages), concluded that the Paraná magmatism began at 133±1 Ma and lasted less than one million years, consistent with the data of Hawkesworth et al. (1992) for this region. On the other hand, Turner et al. (1994) and Stewart et al. (1996) suggested that the Paraná lavas were erupted over a longer interval (~10 my.) between 137 Ma and 127 Ma.

Analyses ^{40}Ar/^{39}Ar by Renne et at. (1996) on the Ponta Grossa dykes (inset of Fig. 1) that are inferred to be the feeders of the northern Parana lavas, gave distinctly younger ages (129.2±0.2 to 131.4±0.4 Ma) than those measured for the southern lavas. Thus, Renne et al. (1996) revised their estimate of the duration of the main pulse of magmatism to about 3 m.y.

The older ^{40}Ar/^{39}Ar ages (138 to 135 Ma) of Turner et at. (1994) and Stewart et al. (1996) are found only in flows and dykes in the northern and western margins of the Paraná lava field and at the base of some of the central Parana boreholes, but a ^{40}Ar/^{39}Ar age of 132 Ma has been determined for a tholeiitic flow at about 50 km NW of Pedro Juan Caballero township (cf. Fig. 1), and a K/Ar age of 131.8±1.9 was obtained for the Cerro Obí sill intruding the Ordovician-Silurian sediments of Caacupé and Itacurubí Goups (Fig. 2; cf. Fig. 7 of Comin-Chiaramonti et al., 1996c). In particular, Gibson et al. (2006), in their Fig.4, reported the following ages, after Stewart et al. (1996): San Estanislao, 138.1 Ma; Foz do Iguazú, 139.1 and Encarnación 137.9. In general these samples are strongly affected by secondary alteration and weathering (as shown e.g. by the diffusion of celadonite and iddingsite in the groundmass, i.e. deuteric alteration; cf. Appendix I of Piccirillo and Melfi, 1988). As matter of fact, measurements achieved in very fresh samples (e.g. Guayaquil sill, high-Ti, granophiric concentrates) and at Foz do Iguazú and at Encarnación (low-Ti) tholeiitic rocks gave ^{40}Ar/^{39}Ar ages around 133 Ma (Renne et al., 1993).

In summary, values varying from 134 to 130 Ma may be considered as the best age span for the **Serra Geral tholeiitic magmatism** from Paraguay (cf. Fig. 1), mainly based on the "high quality" ^{40}Ar/Ar^{39} determinations from the "very fresh" samples (cf. Comin-Chiaramonti, 1988; Renne et al., 1992, 1993, 1996), on the paleomagnetic results of Ernesto et al. (1996, 1999, 2000, 2002) and Ernesto (2005) and on the crystallographic data (cf. Piccirillo and Melfi, 1988). This result approaches that of Stewart et al. (1996) proposing that the main pulse of the tholeiitic magmatism occurred between 133 and 129 Ma in the whole Paraná-Angola-Namibia system.

Table I. Selected analyses of the main "primitive" alkaline rock-types from Eastern Paraguay (after Comin-Chiaramonti *et al.*, 1999, 2007, and Comin-Chiaramonti and Gomes, 1996, 2005). $(La/Ta)_N$: normalized ratios to the primitive mantle of Sun and Mc Donough (1989). TDM are calculated assuming the following values for the depleted mantle: $^{143}Nd/^{144}Nd$ = 0.513151 and Sm/Nd = 0.2188 (Faure, 1986). $f_{Sm/Nd}$ = $[(^{147}Sm/^{144}Nd)_{Sample} - (^{147}Sm/^{144}Nd)_{CHUR}]/(^{147}Sm/^{144}Nd)_{CHUR}$ (DePaolo, 1988).

	ALTO PARAGUAY	VALLE-MÍ	AMAMBAY	VALLE-MÍ	VALLE-MÍ	CENTRAL REGION	CENTRAL K-ASU	CENTRAL K-ASU	MISIONES	ASUNCION
Rock-type	Na-Nepheline syenite	K-Basanite	K-Tephrite	L-Ti Tholeiitic basalt	H-Ti Tholeiitic andesi basalt	L-Ti Tholeiitic basalt	K B-P Ijolite	K AB-T Trachy basalt	Na-Ankaramite	Na-Mela nephelinite
Sample	RP-232	VM-3	SA-94	ST-1	VM-2	3006	77-PS245	D159-PS9	01A	3209
wt%										
SiO_2	54.15	43.38	46.01	48.23	51.49	49.00	44.11	49.43	40.47	42.51
TiO_2	1.62	1.87	1.73	1.44	2.42	1.43	2.01	1.65	3.44	2.05
Al_2O_3	15.70	11.20	13.25	16.20	15.36	14.41	12.82	14.36	12.51	13.41
FeO_{tot}	8.35	10.17	8.31	12.33	12.22	12.28	9.16	8.37	11.64	10.10
MnO	0.43	0.20	0.12	0.17	0.20	0.16	0.19	0.16	0.19	0.20
MgO	2.75	12.08	5.70	7.51	4.13	7.12	9.53	7.61	10.06	9.54
CaO	3.96	15.66	8.46	8.59	6.80	10.92	10.32	7.55	11.27	10.45
Na_2O	6.42	1.38	2.92	2.52	3.04	2.19	3.34	2.29	4.03	5.80
K_2O	4.35	1.61	6.36	0.74	1.24	0.33	5.41	5.72	1.82	1.46
P_2O_5	1.13	0.54	0.59	0.20	0.37	0.14	0.75	0.34	0.71	1.18
LOI	0.38	1.95	6.04	1.58	2.48	1.53	1.23	1.07	1.82	2.19
Sum	99.24	99.94	99.49	99.51	99.75	99.49	98.87	98.55	97.96	98.89
Age (Ma)	241	139	139	133	133	133	127	127	118	58
ppm										
Cr	5	317	110	251	28	349	288	376	301	648
Ni	12	91	32	119	17	114	109	81	126	273
Rb	93	41	121	29.1	39	13.8	114	119	77.4	59
Ba	859	973	2465	301	463	160	1958	1334	953	980
Th	8.6	19.0	16.0	2.16	6.5	1.00	6.6	32.2	5.80	11.0
U	3.0	4.2	4.1	0.95	1.5	0.20	1.7	7.4	1.00	2.4
Ta	11.6	4.5	3.7	0.55	1.1	0.25	3.1	1.1	4.10	8.1
Nb	241	47.6	48.6	4.02	16	1.82	41	37	72	141
Sr	384	1151	2916	376	395	163	1624	1163	1001	1013
Hf	13.9	4.7	9.6	2.80	6.9	1.82			6.10	5.5
Zr	835	203	415	109	240	73	279	268	267	234
Y	71	23	31	31	52	27	19	19	23	33
La	136.00	156.6	162.6	12	23.1	5.50	108	81	63.21	119
Ce	273.01	309.2	268.7	39	53.1	15.01	204	119	117.98	186
Pr	28.50						23.8	13.0		
Nd	99.21	148.7	137.2	20	28.3	12.2	90.2	49.1	57.84	63.70
Sm	19.32	23.8	14.7	3.54	6.8	3.1	13.8	9.81	10.62	11.23
Eu	2.40	6.30	3.88	1.21	2.52	1.05	3.67	2.59	3.04	2.15
Gd	18.40	21.71			8.26		9.09	4.71	5.87	5.16
Tb	2.71	3.02	1.05	0.67	1.36	0.66	1.11	0.65	1.00	0.75
Dy	17.19	7.60			7.95		4.70	3.40	5.70	4.21
Ho	2.12	1.12	0.50		1.44		1.09	0.64		
Er	6.42	3.23	1.41		4.31		1.77	1.70	2.99	2.75
Tm	1.10	0.36			0.66		0.24	0.27		
Yb	5.80	3.20	1.30	2.11	4.48	2.10	1.36	1.32	1.87	1.79
Lu	0.80	0.61	0.21	0.39	0.63	0.27	0.24	0.19	0.27	0.27
$(La/Ta)_N$	0.70	2.08	2.16	1.30	1.25	1.31	2.02	4.39	0.92	0.88
Initial ratios										
$^{87}Sr/^{86}Sr$	0.703749	0.706618	0.707341	0.705862	0.705710	0.705157	0.707342	0.707249	0.704157	0.703596
$^{143}Nd/^{144}Nd$	0.512390	0.511868	0.511635	0.512420	0.512341	0.512266	0.511844	0.511650	0.512411	0.512717
$^{206}Pb/^{204}Pb$	18.278	19.968	17.033	17.432	17.752	18.300	17.624	17.040	18.197	18.935
$^{207}Pb/^{204}Pb$	15.662	15.641	15.506	15.511	15.546	15.618	15.620	15.439	15.682	15.677
$^{208}Pb/^{204}Pb$	38.062	38.589	37.465	38.103	38.145	38.315	37.915	37.156	37.936	38.432
TDM(Nd)	867	1490	1440	870	1415	1751	1578	2323	925	533
$f_{Sm/Nd}$	-0.40	-0.51	-0.67	-0.46	-0.26	-0.22	-0.53	-0.39	-0.44	-0.46
μ	14.02	15.03	13.21	23.48	9.31	6.83	12.24	11.91	12.73	12.60
κ	3.34	3.50	1.51	2.35	4.87	5.17	4.01	6.76	5.56	5.62
Fe_2O_3/FeO	0.56	0.47	0.22	0.17	0.22	0.22	0.33	0.33	0.23	0.33
Mg#	0.51	0.72	0.59	0.56	0.42	0.55	0.71	0.68	0.66	0.69

GEOCHEMISTRY

Incompatible Elements, IE, Large Ion Lithophile Element, LILE, and High Field Strength Element, HFSE, ratios, coupled with the Sr-Nd-Pb isotopic compositions, appear to indicate that the magmatic events in the Eastern Paraguay were generated from geochemically distinct sources (enriched vs. depleted mantle sources; Comin-Chiaramonti and Gomes, 1996, 2005; Comin.Chiaramonti et al, 1997, 2007). Chemical analyses, representative of the "most primitive" alkaline rocks are reported in Table I.

Incompatible elements.

The IE patterns (mantle normalized) for the various and different magmatic rock-groups are diagrammatically represented in Fig. 6.

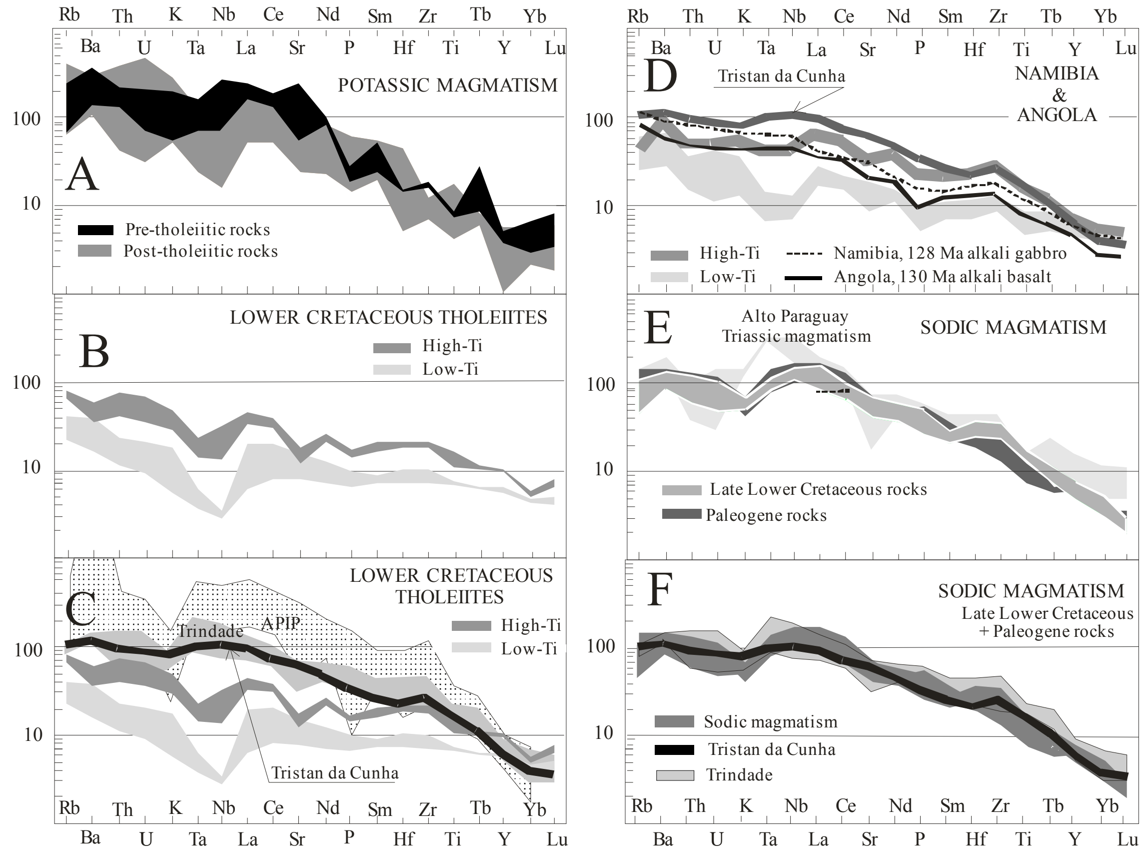

Fig. 6. - Eastern Paraguay: incompatible elements (data sources: Comin-Chiaramonti and Gomes, 1996, 2005; Comin-Chiaramonti *et al.*, 1997, 1999) normalized to the primitive mantle (Sun and McDonough, 1989) representative of the compositions of the mafic K-alkaline rocks (A) and tholeiites (B), compared with Trindade and Tristan da Cunha basanites and APIP rocks (C: Le Roex and Lanyon, 1998; Marques *et al.*, 1999*a*; Siebel *et al.*, 2000; Comin-Chiaramonti and Gomes, 2005). D: high- and low-Ti «uncontaminated» tholeiitic basalts from Angola and Namibia in comparison 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 Paleocene ages from Paraguay (Comin-Chiaramonti *et al.*, 1999; Velázquez *et al.*, 2006). F: sodic mafic magmatism (late Lower Cretaceous+Paleocene) related to the field of the Tridade and Tristan da Cunha basanites.

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

Pre- and post-tholeiites potassic alkaline rocks from Rio Apa-Amambay and ASU, respectively, representative of low-Ti potassic variant (cf. Gibson et al., 1995a,b, 1997, 1999; Carlson et al., 1996; Comin-Chiaramonti et al., 1999, 2004, 2007), show quite similar IE patterns that, in general, are characterized by LILE enrichment and HFSE depletion (Fig. 6A). The latter geochemical features suggest that the enrichment processes were related to small-volume melts in a lithospheric mantle (Castorina et al., 1997; Comin-Chiaramonti et al., 1997, 2004, 2007). On the other hand, high-Ti potassic rocks are typical of the Late Cretaceous potassic magmatism from the APIP (Alto Paranaíba Igneous Province of Gibson et al., 1995a) and Namibia suites which, on the contrary, are characterized by HFSE enrichments (cf. Fig. 6D; Milner et al., 1995; Milner and Le Roex, 1996; Le Roex and Lanyon, 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. 6B). In general, the marked Ta-Nb negative spikes of the Paraná tholeiitic basalts are similar to those of the potassic alkaline magmas, but clearly they differ from the Mesozoic to Cenozoic sodic alkaline rocks from the same area, and from the “hot-spot” basalts from southern Atlantic islands (Tristan da Cunha and Trindade, OIB) that display a potassic affinity (Figs. 6 E and F).

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

Sr-Nd isotopes.

The investigated rocks from Eastern Paraguay show a large distribution on the Sr-Nd isotopic compositions (Fig. 7A), describing a trend similar to the "low Nd" array of Hart and Zindler (1989; cf. “Paraguay array” of Comin-Chiaramonti et al., 1996c). Due to the high Sr and Nd content of the most "primitive" alkaline rocks (and associated carbonatites, see below) from Eastern Paraguay, Comin Chiaramonti et al. (1999) suggested that initial Sr-Nd isotopic ratios of such rock-types can be considered crustally uncontaminated and, as a result, representative of the isotopic composition of the mantle source(s) (cf. Comin-Chiaramonti et al., 1997, 1999).

The potassic alkaline rocks, both pre- and post-tholeiites, have the highest initial (time integrated) Sr_i and the lowest initial Nd_i. Including the Cerro Chiriguelo and Cerro Sarambí carbonatites (Comin-Chiaramonti and Gomes, 1996, 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 Province: ca. 118 Ma; Sr_i=0.70486±0.00043, Nd_i=0.51226±0.00015), and of the Paleocene sodic rocks (Asunción Province, 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, Sr_i and Nd_i 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., 2005a, 2007).

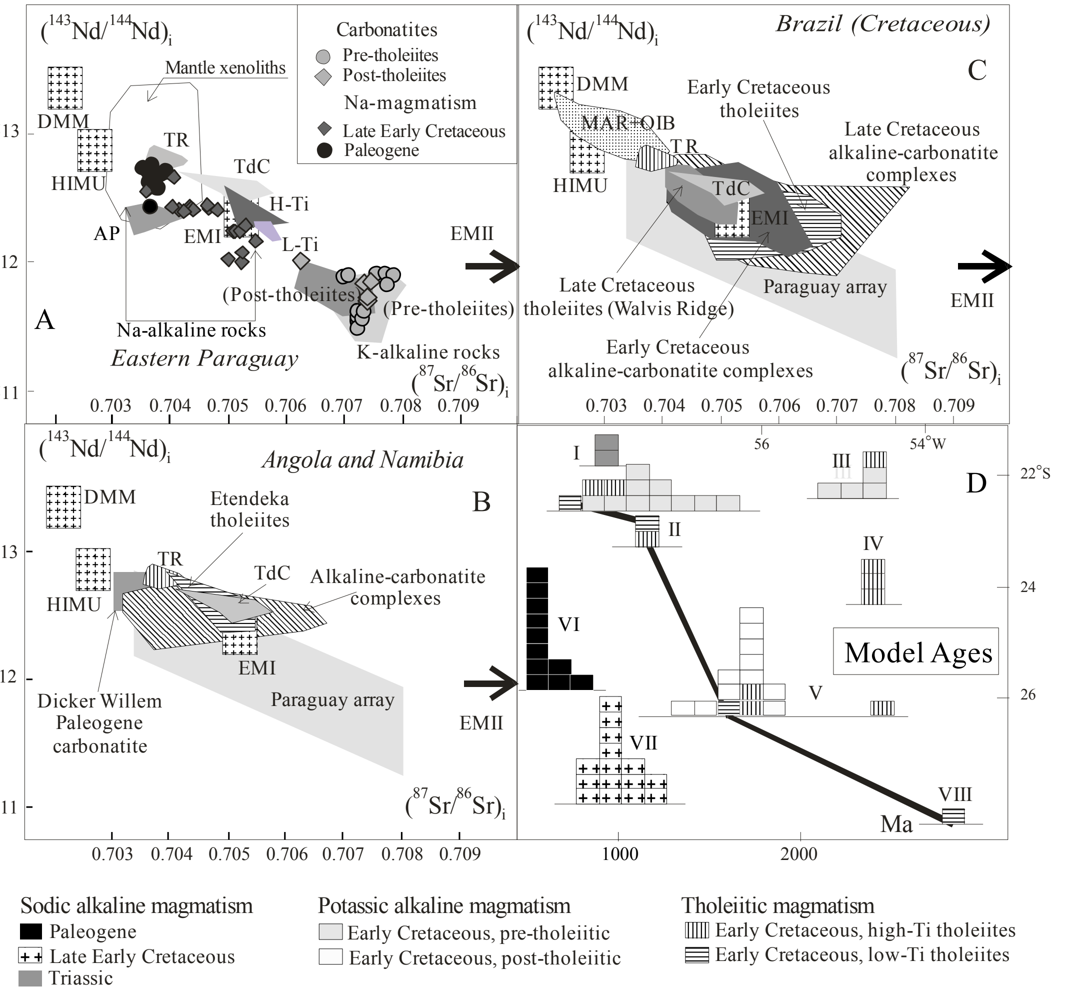

Fig. 7. - Initial $^{87}Sr/^{86}Sr$ (Sr_i) vs. $^{143}Nd/^{144}Nd$ (Nd_i) diagram for the magmatic rocks from Eastern Paraguay (A) compared with Angola and Namibia (B) and Brazil (C). AP, Alto Paraguay; TR: Trindade; TdC, Tristan da Cunha; H-Ti and L-Ti, high-Ti and low-Ti tholeiites, respectively. Data source and other symbols as in fig. 6. DMM, HIMU, EMI and EMII fields after (Zindler and 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. Heavy line joins «L-Ti» tholeiites. Data sources: Comin-Chiaramonti and Gomes (1996, 2005).

These intrusions have elemental and Sr-Nd isotopic compositions similar to those of the coeval (~132 Ma) high-TiO_2 tholeiites from southern Paraná Basin (Urubicí-type, Brazil, of Peate et al., 1999) and from northern Etendeka (Khumib-type, Namibia, Peate et al., 1999; Ewart et al., 2004). The genesis of these tholeiites requires lithospheric mantle components, as represented by K-alkaline (and carbonatitic) rocks from the Asuncion–Sapucai graben (Paraguay), that highlight the intriguing Pb-isotope relationships involving the Urubicí and Khumib tholeiites (see below).

Notably, few 130 Ma high-Ti tholeiitic dykes (Urubicí type, southern Paraná region, of Peate, 1997; cf. Peate et al., 1999) outcropping at the southernmost part of the S.Francisco craton (northern Paraná Basin) show high radiogenic Sr isotopic data not related to crustal contamination (Sr = 600-1000 ppm) and comparable with those from the ASU potassic rock-types (Rosset et al., 2007).

Late Cretaceous potassic alkaline-carbonatitic complexes have the following Sri and Ndi 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).

It should be noted 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 and Rabinowitz, 1984).

Mantle xenoliths.

Mantle xenoliths of the protogranular spinel facies are widespread in the Asunción and Misiones Provinces, respectively and were classified into two main suites, LK (relatively low in potassium and incompatible elements, IE) and HK (high in K and IE), both ranging from lherzolite to dunite and showing trends of "melt extraction", as indicated by the chemistry of the major elements (Comin-Chiaramonti et al., 1986, 1991, 2001; Demarchi et al., 1988), and by modal analyses (LK: Cpx 2-10 vol%, Cpx/Opx = 0-0.10; HK: Cpx 0.01-12 vol%, Cpx/Opx = 0.1-0.8; Demarchi et al., 1988) . In particular, the HK suite is characterized by spongy texture of the clinopyroxenes (hosting up to 17vol% of glassy drops) and by glassy patches (blebs).

The IE contents of the clinopyroxenes encompass the world-wide occurrences (Comin-Chiaramonti et al., 2001). This fact suggests that metasomatizing processes, other than depletion, occurred in the mantle sources. K is mostly partitioned into blebs in the xenoliths and glassy drops in clinopyroxenes. The blebs have been interpreted as derived from break down of volatile-bearing phases, such as amphibole and/or phlogopite, which melted during the ascent to the surface. Sometimes the blebs contain primary carbonates (δ^{18}O‰=+8; δ^{13}C‰ =-9.5). On the other hand, the glassy drops may represent the products of incongruent partial melting induced by the decompression processes. Both blebs and drops probably are the remnants of hydrous phases and/or products induced by the influx of small-volume, volatile-rich melts (Comin-Chiaramonti et al., 1986; Demarchi et al., 1988).

The clinopyroxenes from xenoliths 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 showing 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 also 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 approach enriched or undifferentiated compositions (Comin-Chiaramonti et al., 2001).

Alkaline basaltic magmas from deeper, garnet-bearing mantle source 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 (Comin-Chiaramonti et al., 2001). 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 the ^{18}O‰ (cpx-ol). The oxygen isotope compositions on separates of clinopyroxene and coexisting olivine (Δ^{18}O‰) range from 5.5 to 6.0‰, and from 5.0 to 6.1‰, respectively (Table 1 of Comin-Chiaramonti et al., 2001). These measured isotopic ratios are in the range of values for worldwide mantle phases (olivine 4.4 to 7.5‰, clinopyroxene 4.8 to 6.7‰; cf Chazot et al., 1994 and therein references) and for South America mantle xenoliths (olivine 4.9 to 6.4‰, clinopyroxene 5.0 to 6.0‰; cf Kyser, 1990).

All 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 a mixing with an 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 Paleocene: 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; cf. Comin-Chiaramonti et al., 1997, 1999, 2001), 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 the lithospheric thinning and repeated interactions between fluids and overlaying peridotites (i.e. metasomatized upper mantle; cf. Comin-Chiaramonti et al., 1986, 1999, 2001, 2007).

Carbonatitic imprinting.

Carbonatitic magmatism, although limited from the point of view of the volumes in Eastern Paraguay, is relevant as it reveals a CO_2 imprinting in the source prior and after the tholeiitic magmatism. In particular, carbonatitic bodies are present in the Amambay Province (Cerro Chiriguelo and Cerro Sarambí, about 139 Ma; Censi et al., 1989; Castorina et al., 1997), as silico-carbonatitic lavas in the Sapucai lava sequences (about 126-124 Ma; Comin-Chiaramonti et al., 2007), and as "ocelli" at the

Canãda K-alkaline and Cerro E Santa Helena complexes (dated at about 126 Ma, Comin-Chiaramonti et al:, 2007) .

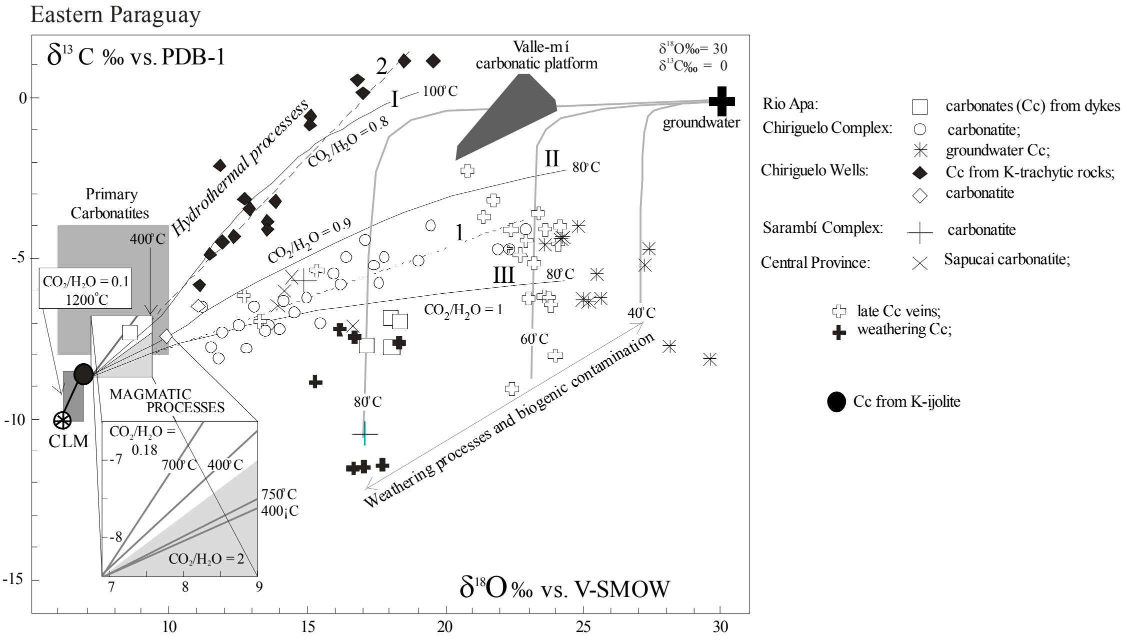

Fig. 8. - Plot of $\delta^{18}O$ vs. $\delta^{13}C$ for carbonates from Eastern Paraguay (Early Cretaceous, cf. tab. I) and evolution of the O-C isotope compositions. Magmatic conditions: 1200-400°C; hydrothermal environment: I up to 100°C, II and III up to 80°C (cf. Castorina *et al.*, 1997, and references therein; Comin-Chiaramonti *et al.*, 2005*b*); low temperature conditions: biogenic component with pH ~ 5 and temperature = 40-80°C. Arbitrary starting compositions of groundwater: $\delta^{13}C$ = 30‰, $\delta^{18}O$ = 0; cf. Taylor (1978) and Usdowski (1982). CLM: continental lithospheric mantle (Kyser, 1990). 1 and 2: regression lines from field and borehole samples, respectively. Primary carbonatites after Taylor *et al.* (1967) and Keller and Hoefs (1995). Data source for Valle-mí carbonate platform: Castorina *et al.* (1996).

Regarding these occurrences, i.e. Chiriguelo and Sarambí complexes and Sapucai sequences, significant variations in O-C isotopes are found in the primary carbonates. These variations are mainly due to isotope exchange between carbonates and H_2O-CO_2 rich fluids, whereas the magmatic processes, i.e. fractional crystallization or liquid immiscibility, probably affect the $\delta^{18}O$ and $\delta^{13}C$ not more than 2‰ (Fig. 8). The isotope exchange model implies that the main isotopic variations occur in hydrothermal environment, i.e. temperature in the range ~ 400-80°C, involving fluids with CO_2/H_2O ratios ranging from 0.8 to 1. Two main paths of $\delta^{18}O$ - $\delta^{13}C$ fractionation, with slope 0.89 and 0.31, respectively, are driven by subvolcanic ("less open") and volcanic ("open") conditions, respectively. Weathering and groundwater fluids seem to have played an important role, and some samples strongly enriched in light carbon appear interested by a biogenic component. The behaviour of trace element (e.g. Sr and REE) is also consistent with the above model (cf. Comin-Chiaramonti et al., 2005b).

The carbonate-bearing "ocelli" in the Cañada alkaline complex (Fig. 9) and in the complex from E. Santa Helena are also important because give the isotopic equilibria temperatures (Table 2) of the coexisting phases of both the complexes, correlating the pristine crystallizing minerals with orthomagmatic temperatures.

In general, radiogenic isotopes and trace-element data from the potassic complexes of Eastern Paraguay show that the associated carbonatites and primary carbonates reflect to some extent the composition of their mantle source, and, in particular, Sr and Nd isotopic results indicate that the carbonatite system is dominated by a mantle component without appreciable crustal contamination, pointing towards a distinctive end member (see below) which probably characterized the lithospheric mantle after the geodynamic events belonging to the Statherian taphrogenesis (1.8-1.6 Ga; Hartmann, 2002; De Min *et al.*, 2003; Rosset *et al.*, 2007).

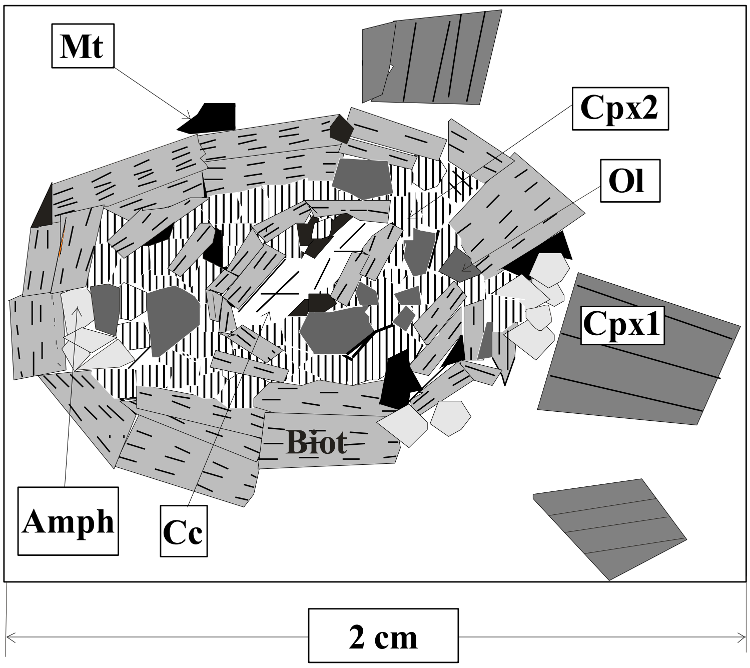

Fig. 9. - Sketch of an «ocellus» in ijolite from the Cerro Santa Elena alkaline complex (Early Cretaceous, Central Eastern Paraguay). Cpx1, clinopyroxene phenocrysts; Cpx2, clinopyroxene from «ocelli»; Mt, magnetite, Biot, biotite; Amph, amphibole; Cc, carbonate. Groundmass (white field), leucite + nepheline + alkali feldspar.

Notwithstanding the complex evolution shown by stable isotopes and trace elements, i.e. crystal fractionation, liquid immiscibility, subvolcanic to subvolcanic environment, volatile transport within magmatic and hydrothermal system, Sr and Nd isotopic systems are related to an isotopically enriched source where the heterogeneities of a depleted lithospheric mantle are derived by a pervasive invasion of fluids rich in incompatible elements and C-H (and F). These are expected to have promoted crystallization of K-rich phases developing a veined network variously enriched in LILE and LREE; the newly formed veins ("enriched component") and peridotite matrix ("depleted component") underwent a different isotopic evolution with time, where the carbonatites maintain this imprinting (cf Comin-Chiaramonti et al., 1997, 1999). The model may be extended to the whole Paraná Basin, where isotopically distinct magmas were generated following two main "enrichment events" of the subcontinental upper mantle estimated at 2.0-1.4 and 1.0-0.5 Ga, respectively (Comin-Chiaramonti et al., 2007). This would have preserved the isotopic heterogeneities over a long period of time, pointing to a non-convective lithospheric mantle beneath different cratons or intercratonic regions.

Table. II. Measured isotope compositions of silicates, oxides, apatite and calcite in some alkaline and alkaline-carbonatitic occurrences in the Brazilian platform,δ‰ notation; a, unpublished data; b, Comin-Chiaramonti and Gomes, 1996 and 2006. Abbreviations: Cpx, clinopyroxene; Ol, olivine; Mt, magnetite; Amph, amphibole; Biot, biotite; Cc, calcite; Ap, apatite. Calculated isotopic temperatures based on fractionation of oxygen isotopes in mineral pairs according to the general equation $1000\ln\alpha = A. (10^{6}T^{-2}) + B$, where A and B are coefficients of the equation and T is the absolute temperature (cf. Faure, 1986). 1, Bottinga and Javoy (1975); 2, Matthews et al. (1983); 3, Chiba et al. (1989); 4, Haynes et al. (2003); 5, Fortier and Giletti (1989, 1991); 6, Fortier and Luttge (1995).

CERRO EAST of S. ELENA Ijolite	$\delta^{18}O$‰ (V-SMOW)	$\delta^{13}C$‰ (PDB-1)		A	B	Ref.	T°C
Clinopyroxene^{a}	4.85		Cpx-Ol	1.24	0	1	852
Olivine^{a}	3.87		Cpx-Mt	4.03	0	2	808
Magnetite^{a}	1.40		Cpx-Amph	0.478	-0.30	2	746
Amphibole^{a}	4.69		Cc-Cpx	2.37	0	3	908
Biotite^{a}	4.62		Cc-Mt	5.91	0	3,4	798
Calcite^{a}	6.55	-8.90	Average				822 ± 61
			Biot-Amph	2.33	+0.60	1	799
			Cc-Biot	1.84	0	5,6	703
			Biot-Cpx	-0.57	+0.60	1	556
			Biot-Mt	-0.092	+0.30	2	510
			Average				642 ± 133
CAÑADA Ijolite							
Clinopyroxene^{b}	5.20		Cpx-Ol	1.24	0	1	1202
Olivine^{b}	4.63		Cc-Cpx	2.37	0	3	908
Biotite^{b}	5.54		Biot-Cpx	-0.57	+0.60	1	1208
Calcite^{b}	6.90	-8.50	Cc-Biot	1.84	0	5,6	890
			Average				1052 ± 180

Lead isotopes.

Pb isotopes are believed to discriminate between DMM and HIMU components [cf. "Mantle components" review of Zindler and Hart (1986) and Sracke et al. (2005)]. For this purpose further lead isotopic compositions have been carried out on four selected late Early Cretaceous and Paleocene rocks from South Eastern Paraguay (Table 3 of Velázquez et al., 2006) and compared with the whole magmatism from the Eastern Paraguay (Fig. 10), 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), La Rosada sill excepted (Low-Ti andesi-basalt from central Paraguay). Also it should be noted that some low-Ti tholeiites tend to plot in the field of the Palaeozoic basement rocks (Brasiliano cycle; ~500 Ma; cf. Table 3 of Antonini et al., 2005), and then their lead isotopic compositions could be partly affected by interaction with crustal material.

The sodic alkaline rocks (Misiones and ASU) have different Pb isotopic compositions and differ from the potassic anjalogous: 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 Paleocene 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. 10).

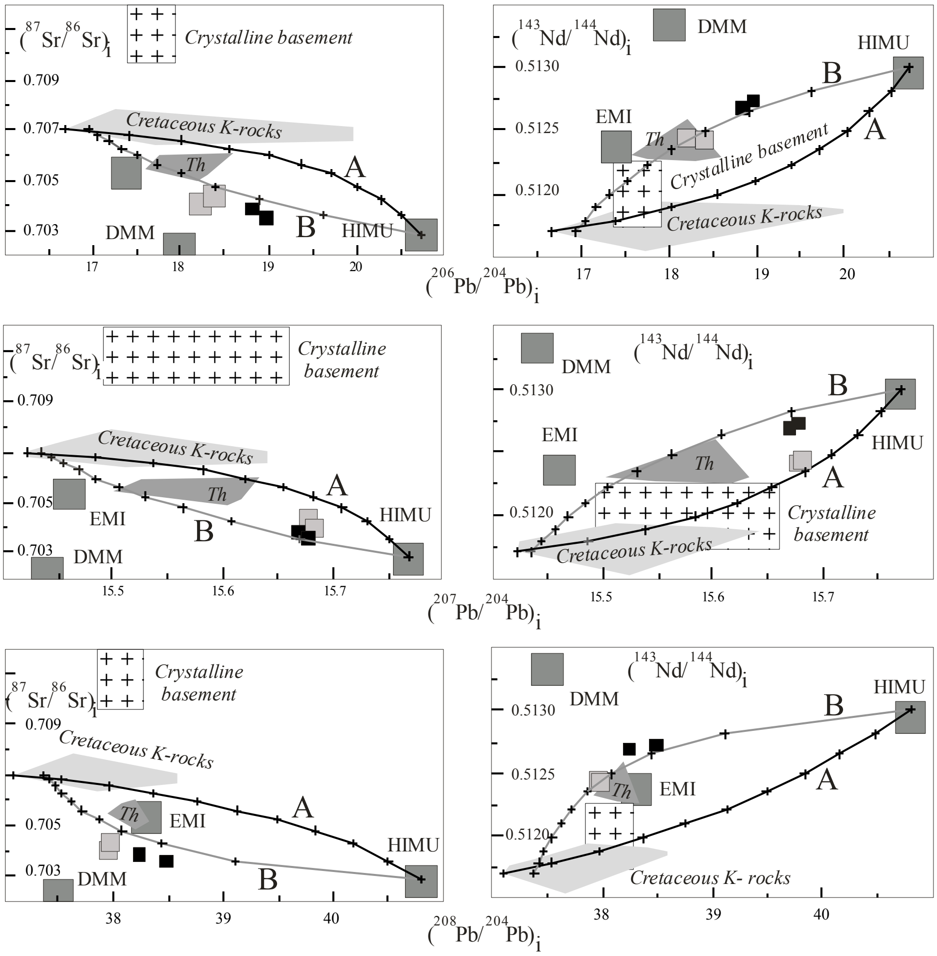

Fig. 10. - Isotopic mixing curves (A and B) between HIMU and potassic magmas from Lower Cretaceous Potassic rocks (LCK, Eastern Paraguay), computed using the following isotopic composition: HIMU (St. Helena; Chaffey *et al.*, 1989), ^{87}Sr/^{86} Sr = 0.70282, Sr = 650, ^{143}Nd/^{144}Nd = 0.5130, Nd = 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**: ^{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 and 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 al., 2006). It should 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 of Velázquez et al., 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 and Gomes, 2005). These observations seem 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.

In Eastern Paraguay, similarly to the flood basalts from the whole Paraná basin (cf. Piccirillo and Melfi, 1988; Peate, 1997), the high-Ti tholeiites have IE abundances higher than the coeval low-Ti analogues and corresponding negative Sr anomaly (Bellieni et al., 1986a; Comin-Chiaramonti et al., 1995c, 1997, 1999, 2002, 2004; Comin-Chiaramonti and Gomes, 1996, 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 and Comin-Chiaramonti, 1996), possibly due to a veined garnet peridotite where the distribution and the frequency of the "metasomatizing" channels determine the different chemical signatures (Comin-Chiaramonti and Gomes, 1996, 2005).

On the whole, the low-Ti basalts from the Eastern Paraguay (and north-eastern Argentina; Central Paraná basin of Bellieni et al., 1986a) turn out to have some chemical features which are similar to those of the low-Ti analogues of the southern Paraná basin (e.g. Ba, La, Ce, Zr contents), and others (e.g. SiO_2 and FeO_{total} contents) which, instead, are characteristics of the basalts from the northern Paraná basin (Bellieni et al., 1986a).

Mass-balance calculations yielded (up to about 3 times) differences in incompatible element ratios between low-Ti and high Ti basalts. These differences cannot be explained by fractional crystallization, or by means of melting and zone refining processes of a homogeneous mantle source. A genesis from chemically different lithospheric mantle materials is therefore preferred (Bellieni et al., 1984a, b, 1985, 1986a, b).

Moreover in Eastern Paraguay, IE suggest a common signature for potassic alkaline magmatism from Central Province, both B-P and AB-T suites, and PAE tholeiitic magmas, whereas sodic alkaline rocks display similar IE patterns as the Atlantic OIBs and African potassic alkaline basalts (Comin-Chiaramonti and Gomes, 2005). Strongly LREE-enrichment patterns suggest that Paraguayan potassic and sodic alkaline magmas issued from a garnet-bearing lithospheric mantle, yet their mantle source compositions were clearly distinct both in terms of IE concentrations and mineralogy. As proposed by Comin-Chiaramonti et al. (1997, 1999, 2007), 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 different 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).

Alternatively, the sodic magmatism may be derived by partial melting (5-8%) of an eclogitic mantle, without phlogopite as residual phase (Comin-Chiaramonti et al., 2007).

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(s), 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 component), respectively.

In any case, on the basis of the isotopic compositions, it is possible to infer a time related (Early Cretaceous to Paleocene) progressive increase of the role of the depleted mantle domain(s) in the genesis of alkaline magmatism in Eastern Paraguay (Comin-Chiaramonti and Gomes, 1996, 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 (cf. Fig. 7A).

The Sr-Nd isotopic variation of the Paraguayan alkaline rocks is larger than all the other alkaline occurrences from Paraná-Angola-Namibia system (PAN). 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 complexes (Fig. 7B) vary between 0.70321 and 0.70466, and between 0.51273 and 0.51237, respectively, showing in general depleted characteristics relative to the Bulk Earth (cf. Hart and Zindler, 1989). Notably, the Early Cretaceous alkaline-carbonatite complexes from Namibia have a similar Sr_i wide range (0.70351-0.70466), but almost constant Nd_i (0.51250 to 0.51244; Milner and Le Roex, 1996; Le Roex and Lanyon, 1998).

Model Ages.

Despite uncertainties related to the Sm/Nd fractionation (*f*) during the melting and magma differentiation (cf. Arndt and Goldstein, 1987), Nd model ages (depleted mantle, TDM; DePaolo, 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 Paraguay potassic magmas display TDM comparable to those of the PAN tholeiites and older than those of sodic magmas (cf. Fig. 7D).

TDM of the potassic alkaline rocks increases from the pre-toleiitic rocks of northeastern 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), corresponding to the Statherian taphrogenesis (cf. Hartmann, 2002).

Similar TDM ages, as well as similar $^{87}Sr/^{86}Sr$ isotopic ratios, are shown by the 130 Ma H-Ti tholeiitic dykes fom the S.Francisco craton (Rosset et al., 2007). On the other hand, the sodic alkaline rocks display Neoproterozoic TDM (0.9 Ga, Alto Paraguay; 0.6 Ga, Na-ASU; 1.0 Ga, Misiones, for $f \approx -0.4$ to -0.5), similar to the TDM of potassic alkaline rocks from APIP province (~1.0-0.8 Ga; cf. Gibson et al., 1997). To be noted that the younger model ages of the Eastern Paraguay parallel the Rio Paraguay lineament, characterizing the sodic magmatism (Antonini et al., 2005), and seem to refer to the Rodinia aggregation (1-0.9 Ga) and to the Rodinia Break up (Brasiliano cycle, 0.7-0.5 Ga).

As a role, calculated TDM are comparable to the zircon SHRIMP U-Pb ages measured in the Apa and Tebicuarí blocks, probably testifying some contribution relative to the ancient protoliths modified by the ancient events, i.e. Transamazonic, Uruaçano and Brasiliano cycles (cf. Cordani et al., 2001, 2005).

The different model ages and geochemistry of the sodic magmatism probably are not casual and may reflect ancient subductions adversus the mantle flow, i.e. westerly-directed, and an eclogitization of the slab corresponding to the Brasilides, whereas the potassic magmatism may remember contribution of orogenic events with easterly-directed subduction (cf. Panza et al., 2007). The combined effect of different subduction styles on the lithospheric mantle may explain even both sodic and potassic alkaline magmatism in NW Argentina where the magmatic suites have been generated during extensional regimes preceding the break-up of the South America-Africa plates (Cristiani et al., 2005).

The different geochemical behaviour in the different sectors of the PAN implies also different sources. Utilizing the TDM (Nd) model ages on the whole Paraná-Angola-Etendeka system (cf. Comin-Chiaramonti and 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 TDM 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 show model ages ranging from 0.6 to 1 Ga, similar to the age shown by the Triassic to Paleocene sodic alkaline rock-types along the Paraguay river.

At any rate, the model ages seem 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, 1995, 1997, 1999, 2005, 2007; Comin-Chiaramonti and Gomes, 1996, 2005; Antonini et al., 2005).

The meaning of model ages may be supported by another point of view. Considering that 1) the isotopic overlapping of different igneous rocks (i.e. tholeiites, alkalines and carbonatites) cannot be accidental and points to sampling of ancient reservoirs formed at different times from the same subcontinental upper mantle (cf. also the Re-Os model ages of Carlon et al., 1996); 2) whatever the implication, i.e. heterogeneity induced by recycled crust in the mantle (Menzies, 1990; Weaver, 1991) or occurrence of variably veined material in the subcontinental upper mantle, or both, Pb isotope data indicate a mantle source of ca. 1.8 Ga for the Paraná high-Ti tholeiites, and since much of the crust in southern Brazil appears to have been formed at ca. 2 Ga ago (cf. Hawkesworth et al., 1986), it follows that magma genesis involved ancient lithospheric mantle reset at well defined isotopic ranges. A veined lithospheric mantle (amphibole/phlogopite-carbonate-lherzolite and amphibole-lherzolite+CO_2-fluid type III and IV veins of Meen et al., 1989) of Proterozoic age may well account for the magmatism of the PAN (Fig. 11).

In summary, the pre- and post-tholeiites potassic rocks yielded TDM ages mainly ranging from 1.8 to 1.5 Ga, respectively, similar to those of the associated carbonatites (ca. 1.6 Ga) and low-Ti tholeiites from central-eastern Paraguay (ca. 1.7 Ga). The low-Ti tholeiites from the northeastern Paraguay yielded more recent TDM ages (1.2-1.4 Ga), whereas the oldest ages are given by the Paraguayan high-Ti tholeiites (1.8-2.0 Ga). The youngest TDM values are those of late Early Cretaceous Na-alkaline rocks from Misiones Province (0.93 Ga), as the potassic rocks and carbonatites from eastern Paraná basin, Angola and Namibia (0.6-1.0 ga; Comin-Chiaramonti et al., 1999), and of the ASU Paleogene Na-alkaline rocks (0.57 Ga). The latter model ages are similar to those shown by the analogue rocks from Argentina Central Rift (0.48±0.04 Ga) and from the Bolivian Ayopaya complex (0.52±0.06 Ga) and correspond to the ages of the Brasiliano Cycle in southern Paraguay (cf. Kanzler, 1987). Finally, it should be noted that the Tristan da Cunha and Trindade modern volcanics yielded 0.7 Ga and less than 0.5 Ga, respectively (cf. Marques et al,, 1999; Siebel et al., 2000).

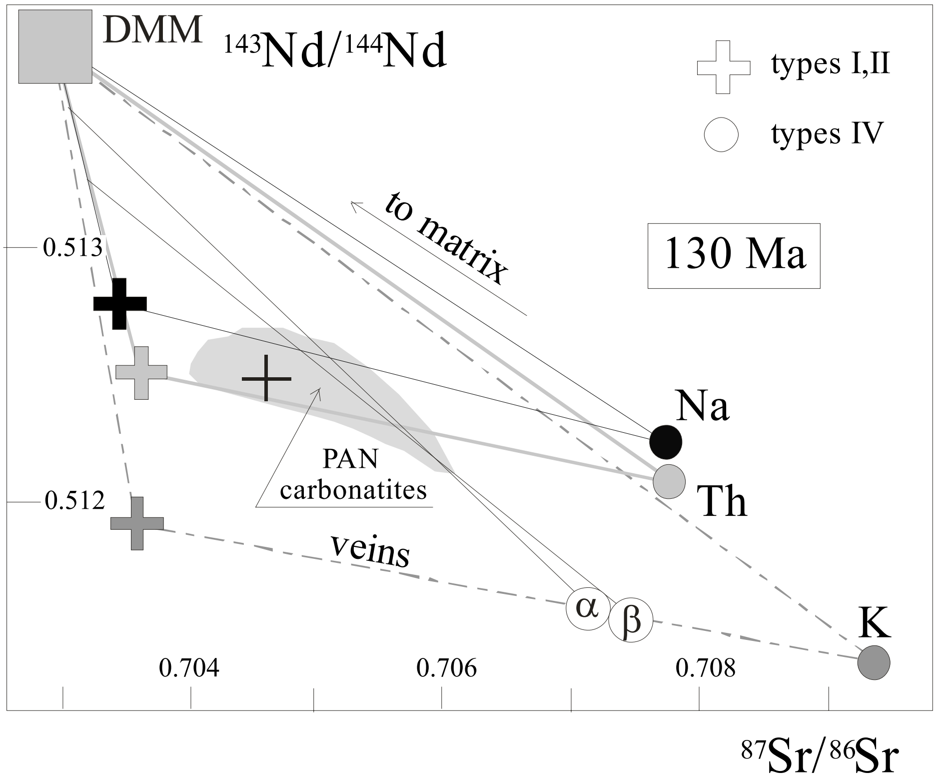

Fig.11. - Calculated SCUM isotopic composition at 1.8 Ga ago, projected to 130 Ma. Parental melts with various Rb/Sr and Sm/Nd ratios are assumed for K , Na (potassic and sodic rocks from Paraguay, respectively; Comin-Chiaramonti *et al.*, 1997) and Th (PAN tholeiitic basalts; Piccirillo and Melfi, 1988). It ishould be noted that the compositions of metasomites formed from a single metasomatizing melt vary with the evolution of the melt. Consequently, the veins will define a trend of shallow slope, and mixing curves between vein and matrix will define an array towards the matrix (cf. α and β regression lines). Model DMM: Rb = 0, Sr = 0.133, Sm =0.314, Nd = 0.628; present day Bulk Earth: $^{87}Sr/^{86}Sr = 0.70475$, $^{87}Rb/^{86}Sr = 0.0816$, $^{143}Nd/^{144}Nd = 0.512638$, $^{147}Sm/^{143}Nd = 0.1967$; $(Rb/Sr)_{diopside}$: $(Rb/Sr)_{melt} \approx 0.125$, $(Sm/Nd)_{diopside}$: $(Sm/Nd)_{melt} \approx 1.5$; K: Rb/Sr = 0.0957, Sm/Nd = 0.1344; Na: Rb/Sr = 0.0732, Sm/Nd = 0.2295; Th: Rb/Sr = 0.0733, Sm/Nd = 0.2082.

On the whole, the model ages obtained for the Eastern Paraguayan rocks, as well those calculated for the PAN magmatic occurrences, suggest that almost two distinct major mantle metasomatic events occurred in Meso- and Neoproterozoic times as precursor to the genesis of tholeiitic and K- and Na-alkaline magmatism, respectively (cf. Comin-Chiaramonti et al., 1999). This conclusion is distinct from the proposal of Gastal et al. (2005) who suggest that the major events of metasomatism in the region took place mainly during the Neoarchean-Paleoproterozoic. As a matter of fact, the TDM (Nd) ages of the magmas do not always return the timing of metasomatic event in the source(s), rather recording an "averaged" series of events.

In summary, the alkaline and alkaline-carbonatitic magmatism from Eastern Paraguay (and on the whole PAN) appears to be related to the lithospheric mantle, and the contribution of asthenospheric components, derived from the hypothetical Tristan da Cunha and Trindade mantle plumes, are not appreciable almost in terms of geochemistry and Sr-Nd isotopes.

Genesis of the magmatism.

Some authors (e. g. Le Roex and 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 the Alto Paranaíba-Serra do Mar (southeastern Brazil) would reflect the variable contributions of the asthenospheric mantle components related to the Tristan da Cunha and Trindade plumes, respectively. Conversely, 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 addition to the high- and low-Ti flow tholeiites in the PAN, originated from lithospheric mantle sources without appreciable participation 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 reflect 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 and Anderson, 2005; Lustrino, 2005; Foulger et al., 2005; Anderson, 2006).

In the Pb isotopic diagrams (cf. also Figs. 11 and 12 of Comin-Chiaramonti et al., 2007), the Early Cretaceous potassic alkaline and tholeiitic magmatism from the PAN appears to be related to heterogeneous mantle sources spanning from time-integrated HIMU to EM (enriched mantle) 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 also the decrease of Nd model ages for potassic rocks from Paraguay towards East. These results suggest that the PAN 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 Early Cretaceous alkaline-carbonatitic magmatism from Angola and Namibia, but quite different from that (EMI signature) of the Late Cretaceous-Cenozoic analogues from the Alto Paranaíba (APIP), Ponta Grossa Arch, and Cabo Frio-Taiúva-Serra do Mar areas (Comin-Chiaramonti and 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 an asthenospheric components related to the that plume is difficult to account for (cf. Ernesto et al., 2002; Ernesto, 2005).

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 the 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 may reflect 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 already demonstrated by Ernesto et al. (2000, 2002) and Ernesto (2005), that the hypothesis of asthenospheric plumes for the PAE magmatism is not compelling, except that it may represent a thermal perturbation.

Finally, according to Velázquez et al. (2006), it should be stressed that assuming an average heat flow value of 58 $mW{\cdot}m^{-2}$ for the Paraná basin (Hamza, 1996) in Mesozoic-Cenozoic times and a peridotite solidus with $CO_2/(CO_2+H_2O)=0.8$ (cf. Wyllie, 1987), volatile fluids could be related to partially melted diapirs generated mainly at depths of less than 200 km. Thus, a wide zone of mantle metasomatism may extend itself between the lower part of the lithosphere and its solidus ledge: As matter of fact, the existence of primary carbonates in Eastern Paraguay suggests a CO_2-bearing peridotite source with variable H_2O content (cf. Fig. 8).

GEODYNAMIC IMPLICATIONS

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, betwen the Atlantic and Pacific systems (Trompette, 1994). The Brasiliano cycle was developed between about 890 to 480 Ma in a diachronic 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 fragments linked by several (accretionary, collisional) Neoproterozoic mobile belts amalgamated to form Gondwana (Unrug, 1996). After the amalgamation, the Gondwana supercontinent accumulated Paleozoic and Mesozoic sediments, where the main periods of apparent quiescence, late Paleozoic and early Mesozoic, are each preceeded by rapid deposition which may be taken to represent periods of rifting (Hegarty et al., 1996). Concomitantly, it was continuously 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, 2003a, b). 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 and Cordani, 2003). In this context, the magmatism was driven by the extensional regimes derived by the relative movements of the ancient blocks. For example, the Alto Paraguay Triassic alkaline magmatism is located at the boundary between the Rio Apa and Arequipa-Antofalla blocks and reveals an extensional event at about 241 Ma, probably induced by counterclockwise and clockwise movements (North and South, respectively) hinged at the about 20° South latitude and inserted into the compressional style of Cabo-La Ventana orogenesis (Prezzi and Alonso, 2002; Velázquez et al., 2006).

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 and 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 PAN magma types is the link with the geodynamic processes which promoted the opening of the South Atlantic and the rift systems. According to Chang et al. (1988) and to Nürberg and Müller (1991), the sea-floor spreading in the South Atlantic at the PAN latitudes 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 and 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 and Jurdy, 1984), or shallow thermal anomalies (Holbrook and 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 displacement between the two South American domains across these boundaries.

Smith and 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 and 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 and Ussami, 1999) intersect the axis of major rifting, possibly related to the erosion and cycling of continental mantle towards the ridge axis.

Rift propagation is not random, but tends to follow the trend of the orogenic fabric of the plates, suggesting reactivation of ancient lithospheric structures (e.g. Tommasi and Vauchez, 2001). In southern Brazil, the alkaline and alkaline-carbonatitic magmatism is concentrated in regions showing positive gravimetric anomalies of the geoid (Ernesto et al., 2002, Molina and Ussami, 2004, Ernesto, 2005) 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 should be stressed that the combined presence of even small amount of water and carbon dioxide in the upper mantle may lower the melting temperature even of some hundred degrees (Thybo, 2006). This scenario could explain the presence of Late Cretaceous to Cenozoic sodic magmatism in the PAN, 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 and Fernandes, 1995).

Relationships between P-wave, low velocity anomalies and the distribution of Late Cretaceous alkaline provinces in SE Brazil was observed by Assumpção et al. (2004) and interpreted as related to a weaker lithosphere caused by high temperatures associated with the ponding of the Trindade plume head beneath the lithosphere. VanDecar et al. (1995) and Schimmel et al. (2003) mapped in the upper mantle and mantle transition zone (MTZ) beneath the northeastern Paraná Basin (Iporá Late Cretaceous magmatic province -São Francisco craton) a "cylindric" low-velocity volume which they interpreted as a thermal anomaly corresponding to the "fossil" Tristan da Cunha plume (TdC) that has moved with the lithospheric plate. On the contrary, Liu et al. (2003) suggest that the thermal anomaly does not extend into MTZ or, alternatively, that the observed anomaly is not primarily thermal, but dominantly compositional in origin (e.g. "veined mantle").

However, considering that the lithosphere has a typical time constant of about 60 Ma (cf. Gallagher & Brown, 1997) for dissipating heat and consequently attenuating topography, it is quite improbable that a head of a plume that reached the base of the lithosphere more than 130 Ma ago could still persist. Moreover, no geoid anomaly, nor surface expression of the TdC thermal anomaly is recognized in this region (cf. Molina & Ussami, 1999, and Ernesto *et al.*, 2002 for a discussion). Schimmel *et al.* (2003) argued that in South America all areas with Late Cretaceous post-rift alkaline intrusions are characterized by low velocities of seismic waves at lithospheric depths: if we accept this statement the Late Cretaceous alkaline intrusions may be extended up to the Apoyaya complex (NW Bolivia; Schultz *et al.*, 2004) through Goiás and Mato Grosso States (Brazil; Gibson *et al.*, 1995b; Sousa *et al.*, 2005) and southeastern Bolivia (Comin-Chiaramonti et al., 2005), generating a lineament corresponding to the "125°AZ" of Bardet (1977), but in contrast with the geophysical evidences.

Mantle plume(s).

Any model of mantle plumes is not exhaustive for explaining the most of continental flood basalts and the recurrent intraplate alkaline magmatism (cf. CAMP of Marzoli et al., 1999). For example, the Asunción sodic magmatism (58.4 Ma), being located 180 km NNW from the Misiones analogous (118.3 Ma), in terms of the classic mantle plume-hot spot model, the two occurrences would be related to a SSE drift of the Paraguay block over the tail of a new, unknown, mantle plume. Unfortunately, this drift woud correspond to a change in the South America movement at about 80 Ma, whereas a N-S displacement is instead apparent at the time (cf. Velázquez et al., 2006).

Therefore, following Ernesto et al. (2000, 2002) and Ernesto (2005), alternative thermal sources should be found in the mantle with no implication of material transfer from the core or lower mantle to the lithosphere. Besides the indications from the 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 and Tanimoto, 1993; Li and Romanovicz, 1996, Van der Hilst et al., 1997; Liu et al., 2003).

Ernesto et al. (2002), in their paleomagnetic and gravimetric studies stated that:

1) Paleogeographic reconstructions of the Paraná-Tristan da Cunha (TC) system, assuming TC hotspot as a fixed point in the mantle, indicate that the TC plume was located ~800-1000 km south of the Paraná Magmatic Province (PMP). 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 134-130 Ma (main magmatic 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 accommodation of stresses in the lithosphere during rifting (Ferrari and Riccomini, 1999), 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 Paraná flood basalts and surrounding alkaline rocks. There are sufficient good quality paleomagnetic data (Renne et al., 1992, 1993, 1996; Ernesto et al., 1996, 2000, 2002, 2005) to delineate the Mesozoic apparent polar wandering in South America, many of these data derived from igneous rocks from the Paraná 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 139-133 Ma interval, on the basis of mantle anchored plumes, founding support for this proposition on the work by O'Connor and 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 geodynamic 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 the model of Gibson et al. (2006), exceeds almost three times the 3.5 cm per year estimated by O'Connor and Duncan (1990).

On the whole, all these observations point to a major role of the pre-existing lithospheric structure in plate tectonics. According to Berkovici (1998) and Tommasi and Vauchez (2001), we suggest that the preservation within the lithospheric mantle of a lattice preferred orientation of olivine crystals formed during the major tectonic episodes (e.g. Transamazonic, Uruaçano, Brasiliano) that formed the plates ("structural memory" at the lithosphere scale) leads to a directional strain softening, explaining the "perennial" nature of plate-subplate and their systematic reactivation boundaries.

Both the Late Archean-Proterozoic and Mesozoic tholeiites from the South American Platform (SAP) are characterized by high- and low-Ti (TiO_2>2 and <2 wt%, respectively) and by high and low contents of incompatible elements, respectively (cf. Jacumin et al., 2003). According to Jacumin et al. (2003), the Precambrian and Mesozoic SAP tholeiites reflect heterogeneous mantle sources, including EMI (e.g. fluids, small volume melts) and EMII (e.g. ancient subduction-related metasomatism) components. These authors suggest that all the data support mantle source heterogeneity well established at least since Late Archean times. This is documented by the Precambrian and Mesozoic SAP tholeiites having similar compositional features, particularly tholeiites cropping out in the same craton. Finally, the concentration of the Precambrian and Mesozoic SAP tholeiitic magmatism towards craton/mobile belt boundaries points to an important genetic role played by upper mantle "edge drive convection" geodynamics.

CONSIDERATIONS ON THE FLUIDODYNAMMICS IN THE EARTH VS PLUME MODELS

The Paraguay magmatism prompts some general considerations relative to the mantle plumes (cf. Gibson et al., 2006). After the pioneering papers of Morgan (1971, 1972) and later papers on this topic (e.g. Carlson, 1998; Albarede and Hilst, 1999; Arndt, 2000; Gonnerman et al., 2004), i.e. the *Ptolemaic model*, the Earth should be considered as a *Keplerian system*. There are two different ways of thinking about the energy of the Earth. According to Holbrook (2005), the kinetic (or potential) energy of a body relative to other bodies is a function of the inertial mass/energy of the body relative to absolute space, i.e. a body always has two energies, one vectorial and one scalar value, kinetic and mass, respectively.

The mantle plume suggestions (cf. Kerr et al., 2005) that consider the material transfer from the outer core to the upper mantle and the crustal sectors (use and abuse of the mantle plume theory), in our opinion must be expressed from an integrated fluidodynamic point of view, considering also that e.g. for the CAMP (the largest igneous province of the Earth, 10,000,000 sq. km) there is not any evidence of hot spots (Marzoli et al. 1999, De Min et al., 2003). Some reasons to consider:

A) It is well known that the rotation of planet Earth is gradually slowing from about 6.5 hours, 4.5 Ga ago, to actual 24 hours per day (Hamilton, 1996). The constant struggle between gravitational force and the weakening angular momentum caused by the slowing of the Earth's rotation, has had a profound effect on the Earth's geophysical activity throughout times, causing continuing modifications of the Earth's shape as the ratio of the strengths of angular momenta and gravity have changed. Gravity is a centripetal force, always trying to form the Earth into a perfect sphere, while the angular momentum is an outward tangential inertial reaction (centrifugal force) that causes the oblate shape of the Earth. This contrasting effects produce slow continual change which has set up dynamic pressures and stress within the Earth's crust as it endeavours to conform to the ever changing mantle upon which it floats. It is the imbalance between the angular momentum and gravity that causes the dynamic movements of the continental crustal plates as the crusts shifts and crunches to fit into the ever diminishing area of the mantle. The equatorial oblate shape of the Earth shrinks, the resulting pressure within the mantle causes it to gradually ooze upward creating the Atlantic and Pacific ridges.

B) The system Earth-Moon-Sun drives the Earth tides (in particular the outer fluid core), along with the rotational and revolution movements of the Earth (e.g. Dickey, 1995; Anderson, 2002; Dehart and de Viron, 2002; Greiner-Mai et al., 2003). In particular, the energy dissipated in generating tides is directly responsible for the reduction in potential energy in the Moon-Earth orbit barycentre, resulting in a 3.8 cm yearly increase in the distance between the two bodies (Canup and Asphaug, 2001).

C) The different inertial, angular momenta and the the physical and chemical characteristics of the various shells of the Earth, i.e. inner core, outher core, mantle shells, and crust (Albarede and Hilst, 1999, 2003; Chao et al:, 2000; Ishii and Dziewonski, 2002; Thybo, 2006; Anderson, 2006) are responsible of differential effects on the superficial masses.

D) Not considering the meteoritic impacts (cf. Jones, 2005 for a discussion), the continental masses, differential distributed in the time and space, may drive the continental break-up and drift along with the changing of the rotational axis of the Earth (cf. Evans, 2003).

CONCLUDING REMARKS

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 PAN in terms of HIMU and EM mantle end-members must be consistent with the following constraints: (a) HIMU and EMI-EMII are not restricted to the oceanic environment; (b) end-members are variously associated in space as a function of the various protoliths, variously modified by previous events, i.e. Transamazonic to Brasiliano, and mantle regions having different HIMU and EMI isotope imprinting are capable of generating melts that can lead to the formation of a wide variety of silicate rocks, including melts enriched in H-C-O-(F) (Bell, 1998); c) the sodic alkaline rock-types appear systematically grouped together, clustering geochemical fields well distinct in comparison with the potassic alkaline and tholeiitic fields of Paraguay magmatic rock-types, but fitting the geochemical fields of potassic alkaline-carbonatite fields of the analogues from Angola and Namibia.

Whatever model is favoured, it will require an evaluation of the extreme heterogeneity of the magmatic events in Eastern Paraguay, reflecting heterogeneity in their mantle source(s): e.g. potassic rock-types appear to evolve starting from different parent liquids, i. e. basanite and alkali basalt, respectively. At their turn, the latter appear well different with respect with ankaratritic liquid parent of the sodic magmatism. Even the flood tholeiites are distinguished in high- and low-Ti variants, sometimes alternating in a same lava pile (e.g.high- and low.Ti tholeiitic lavas partly covering Cerro Chiriguelo alkaline-carbonatite complex).

In summary:

1. The alkaline and alkaline-carbonatitic magmatism from the PAN is distributed along tectonic lineaments in both American and African continents (cf. Fig. 8 of Comin-Chiaramonti et al:, 2007). The intruded crystalline basement is generally observable. The carbonatites mainly occur in the inner parts of circular/oval shaped alkaline-carbonatitic complexes, being the rock bodies usually associated with evolved silicate rocks. Liquid immiscibility processes played an important role in the genesis of the PAN carbonatites Comin-Chiaramonti and Gomes, 2005).

2. Field relationships, geochemistry and new "high-quality" $^{40}Ar/^{39}Ar$ ages, show that several distinct magmatic events took place in Eastern Paraguay since the Triassic in a region strongly characterized by extensional tectonics. The oldest magmatism occurred during the Triassic times along the Paraguay river, at the boundary between the Chaco-Pantanal and Paraná basins, and was represented by relatively evolved rocks of sodic affinity.

During the Early Cretaceous, potassic alkaline rock-types, in the Rio Apa-Amambay and in Central Provinces, respectively, pre- and post-dating (139 and 127 Ma, respectively) the emission of the Paraná Basin flood tholeiites, both high- and low-Ti variants. The latter sometimes are found in the same locality. The tholeiitic magmatism, both high- and low-Ti variants, spans from 134 to130 Ma ago (preferred maximum span of age). Since late Lower Cretaceous to Paleocene, only sodic magmatism occurred in Eastern Paraguay, being concentrated in the Asunción and Misiones Provinces, roughly along the Paraguay river.

The Sr-Nd-Pb isotopic data indicate the contribution of two main mantle components, i.e. a) an extreme and heterogeneous EMI component, which was prevalent above all in the Cretaceous K-alkaline magmatism, and b) a depleted component, which appears important for the sodic magmatism spanning from Triassic to Paleogene.

3. The potassic rocks form a compositional continuum from moderately to strongly potassic, with two well distinct suites, i.e. from alkali basalt to trachyte and from basanite to phonolite. Both suites started from different parental magmas, evolving through fractional crystallization, and are associated to carbonatites bodies or to carbonate rich rock-types.

The sodic rocks include mainly ankaratrites, melanephelinites and phonolites; the ultramafic rocks contain very abundant mantle xenoliths (spinel facies), at their turn represented by two suites, i.e. high- and low-potassic suites showing imprinting of a variously metasomatized lithospheric mantle.

4. The potassic suites (both pre- and post tholeiitic) are characterized by strongly fractionated REE and I.E. patterns showing negative "Ta-Nb-Ti anomalies". Also tholeiitic rocks show negative Ta-Nb anomalies, but the high Ti variants are characterized by patterns 2-3 times more enriched in I.E. with respect to the low-Ti equivalents, excepted for Sr and Yb which present negative anomalies.

On the contrary, slight positive anomalies for Ta and Nb were observed in the alkaline sodic suites.

5. Sr-Nd isotope, initial ratio, define an array from depleted composition of the sodic rocks and associated mantle xenoliths, to enriched ones of the potassic rocks and associated carbonatites, where the tholeiites fit intermediate compositions. The carbonatites and primary carbonates in the host rock-types show the same isotopic ratios of the associated alkaline silicate rocks.

The large variations of incompatible elements and REE of the carbonatites appear to be in many cases mainly related to hydrothermal processes (up to low thermality). This evidence is also supported by the O-C isotope systematics and by the calcite-dolomite isotopic equilibrium temperatures indicating complex trends from magmatic to hydrothermal environments at variable CO_2/H_2O ratios. On the other hand, many O-C isotopic ratios data, falling into the primary carbonatite box and strictly linked to orthomagmatic phases, are believed to represent primary isotopic signature of the mantle.

Crustal contamination does not appear to have been significant in the generation of all the investigated rock-types above all for the high contents of unradiogenic Sr and Nd of the carbonatites.

6. The different magma types, the calculated parent liquid derived from different degrees of partial melting, the IE and REE different patterns, and the Pb-Sr-Nd isotopic systematics indicate that the Early Cretaceous alkaline magmatism from the Paraná-Angola-Etendeka appears to be related to heterogeneous mantle sources spanning from DM-HIMU to time-integrated enriched mantle components.

The alkaline magmatism from Eastern Brazil, Angola and Namibia is similar, in terms of isotopic compositions, to the coeval flood tholeiites, being probably induced by different interaction during the Gondwana assemblage. The enriched isotopic signatures of the Early Cretaceous alkaline magmatism, decreases from West (Paraguay) to East (SE-continental margin of Brazil, and Angola and Namibia). A similar decreasing isotopic shift is also observed for the age of the magmatism, in Paraguay and Brazil, i.e. Early- Late Cretaceous to Paleogene. These results suggest that the magmatism from the Paraná-Angola-Namibia system is related both to large- and small-scale heterogeneous source mantle.

It shoud be stressed that an active role of hypothetical mantle plume heads is not compelling to explain the widespread distribution of the South American tholeiites, especially for the Central Atlantic Magmatic Province (CAMP) that is not related to Jurassic hotspots, as stressed by De Min et al. (2003) and by Rosset et al. (2007). These authors suggested "edge drive convection" models (cf. King and Anderson, 1995), where the rifting processes were triggered by different lithospheric thickness beneath the edge of cratonic shields, where small-scale convection cells were operative.

7. In Eastern Paraguay, the close association of potassic and sodic rock suites demands that their parental magmas derived from subcontinental mantle masses, vertically and laterally heterogeneous in composition and variously enriched in incompatible elements (veined mantle and/or wet spots). Mechanism of a small-scale metasomatism is suggested by the different suites of mantle xenoliths. On the whole, in Paraguay, the isotopic data relative to the mantle xenoliths seem to indicate that the lithospheric mantle prior to the enrichment event 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. In the Andes, the composition of the source is also believed the depleted mantle by Lucassen et al. (2005), but different from a MORB type source , showing slightly more radiogenic ^{87}Sr and less radiogenic ^{143}Nd than the Pacific MORB.

The Nd-TDM (model ages referred to depleted mantle; cf. Comin-Chiaramonti et al., 2001, for a discussion) of clinopyroxenes and host rocks record earlier fluid-infiltrations events. These appear defined by an averaged age of 0.47± 0.18 Ga, with more than 60% model ages spanning the Brasiliano cycle (i.e. 900-460 Ma).

The substantial compositional variations in some xenoliths and host lavas could reflect small-scale sampling of the lithospheric mantle, and differential interactions between fluids and overlaying peridotites. Significant H-O-C and F are also expected in the mantle source from the occurrence of the related primary carbonates. The latter allow to the lowering of the solidus, and along with a extensional tectonic, favour the melting mantle and magma rising. These considerations may be extended to the whole Paraná-Angola-Etendeka system.

8. Any hypothesis of mantle plume activity at the margin of the Paraná Basin should account for distinct lithospheric mantle characteristics, e.g. lattice preferred orientation of the olivine and mantle flow, supported by paleomagnetic results. This does not preclude that thermal perturbations from the asthenosphere may have triggered magmatic activity in the lithospheric mantle beneath the Eastern Paraguay. On the whole, the magma genesis and emplacement in south Eastern Paraguay, and even in NW Argentina, may be related to the reactivation of pre-existing lithospheric faults, which promoted local decompression melting of the upper mantle that was previously veined during decompression episodes associated with various extensional rifting phases.

9. IE-C-H-F rich fluids are expected to have promoted crystallization of K-rich phases (e.g. phlogopite) in a pristine peridotitic mantle, variously affected by the different oriented subducting slabs during the Gondwana assemblage, where they developed a veined network variously enriched in LILE and LREE under various redox conditions (wetspots). 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.

10. TDM model ages show that isotopically distinct magmas were generated following roughly two main "enrichment" events of the subcontinental upper mantle estimated at 2.0-1.4 Ma and 1.0-0.5 Ga, respectively. These ages are also confirmed also by U-Pb ages on Zr fom various cratonic blocks and mobile blocks from Eastern Paraguay and Brazil (cf. Cordani 2000; 2001; 2003a,b: 2005). 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.

11. It should be also stressed that the continental rift systems, mainly trending N-S, developed on the Paleozoic crust at the Salta longitude (Mid-Cretaceous-Paleogene; Argentina Central Rift of Lucassen et al., 2001, 2002, 2005) mark the western limit of the Chaco-Pantanal Basin system. The latter represents an intercontinental basin, probably due to the Paleozoic basement reactivation in a sub-Andean flexural bulge (Ussami et al., 1999), delimitated to the East by the ~ N-S Paraguay lineament that corresponds to the western border of the Atlantic domain, where the main structural lineament has a NW-SE trend (cf. Fig. 1).

12. The over-simplified model of mantle plumes is not satisfactory for explaining the genesis of most continental flood basalts and the recurrent intraplate alkaline magmatism, above all at the light of the fluidodynamic considerations. Therefore, following Ernesto et al. (2002), an alternative mechanism and thermal sources must be found in the mantle with no implication of material directly transferred 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 and Tanimoto, 1988; Li and Romanovicz, 1996; Van der Hilst et al., 1997; Liu et al., 2003).

13. The centripetal and centrifugal forces may significantly influence the main dynamics, physical and geochemical characteristics of hypothetical mantle plumes following alternative trends. In particular, the fluids, driven by gravitational tides, especially from outer core versus the mantle, must be considered concurrently as advection, diffusion (both mechanical and chemical), convection, buoyancy, inertial and angular momenta, Rayleigh number, rotation and revolution of the planet in the time etc. Further studies are necessary to test and develop a complete and satisfactory fluidodynamic model through the times, but the strong heterogeneities registered in Eastern Paraguay seem to be in favour of the above suggestions.

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