

Origin of Post-Paleozoic Magmatism in Eastern Paraguay

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The ages of the magmatic rocks are crucial for the understanding of the geodynamic relationships among different magmatic events. Between the compressional Andean and extensional Atlantic systems, Paraguay was the site of six main taphrogenic events since the end of Paleozoic times. Other than the Paraná flood tholeiites (133-134 Ma; Early Cretaceous, Hauterivian), new high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ ages show that other alkaline magmatism of various types occurred, namely sodic at 241.5 ± 1.3 Ma (Middle Triassic, Anisian), 118.3 ± 1.6 Ma (late Early Cretaceous, Aptian) and 58.7 ± 2.4 Ma (Paleocene), and potassic at 138.9 ± 0.7 (Early Cretaceous, Venginian) and 126.4 ± 0.4 Ma (Early Cretaceous, Barremian). The main geochemical characteristics of the sodic alkaline rock-types are systematic characterization by Nb-Ta positive anomalies and by Sr-Nd isotopes trending to the bulk Earth or the depleted mantle components, contrasting with the potassic rocks and tholeiitic basalts that show negative Nb-Ta anomalies and Sr-Nd isotopes trending to the enriched mantle components. The Pb isotope vs Sr-Nd systematics confirm the distinction between the potassic rocks enriched in "high radiogenic" Sr and low in "less radiogenic" Nd-Pb and the sodic rocks ranging from depleted components to bulk Earth, and transitional to the Paraná flood tholeiites. The occurrence of alkaline, both sodic and potassic (and carbonatitic) and tholeiitic magmatism in the whole Paraná-Angola-Etendeka system, and even in the Andean system, implies appropriate lithospheric sources to generate the various types of magmatic rocks. Therefore, any hypothesis of an asthenospheric plume origin is not compelling other than as a thermal perturbation and/or a decompressional environment, and possible mantle sources driven by Precambrian melts

which contaminated and veined the lithosphere. A decompressional environment is inferred as a possible mechanism driven by differential rotation of different subplates in the South America-South Africa plates.

INTRODUCTION

Eastern Paraguay lies in an intercratonic region which includes the westernmost side of the Paraná-Angola-Edendeka system (PAE). It is bounded by an anticlinal structure established since the Early Paleozoic, the Asunción Arch, separating the Paraná Basin in the east from the Gran Chaco Basin in the west (Almeida, 1983; Comin-Chiaramonti *et al.*, 1997). Notably, Paraguay is located in South America between the compressional Andean and extensional Atlantic systems (Fig. 1; cf. Gudmundsson & Samdrige, 1998). A Cretaceous rift system, developed in the Early Paleozoic mobile belt on the Pacific side of the continent, delimitates part of the Brazilian shield (cf. Lucassen *et al.*, 2002). However, at the latitude of Paraguay, the exact limit between Andean and Atlantic systems is unknown due to the presence of the Chaco-Pantanal Paleogene-Neogene basin. The basement rocks are mainly Precambrian to Early Paleozoic granitic intrusions and high- to low-grade metamorphic metasediments. These are considered to be the northernmost occurrence of the Rio de la Plata craton and the southernmost tip of the Amazon craton (Fulfaró, 1996), in southern and northern Eastern Paraguay, respectively. Post-Paleozoic magmatism, both alkaline and tholeiitic, affected the region, following various pulses of western Gondwana evolution and break-up.

This study offers the first high precision $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the ~ 200 Ma span of alkaline magmatism which intermittently occurred in Eastern Paraguay from Triassic to Paleogene times. The objective is to define age, duration and geodynamic significance of the magmatic events from this relatively little-known region. The new data represent new constraints relative on the main magmatic pulses, often in disagreement with older age data (K/Ar and Rb/Sr, mainly). A geochemical review and comparison with the other magmatic, both alkaline and tholeiitic, occurrences in the whole PAE is also presented in order to present a complete picture of the evolution of western Gondwana before, during and after its break-up.

SIX MAGMATIC EVENTS IN EASTERN PARAGUAY

Lying the westernmost side of the Paraná-Angola-Edendeka system, Eastern Paraguay represents a magmatic province in and around the Paraná basin where six main magmatic events occurred in a relatively restricted area (i.e. less than 120,000 km²; Fig. 2) from the end of the Paleozoic to the Cenozoic. This is shown by geological evidence and by previous regional and geochronological studies as follows (cf. Comin-Chiaramonti & Gomes, 1996, 2005 and references therein):

- 1) Permo-Triassic sodic magmatism of the Alto Paraguay Province (255 -210 Ma; Gomes *et al.*, 1995 and references therein) is widespread on the southernmost side of the Amazon Craton (Fulfaro, 1995; Comin-Chiaramonti *et al.*, 2005a).
- 2) Potassic alkaline-carbonatitic complexes and dykes from North Eastern Paraguay, from the Rio Apa (~142 Ma, as inferred from Gibson *et al.*, 1995a) and Amambay areas (avg. 141 Ma; Sonoki & Garda, 1988; Eby & Mariano, 1992) predate the tholeiitic flood basalts (Paraná, Serra Geral Formation, SGF).
- 3) The Paraná SGF flood tholeiites and dykes (133 ± 1 Ma according to Renne *et al.*, 1992, 1993, 1996; 137-127 Ma, according to Turner *et al.*, 1994 and Stewart *et al.*, 1996) are both represented by high-Ti and low-Ti basalts (cf. Bellieni *et al.*, 1986; Piccirillo & Melfi, 1988).
- 4) Potassic alkaline complexes and dykes (132-115 Ma; Bitschene, 1987; Comin-Chiaramonti & Gomes, 1995) with subordinate silico-carbonatite flows and dykes are widespread mainly in the Asunción-Sapucaí-Villarrica graben (ASU, central potassic province; Comin-Chiaramonti *et al.*, 1997; 1999).
- 5) Sodic alkaline complexes, plugs and dykes (~120 Ma; Comin-Chiaramonti *et al.*, 1992), occur mainly at the Misiones Province (San Juan Bautista Region), southwestern Paraguay.
- 6) Paleogene sodic alkaline complexes, plugs and dykes (66-33 Ma; Bitschene, 1987; Comin-Chiaramonti *et al.*, 1991; Comin-Chiaramonti & Gomes, 1995) crop out on the western side of the Asunción-Sapucaí-Villarrica graben.

The Permo-Triassic rocks form subcircular complexes following a N-S trend and are mainly formed by nepheline syenites and syenites and their effusive equivalents (Comin-Chiaramonti *et al.*, 2005a). Early Cretaceous alkaline magmatism, both pre-dating and post-dating the tholeiitic effusions, is moderately to strongly potassic, being represented by rock types spanning from alkali basalt to trachyte and from basanite to phonolite and their intrusive equivalents. They are often associated with carbonatitic rock types (Comin-Chiaramonti & Gomes, 1995; Comin-Chiaramonti *et al.*, 1997; 1999). Early Cretaceous tholeiites are mainly basalts and andesibasalts, both belonging to the high-Ti and the low-Ti suites (Bellieni *et al.*, 1986; Piccirillo & Melfi, 1988; Comin-Chiaramonti & Gomes, 1995; Peate *et al.*, 1999). The Cretaceous and Paleogene sodic rocks, including ankaratrites, nephelinite and phonolites, are both characterized by mantle xenoliths (spinel peridotite facies; Comin-Chiaramonti *et al.*, 1992; 2001 and references therein).

GEOLOGICAL-GEOPHYSICAL BACKGROUND

Seismic-tomography images show two high velocity features beneath Paraguay (P-waves; cf Fig. 1B), up to about 200 km and more than 450 km in depth, respectively. The latter are probably part of the subducting Nazca slab (Liu *et al.*, 2003). A low-velocity anomaly (Fig. 1B) in the upper mantle and the mantle transition zone (MTZ) was interpreted as a fossil plume by VanDecar *et al.* (1995). However, thinning of the MTZ has not been observed and Liu *et al.*

(2003) suggest that either this thermal anomaly does not extend into the MTZ, or, alternatively that the observed anomaly is not primarily thermal, but instead dominantly compositional in origin (e.g. "veined" mantle).

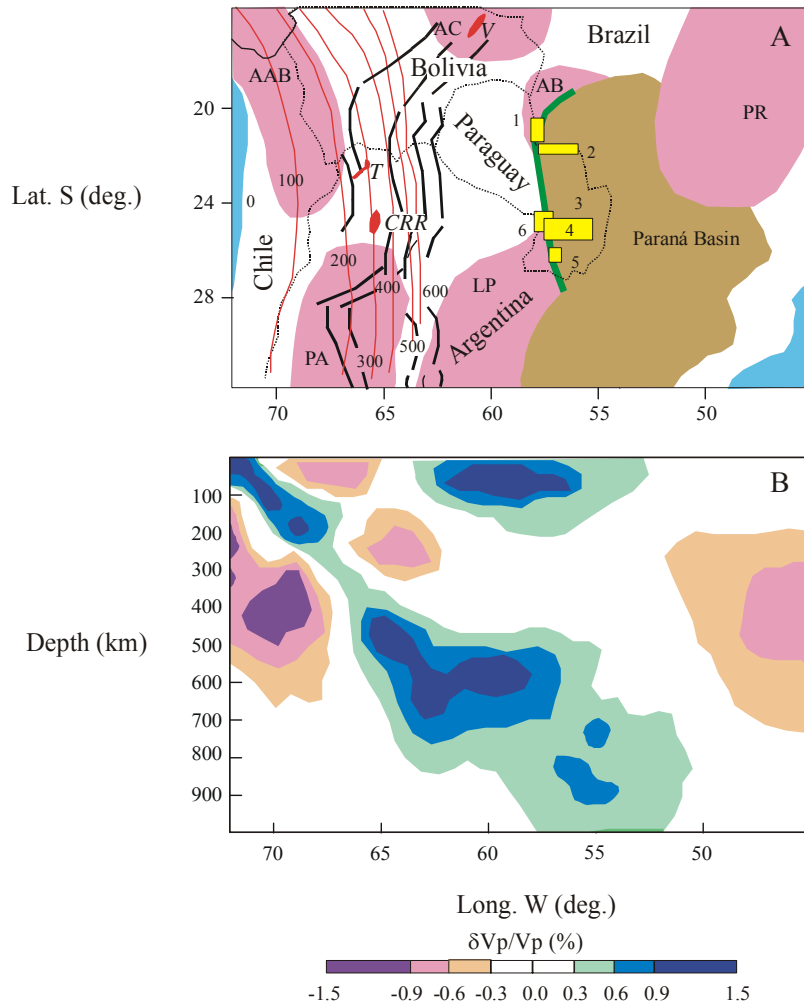


Fig. 1. A: Map of the study region showing contours (red lines) of the depth (km) of the subducting Nazca slab based on seismic data (Gudmundsson & Sambridge, 1998); heavy lines (black) outline the Cretaceous rift systems which roughly marks the limit between the Brazilian shield and the Paleozoic (Pacific) mobile belt (cf. Lucassen *et al.*, 2002); pink fields delineate inferred positions of major cratonic fragments below Phanerozoic cover (after Laux *et al.*, 2005): AAB, Arequipa-Antofalla; AC, Amazon Craton; AB, Apa Block; PR, Paranapanema; LP, Rio de la Plata; PA, Pampia.

1, Alto Paraguay sodic alkaline province; 2, Apa and Amabay potassic alkaline province; 3, Paraná Serra Geral flood tholeiites; 4, Asunción-Sapucaí-Villarica potassic alkaline central province (ASU); 5, Misiones sodic alkaline province; 6, Asunción sodic alkaline province. For comparison: Velasco complexes (V, Bolivia, 139 Ma; Comin-Chiaramonti *et al.*, 2005b); Tusaquillas complexes (T, Argentina, 144-140 Ma; Cristiani *et al.*, 2005); alkaline rock types from the Andean Central rift (CRR, Argentina, 90 Ma; Lucassen *et al.*, 2002).

B: Seismic tomography image of Liu *et al.* (2003) along a profile at approximately 24° Lat. S. The low-velocity feature in the mantle to the East has been interpreted as a fossil mantle plume by VanDecar *et al.* (1995).

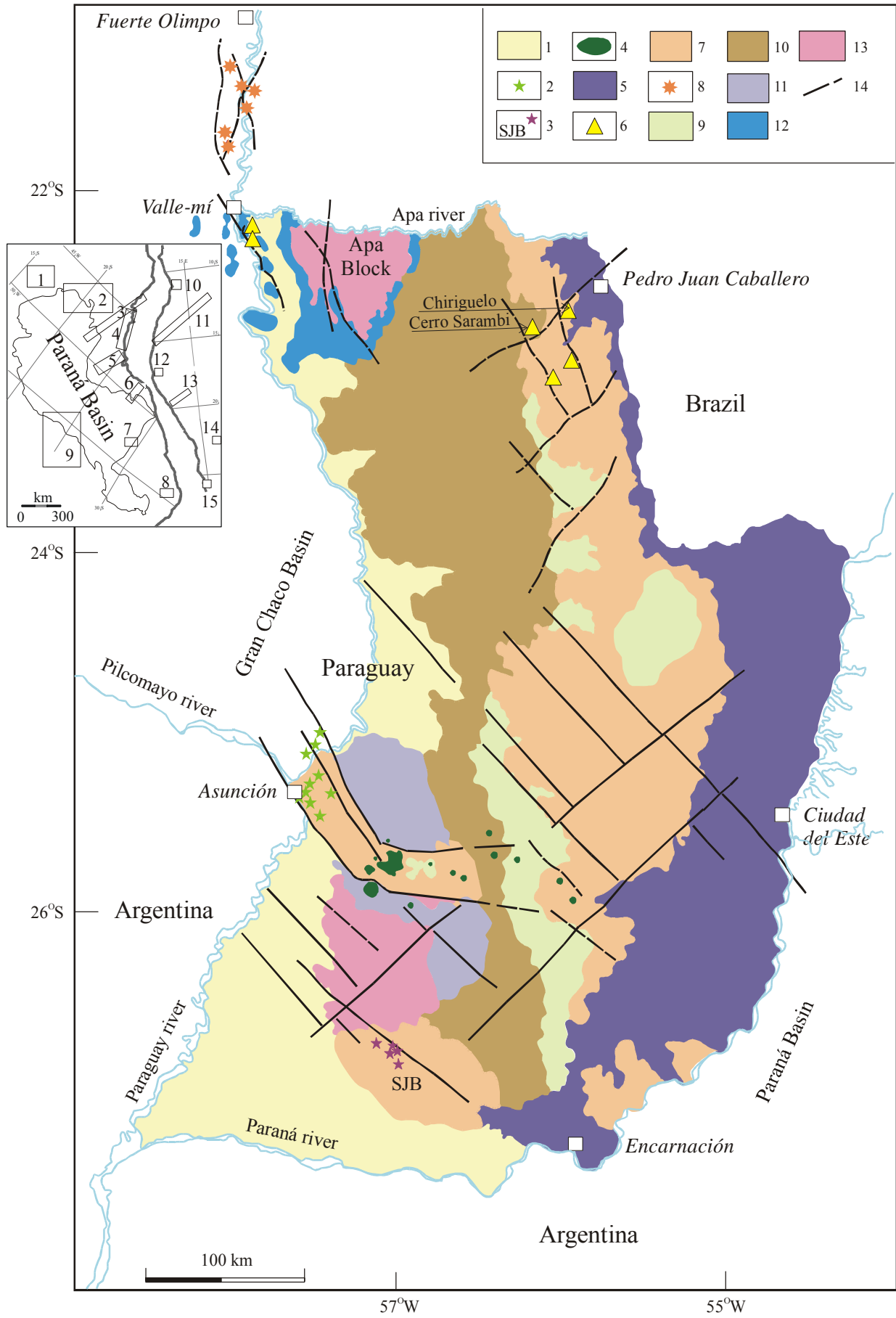


Fig. 2. Geological map of the Eastern Paraguay (after Comin-Chiaramonti & Gomes, 1995). 1: Neogene and Paleogene sedimentary cover (Gran Chaco; Argentina, Partim; Eastern Paraguay); 2: Paleogene sodic alkaline rocks; 3: Late Early Cretaceous sodic alkaline rocks (Misiones Province, San Juan Bautista, SJB); 4: Early Cretaceous potassic alkaline rocks (post-tholeiites; ASU: Asunción-Sapucaí-Villarica graben); 5: Early Cretaceous tholeiites of the Paraná Basin; 6: Early Cretaceous potassic alkaline rocks (pre-tholeiites); 7: Jurassic-Cretaceous sedimentary rocks (Misiones Formation); 8: Permo-Triassic alkaline rocks (Alto Paraguay Province); 9: Permian sedimentary rocks (Independencia Group); 10: Permo-Carboniferous sedimentary rocks (Coronel Oviedo Group); 11: Ordovician-Silurian sedimentary rocks (Caacupé and Itacurubí Groups); 12: Cambro-Ordovician platform carbonates (Itacupumí Group); 13: Archean and Neo-Proterozoic crystalline basement: high- to low-grade metasedimentary rocks, metarhyolites and granitic intrusions; 14: faults. Arrows indicated the localities quoted in the text. **Inset:** Distribution of the main areas occupied by alkaline magmatism in the Paraná-Angola-Etendeka system (cf. also Fig.8). (1) Iporá; (2) Alto Paranaíba; (3) Cabo Frio; (4) Serra do Mar; (5) Ponta Grossa; (6) Anitápolis and Lages; (7) Piratini; (8) Valle Chico; (9) Paraguay; (10) Kwanza Basin, Angola; (11) Moçamedes Arch, Angola; (12) Virilundo, Angola; (13) Damara Belt, Namibia; (14) Blue Hills, Namibia; (15) Dicker Willem complex, Namibia.

In particular, Eastern Paraguay, at the westernmost side of the Paraná intercratonic basin (Figs. 1, 2), is bounded by the N-S Paraguay river lineament, separating the Paraná Basin (East) from the Gran Chaco Basin (West) (Almeida, 1983; Comin-Chiaramonti *et al.*, 1997). The basement rocks are mainly Proterozoic to Early Paleozoic granitic intrusions, rhyolitic flows and high- to low-grade metasediments formed during the assembly of Gondwana and the Brasiliano orogenic cycles, corresponding to the Pan African cycle (Wiens, 1986; Kanzler, 1987; Velázquez *et al.*, 1996; Comin-Chiaramonti *et al.*, 2000, and references therein). According to Brito Neves *et al.*, 1999, the basement of the South American platform displays the lithostructural and tectonic records of three major orogenic collages: the Middle Paleoproterozoic, or Transamazonic, the Late Mesoproterozoic/Early Neoproterozoic and the Late Neoproterozoic/Cambrian (the Brasiliano-Pan African collage).

During Early to Late Mesozoic times, Eastern Paraguay was subjected to NE-SW-trending crustal extension related to the break-up of western Gondwana and sea-floor spreading in the South Atlantic which started at ~125-127 Ma (Chron M4; Nürberg & Müller, 1991). In addition were the effects of relative motions and different angular velocities of various South America sub-blocks (Unternehner *et al.*, 1988; Comin-Chiaramonti *et al.*, 1995a, 1995b, 1996; Turner *et al.*, 1994; Prezzi & Alonso, 2002). The resulting tectonic pattern controlled the development of graben or half-graben structures in response to the NE-SW-directed extension which lasted until the Oligocene (Hegarty *et al.*, 1995; Comin-Chiaramonti & Gomes, 1995; Comin-Chiaramonti *et al.*, 1992, 1999; Riccomini *et al.*, 2001; Velázquez *et al.*, 2005).

The Alto Paraguay alkaline complexes predate the CAMP event ("Central Atlantic Magmatic Province"; cf. Iacumin *et al.*, 2003), and were emplaced along the Paraguay belt, a Cambrian suture between the southernmost tip of the Amazon plate and the Paraná block (Ussami *et al.*,

1999; Fisseha *et al.*, 2005). Alternatively, this suture may represent the eastern limit (marked by the Paraguay river) of the Pungoviscana trough, a large basin of Late Precambrian to Early Cambrian age on the Pacific edge of the Brazilian shield (Jezek *et al.*, 1985; Mantovani *et al.*, 2005).

Potassic magmatism from central-eastern Paraguay (and the Paraná flood tholeiites) is associated with the break-up of Gondwana and predates the separation of Africa and South America, while late sodic magmatism postdates the formation of the southern Atlantic Ocean (Comin-Chiaramonti & Gomes, 1995). Both potassic and sodic magmatic rocks were mainly emplaced along NW-SE trending rift structures in Eastern Paraguay, corresponding to a general NE-SW extensional event that started at least as early as Triassic times (Comin-Chiaramonti *et al.*, 1996, 1999). Similar alkaline magmatic events, i.e. at Early Cretaceous, Later Cretaceous and Paleogene time, are widespread everywhere in the Paraná-Angola-Etendeka system (Brazil, Angola and Namibia; Hawkesworth *et al.*, 1986; Peate *et al.*, 1999; Comin-Chiaramonti & Gomes, 1995; 2005).

EASTERN PARAGUAY: PREVIOUS RADIOISOTOPIC AGES

The ages of the magmatic events in Eastern Paraguay are poorly constrained by a large set of not very precise K/Ar, non-plateau Ar/Ar, Rb/Sr and fission-track data, both on minerals and whole-rocks (Table 1).

The Alto Paraguay rocks (sodic magmatism) and minerals (biotite, amphibole and alkali feldspars) have an age span of 255 to 210 Ma (i.e. Upper Permian, Lopingian, to Upper Triassic, Norian; time scale according to Gradstein *et al.*, 2004). On the whole, the large range of measured ages on amphiboles, alkali feldspars and whole-rock samples indicate that the K/Ar and Rb/Sr isotopic data are affected by complexities linked above all to sub-solidus reactions and exsolutions, hydrothermal alteration and weathering (cf. Velázquez *et al.*, 1992, 1996). The smallest analytical errors and age range (i.e. 248-242 Ma) is yielded by K/Ar and Ar/Ar (non-plateau) analyses of biotite separates (cf. Table 1).

The age of the potassic alkaline magmatism from Amambay and Rio Apa (cf. Fig. 1) is poorly documented by previous K/Ar data on biotite and whole rock and fission-track on titanite and apatite. The ages of basanites to trachytes span from 147 to 128 Ma, i.e. from Upper Jurassic to Early Cretaceous. We note that ages younger than 133 Ma (cf. Eby & Mariano, 1992) are not consistent with the field relationships (e.g. Chiriguelo alkaline-carbonatitic complex; cf. Censi *et al.*, 1989), which clearly show that the alkaline rocks and associated carbonatite predate the Paraná flow tholeiites (main peak at ~133 Ma).

The field relationships relative to the potassic alkaline rocks from the Asunción-Sapucai graben (ASU of Comin-Chiaramonti *et al.*, 1997) in the central provinces show that they represent a post-tholeiitic event. These rocks display a bimodal Early Cretaceous distribution

(Barremian to Aptian), with the older averaged age at 129 ± 4 Ma (intrusive and effusive variants and dykes; mineral K/Ar and Rb/Sr isochron ages, mainly) and the younger one represented only by potassic dykes at 119 ± 2 Ma (K/Ar whole-rock data).

The Misiones, SJB, sodic magmatism is very poorly documented from a geochronological point of view. The only available K/Ar age (whole rock, 120 Ma; cf. Comin-Chiaramonti *et al.*, 1992), is similar to the younger ASU potassic dykes.

Asunción sodic plugs, mainly at the north-western ASU, have an age span from 61 to 39 Ma (Paleocene to Eocene), with an average of 50 ± 8 Ma (K/Ar ages on whole rocks; Compté & Hasui, 1971; Bitschene, 1987; Comin-Chiaramonti, 1991). A few sodic plugs and dykes outcropping in the central ASU yield similar K/Ar ages ranging from 66 to 33 Ma. Despite the large interval of the measured ages, it is clear that ASU sodic magmatism represents the youngest magmatic event in Eastern Paraguay.

NEW $^{40}\text{Ar}/^{39}\text{Ar}$ AGES

Analytical procedures

New $^{40}\text{Ar}/^{39}\text{Ar}$ analyses have been performed on 76 whole-rock samples and on mineral separates (alkali feldspar, plagioclase, amphibole and biotite) from the five main alkaline magmatic suites from Eastern Paraguay and Alto Paraguay at the Berkeley Geochronology Center (BGC, USA; 9 analyses) and at the Geochronological Research laboratory of the São Paulo University (USP, Brazil; 67 analyses). Sample preparation, irradiation and analyses followed methods and facilities described by Renne *et al.* (1996, 1998) and by Vasconcelos *et al.* (2002) for the argon-ion laser-heating system at the BGC and the USP, respectively. The mineral grains and rocks (16 - 25 mesh) were irradiated for 7 and 100 hours, along with Fish Canyon sanidine (FCs; 28.02 Ma, Renne *et al.*, 1998) neutron flux standards, at the TRIGA (Oregon State University) and at IPEN (Instituto de Pesquisas Energéticas/CNEN IEA-R1-USP) nuclear reactors, respectively. At both laboratories, the analyzed materials were step-heated using a fully automated noble gas extraction and purification system and the Ar isotopic compositions were measured in static mode by a MAP-215-50 mass spectrometer. Isotopic run data were corrected for mass discrimination, radioactive decay and nucleogenic interferences. Plateau and miniplateau ages are hereafter defined by at least three successive concordant steps and by at least 70% and 50%, respectively, of the total released ^{39}Ar . Errors are reported at the 2σ level. The decay constants recommended by Steiger & Jäger (1977) were used.

A critical evaluation and selection of the obtained results is based on the observed apparent age and Ar isotopic ratios ($^{38}\text{Ar}/^{39}\text{Ar}$ and $^{37}\text{Ar}/^{39}\text{Ar}$) and on X-Ray diffractometry and electron microprobe analyses of the rocks and single mineral phases. In general, poor results (strongly discordant age spectra) were obtained for feldspars (systematically zoned with albite patches and/or exsolutions), leucite and amphibole (spinoidal exsolution). Also, whole-rock, porphyritic

samples and intrusive rock types are usually characterized by inhomogeneous and relatively high $^{37}\text{Ar}/^{39}\text{Ar}$ and non-concordant apparent age spectra. In particular, whole-rock samples of potassic alkaline complexes, which are feldspars, nepheline and leucite rich, yielded systematically discordant age spectra probably due to the sodium-potassium exchanges by intergranular fluids up to low hydrothermal temperatures (e.g. leucite-nepheline analcimitization and K-Ca feldspar formation of Comin-Chiaramonti *et al.*, 1979 and of Comin-Chiaramonti, 1979). In contrast, the best results (concordant age spectra, $^{37}\text{Ar}/^{39}\text{Ar}$ and $^{36}\text{Ar}/^{39}\text{Ar}$ isotopic spectra, consistent with the chemical analyses of the analyzed material) were obtained for lava whole rocks (mainly sodic alkaline rock types) and chiefly for non altered biotites ($\text{K}_2\text{O} = 9\text{-}10.5$ wt%; Comin-Chiaramonti & Gomes, 1995). Considering the generally low $^{40}\text{Ar}/^{39}\text{Ar}$, consistent with the high K/Ca of the microprobe analyses, biotite analyses particularly yield robust age data, which are not affected by secondary alteration. A total of 33 samples yielded $^{40}\text{Ar}/^{39}\text{Ar}$ plateau and mini-plateau ages and are discussed in this section. A summary of the geochronological results is presented in Table 2, the complete data set is available on request to the corresponding author (A. Marzoli).

Alto Paraguay

Biotite separates were analyzed for the evolved Na-alkaline magmatic (intrusive) rocks from North to South: Cerro Boggiani, Cerro Siete Cabezas, and a small stock South of Cerro Siete Cabezas (Fig. 3). The samples yielded plateau ages which range from 240.6 ± 0.4 to 241.9 ± 0.4 Ma and are defined by 8-12 successive heating steps and more than 85% of the total released gas. Plateau steps are characterized by relatively homogeneous and low $^{37}\text{Ar}/^{39}\text{Ar}$, confirming that the analyzed material was "fresh" biotite. Inverse isochron ages ($^{40}\text{Ar}/^{39}\text{Ar}$ vs $^{36}\text{Ar}/^{39}\text{Ar}$) are indistinguishable from plateau ages, yield slightly larger errors and initial $^{40}\text{Ar}/^{36}\text{Ar}$ intercepts overlapping atmospheric values suggesting absence of excess ^{40}Ar component. Thus the obtained plateau ages indicate that Alto Paraguay sodic magmatism occurred at about 241 Ma during a short time interval (mean age 241.5 ± 1.3 Ma, corresponding to an Anisian age).

The integrated age (242.0 ± 1.6 Ma; no plateau age obtained) of the Pão de Açucar trachyphonolite (Velázquez *et al.*, 1996) is concordant with the plateau ages of the other samples.

Rio Apa and Amambay

Biotite separates of three samples (one basanite dyke from Valle-mí, one lava flow from Cerro Chiriguelo and a glimmeritic vein from Cerro Sarambí) yielded plateau ages defined by 92-95% of the total released gas and range from 137.6 ± 0.7 to 139.5 ± 0.5 Ma (Fig. 4). Very low $^{37}\text{Ar}/^{39}\text{Ar}$ of plateau steps indicates that the analyzed materials were pure biotite. Isochron ages are concordant with plateau ages and yield atmospheric initial $^{40}\text{Ar}/^{36}\text{Ar}$. Thus, the obtained ages (mean age 138.0 ± 1.6 Ma) are robust evidence of carbonatitic-potassic magmatism emplaced in the northern region of Eastern Paraguay before the onset of Paraná-Angola-Etendeka flood

volcanism. Notably, potassic alkaline magmatism of similar age (139 ± 3 Ma; Comin-Chiaramonti *et al.*, 2005b) occurred in SE Bolivia (Velasco complexes).

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

REGION/LOCALITY	Occurrence	Rock-type	Material	Method	Age(Ma)	Re.
ALTO PARAGUAY:						
Sodic magmatism						
Cerro Siete Cabezas	Stock	Nepheline syenite	Am	K/Ar	227.9±7.8	1
Cerro Siete Cabezas	Stock	Nepheline syenite	Bi	K/Ar	249.0±3.0	1
Cerro Siete Cabezas	Stock	Syenite	Am	K/Ar	229.8±8.3	1
Cerro Siete Cabezas	Stock	Syenite	Bi	K/Ar	244.4±10.4	1
Cerro Siete Cabezas	Stock	Syenite - Quartz syenite	AF - WR	Rb/Sr	255±11	1
erorchron						
Cerro Siete Cabezas	Stock	Nepheline syenite	Am	Ar/Ar	236.0±1.6	2
Cerrito	Stock	Nepheline syenite	Bi	K/Ar	253.2±9.2	1
Fecho dos Morros	Stock	Nepheline syenite	Am	K/Ar	212.8±14.8	1
Pão de Açucar	Stock	Nepheline syenite	Am	K/Ar	233.2±7.2	1
Pão de Açucar	Stock	Nepheline syenite	Bi	K/Ar	248.3±5.3	1
Pão de Açucar	Lava flow	Phonolite	WR	K/Ar	219.1±13.3	3
Pão de Açucar	Lava flow	Trachyphonolite	Bi	Ar/Ar	242±1.6	2
Pão de Açucar	Stock	Nepheline syenite	Bi	K/Ar	244.6	4
Pão de Açucar	Stock	Nepheline syenite	Bi	K/Ar	241.7	4
Pão de Açucar	Stock	Nepheline syenite	AF	K/Ar	211.3	4
Pão de Açucar	Stock	Nepheline syenite	Am	K/Ar	209.6	4
Cerro Boggiani	Stock	Nephelinic syenite	Am	K/Ar	234.6±13.7	1
Cerro Boggiani	Stock	Nepheline syenite	Am	K/Ar	234.0±9.0	1
Cerro Boggiani	Lava flow	Peralkaline phonolite	WR	K/Ar	236.7±10.9	1
Cerro Boggiani, Fecho dos Morros, Cerrito		Nepheline syenite, Nepheline syenite, Peralkaline phonolite	WR, Bi, Am, AF	Rb/Sr	255±11	1
RIO APA: Potassic magmatism						
Valle-mi	Dyke	Basanite	WR	K/Ar	142±2	5
AMAMBAY						
Cerro Chiriguelo	Stock	Ca-carbonatite	Bi	K/Ar	128±5	6
Cerro Chiriguelo	Lava flow	Trachyte	Bi	K/Ar	146.7±9.2	6a
Cerro Chiriguelo	Lava flow	Trachyte	WR	K/Ar	138.9±9.2	6a
Cerro Sarambi	Dyke	Syenite	WR	K/Ar	140±1	5

Tab. 1. Continuation

REGION/LOCALITY	Occurrence	Rock-type	Material	Method	Age(Ma)	Re.
Arroyo Gasory	Dyke	Trachyte	Tit	Fission-track	137±7	6
Arroyo Gasory	Dyke	Trachyte	Ap	Fission-track	145±8	6
CENTRAL PROVINCES (ASU):						
Potassic magmatism						
Cerro Km 23	Stock	Theralite	Bi	K/Ar	131.9±5.0	7
Cerro Km 23	Dyke	Basanite	WR	K/Ar	115.8±4.2	7
Ybytyruzù (Cerro Acatí)	Lava flow	Trachyphonolite	Bi	K/Ar	125.9±4.6	7
Ybytyruzù (Cerro Boni)	Lava flow	Latite	Bi	K/Ar	124.6±4.2	7
Ybytyruzù (Cerro Itatí)	Lava flow	Phonotephrite	Bi	K/Ar	128.8±4.6	7
Mbocayaty	Stock	Nepheline syenodiorite	AF	K/Ar	130.0±3.4	8
Mbocayaty	Stock	Nepheline syenodiorite	Bi	K/Ar	129.2± 6.8	8
Mbocayaty	Stock	Essexite	Bi	K/Ar	128.2±4.5	7
Mbocayaty	Stock	Essexite, Nedpheline syenodiorite	WR, Bi, AF	Rb/Sr isochron	126.5±7.6	8
Aguapety Portón	Stock	Malignite	WR	K/Ar	138.1±4.8	7
Aguapety Portón	Stock	Essexite	Bi	K/Ar	132.9±5.5	7
Aguapety Portón	Stock	Essexite, Malignite	WR, Bi, AF	Rb/Sr isochron	128.2±4.5	8
Potrero Ybaté	Stock	Nepheline syenodiorite	WR, Bi, AF	Rb/Sr isochron	126.5±7.6	8
Potrero Ybaté	Stock	Nepheline syenodiorite	AF	K/Ar	127.8±5.6	8
Sapucaí	Stock	Essexite	WR	K/Ar	131.0±8.2	9
Sapucaí	Lava flow	Phonolite	WR	K/Ar	136.4±5.1	9
Sapucaí	Dyke	Basanite	WR	K/Ar	119.6±7.2	9
Sapucaí	Lava flow	Alkali basalt	WR	K/Ar	131.2±5.1	9
Sapucaí	Lava flow	Trachybasalt	WR	K/Ar	122.0±4.0	2
Sapucaí	Dyke	Phonotephrite	WR	K/Ar	119.0±4.0	2
Sapucaí	Dyke	Phonolite	WR	K/Ar	121.0±4.0	2
Sapucaí	Dyke	Trachybasalt	WR	K/Ar	119.0±4.0	2
Sapucaí	Dyke	Basanite	WR	K/Ar	118.0±4.0	2
Sapucaí	Dyke	Phonotephrite	WR	K/Ar	119.0±4.0	2
Sapucaí	Stock	Theralite, Syenogabbro	WR, Bi, AF	Rb/Sr isochron	126.5±7.6	8
Cerro Santo Tomás	Stock	Syenogabbro	Bi	K/Ar	126.0±4.5	7
Cerro Santo Tomás	Stock	Syenogabbro	FC	K/Ar	136.8±5.0	7
Cerro Santo Tomás	Stock	Essexite	WR	K/Ar	136.5±10.2	9

Tab. 1. Continuation

REGION/LOCALITY	Occurrence	Rock-type	Material	Method	Age(Ma)	Re.
Cerro Santo Tomás	Dyke	Basanite	Bi	K/Ar	130.1±4.8	7
Cerro Santo Tomás	Dyke	Basanite	Bi	K/Ar	127.9±4.8	7
Cerro Santo Tomás	Stock	Nepheline syenodiorite	Bi	K/Ar	132.0±11.5	3
Cerro Santo Tomás	Stock	Syenogabbro	WR, Bi, AF	Rb/Sr isochron	128.0±8.0	7
Cerro Santo Tomás	Stock	Syenodiorite	WR, Bi, AF	Rb/Sr isochron	126.5±7.6	8
Cerro Acahay	Dyke	Trachybasalt	WR	K/Ar	118.0±4.0	2
Cerro Arrúa-í	Stock	Nepheline syenodiorite	Bi	K/Ar	132.3±8.4	8
Cerro Arrúa-í	Stock	Nepheline syenodiorite	WR, Bi, AF	Rb/Sr isochron	126.5±7.6	8
Sodic magmatism						
Sapucaí	Dyke	Na-Tephrite	WR	K/Ar	66.0±2.0	2
Sapucaí	Dyke	Na-Tephrite	WR	K/Ar	32.8±0.9	2
Cerro Gimenez	Plug	Na-Phonolite	WR	K/Ar	66.0±4.6	8
MISIONES:	Sodic					
magmatism						
Estancia Guavira-y	Plug	Melanephelinite	WR	K/Ar	120±5	10
ASUNCIÓN:	Sodic					
magmatism						
Cerro Patiño	Plug	Ankaratrite	WR	K/Ar	38.8±2.3	7
Limpio	Plug	Melanephelinite	WR	K/Ar	50.2±1.9	7
Cerro Verde	Plug	Ankaratrite	WR	K/Ar	57.0±2.3	7
Villa Hayes	Plug	Ankaratrite	WR	K/Ar	58.4±2.2	7
Cerro Ñemby	Plug	Melanephelinite	WR	K/Ar	45.7±1.8	7
Remanso Castillo	Dyke	Melanephelinite	WR	K/Ar	40.6±1.7	7
Cerro Confuso	Plug	Phonolite	WR	K/Ar	55.3±2.1	7
Cerro Confuso	Plug	Phonolite	WR	K/Ar	60.9±4.4	7
Cerro Confuso	Plug	Phonolite	WR	K/Ar	59.3±2.4	7
Nueva Teblada	Plug	Melanephelinite	WR	K/Ar	46.3±2.0	7
Nueva Teblada	Plug	Melanephelinite	WR	K/Ar	56.7±2.3	7
Cerro Lambaré	Plug	Melanephelinite	WR	K/Ar	48.9±2.0	7
Cerro Lambaré	Plug	Melanephelinite	WR	K/Ar	48.9±2.2	7
Cerro Tacumbú	Plug	Melanephelinite	WR	K/Ar	46.0±7.0	3
Cerro Tacumbú	Plug	Melanephelinite	WR	K/Ar	41.3±1.8	7

Tab. 2. Summary of obtained plateau, mini-plateau and integrated $^{40}\text{Ar}/^{39}\text{Ar}$ ages; plateau defined by > 70% of total released gas; mini-plateau, 50–70% of total released gas, are shown with *; (1) refers to mini-plateau age defined by 40% ^{40}Ar . BGC: Berkeley Geochronology Center, USA; USP: Geochronology Research laboratory, São Paulo University, Brazil.

REGION/LOCALITY	Laboratory	Rock-type	Material	Plateau Age (Ma)	Isochron Age (Ma)	MSWD	$^{40}\text{Ar}/^{36}\text{Ar}$ intercept
ALTO PARAGUAY							
1. Stock 1	BGC	Syenite	Bi	240.6±0.4	240±2	1.3	299±88
2. Cerro Siete Cabezas	BGC	Syenite	Bi	241.9±0.4	239±3	1.1	313±82
3. Cerro Boggiani	USP	Phonolite	Bi	241.3±0.7	241±2	0.9	342±74
RIO APA							
1. Valle-mí	BGC	Basanite (dyke)	Bi	138.7±0.2	139.0±0.3	1.9	187±123
AMAMBAY							
1. Cerro Chiriguelo	BGC	Trachyte	Bi	137.6±0.7	138.1±1.7	0.6	184±97
2. Cerro Sarambí	BGC	Glimmerite (vein)	Bi	139.3±0.5	139.1±0.9	0.2	214±104
CENTRAL PROVINCES							
Ybytyruzú							
1. Cerro Km 23	USP	Essexitic gabbro	Bi	127.7±0.1*			
2. Cerro San Benito	USP	Essexitic gabbro	Bi	127.4±0.3	127.1±1.9	1.3	394±187
3. Cerro Santa Elena Villarrica	BGC	Essexite	Bi	125.6±0.2	126.2±0.5	1.2	194±105
7. Aguapety Portón Serrania de Ybytymy	BGC	Essexite	Bi	126.2±0.2	127.2±0.7	0.35	204±95
11. Cerro Cañada	USP	Alkali gabbro	Bi	126.1±0.5	127.6±1.4	1.7	114± 50
11A. Cerro Cañada	BGC	Ijolite	Bi	126.3 ± 0.2	126.2±0.9	0.14	304±110
Cerro San José							
20. Cerro San José	USP	Syenogabbro	Bi	126.4±0.4*	126.4±3.9	0.81	306±221
20B. Cerro San José	USP	Syenogabbro	Bi	128.5±0.3			
Potrero Ybaté							
23. Potrero Ybaté	USP	Nepheline syenodiorite	Bi	124.1±0.6			
Sapucai							
25A. Sapucai (Cerro Verde)	USP	Essexite	Bi	124.6±0.7	127.1±1.4	0.76	198±123
25B. Sapucai (Cerro Fidel)	USP	Trachyphonolite	Bi	126.4±0.2	128.6±2.9	2.76	138±244
25 C. Sapucai	BGC	Trachyandesite (dyke)	Bi	126.2±0.1	126.2±0.7	0.10	311±52

Tab. 2. Continuation

REGION/LOCALITY	Laboratory	Rock-type	Material	Plateau Age (Ma)	Isochron Age (Ma)	MSWD	$^{40}\text{Ar}/^{36}\text{Ar}$ intercept
Paraguari							
27. Cerro Santo Tomás	USP	Nepheline syenodiorite	Bi	128.8±0.4*	127.7±1.1	2.1	383±123
27A. Cerro Santo Tomás	USP	Basanite (dyke)	Bi	127.2±0.6	129.2±3.1	1.0	226±156
Acahay							
30. Acahay	USP	Trachybasalt (lava flow)	WR	127.0±0.2	126.5±1.5	0.10	294±12
30A. Acahay	USP	Alkali gabbro	Bi	123.6±0.5*			
Yaguarón							
33. Cerro Arrua-I	USP	Nepheline syenodiorite	WR	129.0±0.2*	126.2±1.7	2.1	411±152
MISIONES							
1. Estancia Guavira-y	USP	Melanephelinite (lava flow)	WR	119.8± 0.8*	118±7	2.1	336±77
2. Estancia Ramirez	USP	Melanephelinite (lava flow)	WR	118.3±0.6*			
3. Cerro Caa Jhovv	USP	Peralkaline phonolite (lava dome)	WR	117.9±0.9(1)			
4. Cerro Guayacan	USP	Tephrite (lava flow)	WR	117.2±0.2	119.0±1.3	1.9	257±47
ASUNCIÓN							
1. Cerrito	USP	Melanephelinite (lava flow)	WR	56.0±0.5*			
2. Benjamin Aceval	USP	Melanephelinite (lava flow)	WR	56.4±0.9*			
3. Cerro Verde	USP	Ankaratrite (lava flow)	WR	61.3±0.3*			
4. San Jorge	USP	Ankaratrite (lava flow)	WR	57.0±0.3			
5. Cerro Tacumbú	USP	Ankaratrite (lava flow)	WR	58.4±0.4*			
6. Ñemby	USP	Ankaratrite (lava flow)	WR	60.7±0.6	59±2	0.7	434±130

Central province (ASU)

The largest data set concerns the post-tholeiitic magmatism from the ASU region. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses have been performed on a total of over 18 biotite separates from representative samples and on six whole-rock specimens. Plateau or mini-plateau ages have been obtained on ten magmatic complexes, including the largest ones, i.e. the Sapucaí and Acahay alkaline complexes, and including intrusives, as well as lava flows (Figs. 5). The ten plateau ages (obtained on nine

biotite and one whole-rock sample) range from 124.6 ± 0.7 (Sapucaí, Cerro Verde) to 128.5 ± 0.3 Ma (Cerro San José). Inverse isochron ages are concordant with plateau ages except for the youngest (Sapucaí Serro Verde: isochron = 127.1 ± 1.4 Ma) and oldest sample (Cerro San José, no valid isochron age). Initial $^{40}\text{Ar}/^{36}\text{Ar}$ overlap atmospheric values (despite large error on this initial value, due to the generally high $^{40}\text{Ar}/^{39}\text{Ar}$), suggesting a negligible role for excess ^{40}Ar . No significant age difference is apparent between intrusives and volcanics.

Thus, the highly concordant plateau ages suggest that the peak activity of the ASU potassic magmatism occurred at 126.4 Ma (mean of the plateau ages = 126.4 ± 0.4 Ma) and was emplaced in a short time span, about 5-6 Ma after the peak activity of the Paraná tholeiitic flood volcanism (133-132 Ma; Renne *et al.*, 1994).

This Aptian-Barremian mean and peak activity age for the potassic ASU magmatism is confirmed, but the total duration is slightly extended (123.6 ± 0.5 Ma to 129.0 ± 0.2 Ma) if mini-plateau ages are also considered.

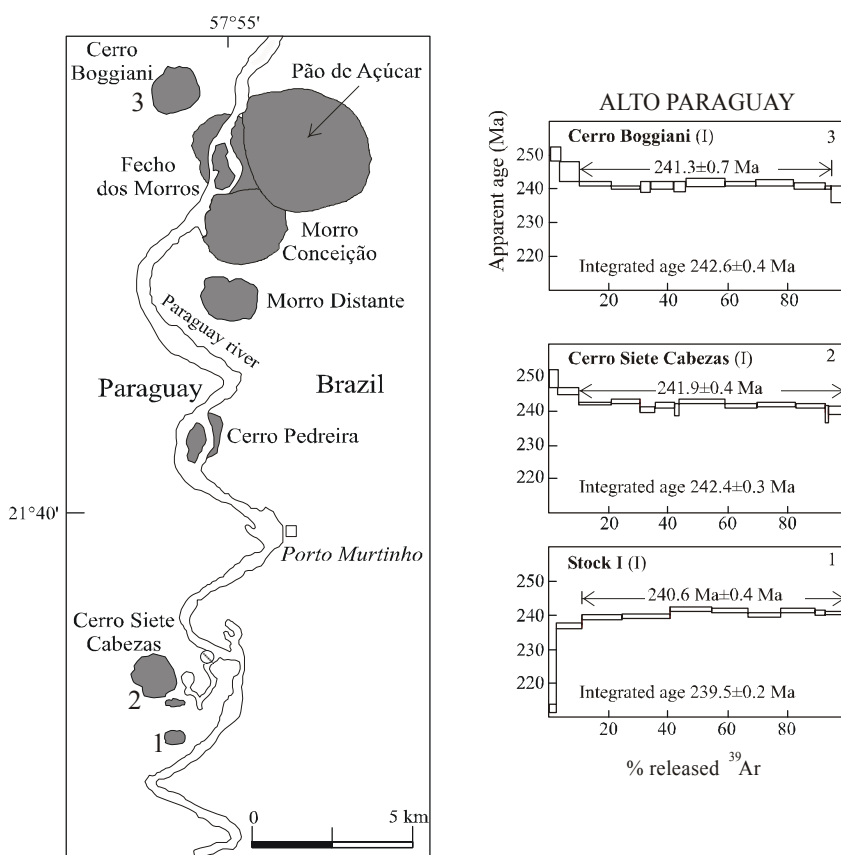


Fig. 3. Sketch map showing the main outcrops along Alto Paraguay river (cf. Fig.2 and Table 2) and the $^{40}\text{Ar}/^{39}\text{Ar}$ spectra. Arrows on apparent age diagrams indicate steps included in age plateau. 2σ errors are shown.

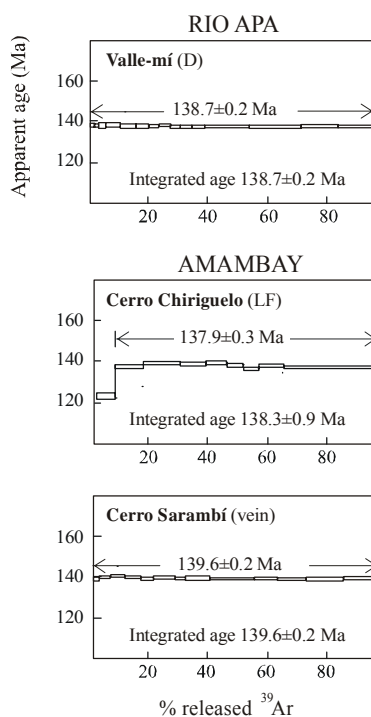


Fig. 4. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra from Amambay and Rio Apa regions from Eastern Paraguay (cf. Fig.2 and Tab.2).

Misiones province

Whole-rock samples from three lava flows and one lava dome of sodic affinity were analyzed (Fig. 6). The specimen from Cerro Guyacan yielded a plateau age of 117.2 ± 0.2 Ma, which is slightly lower than its isochron age (119.0 ± 1.3 Ma; atmospheric initial $^{40}\text{Ar}/^{36}\text{Ar}$). Similar mini-plateau ages have been obtained for the specimens from Estancia Guavira-y (119.8 ± 0.3 Ma) and Estancia Ramirez (118.3 ± 0.6). The mean of the plateau and mini-plateau ages (118.3 ± 1.6 Ma) indicate that Misiones magmatic activity occurred at about 118 Ma (Aptian, late Early Cretaceous), roughly corresponding to the youngest age detected for the Florianópolis (119 Ma; Raposo *et al.*, 1998), Ponta Grossa (120 Ma; Renne *et al.*, 1996b) and Santos-Rio de Janeiro tholeiitic dykes along the southeastern coast of the Brazil (Renne *et al.*, 1993; Turner *et al.*, 1994).

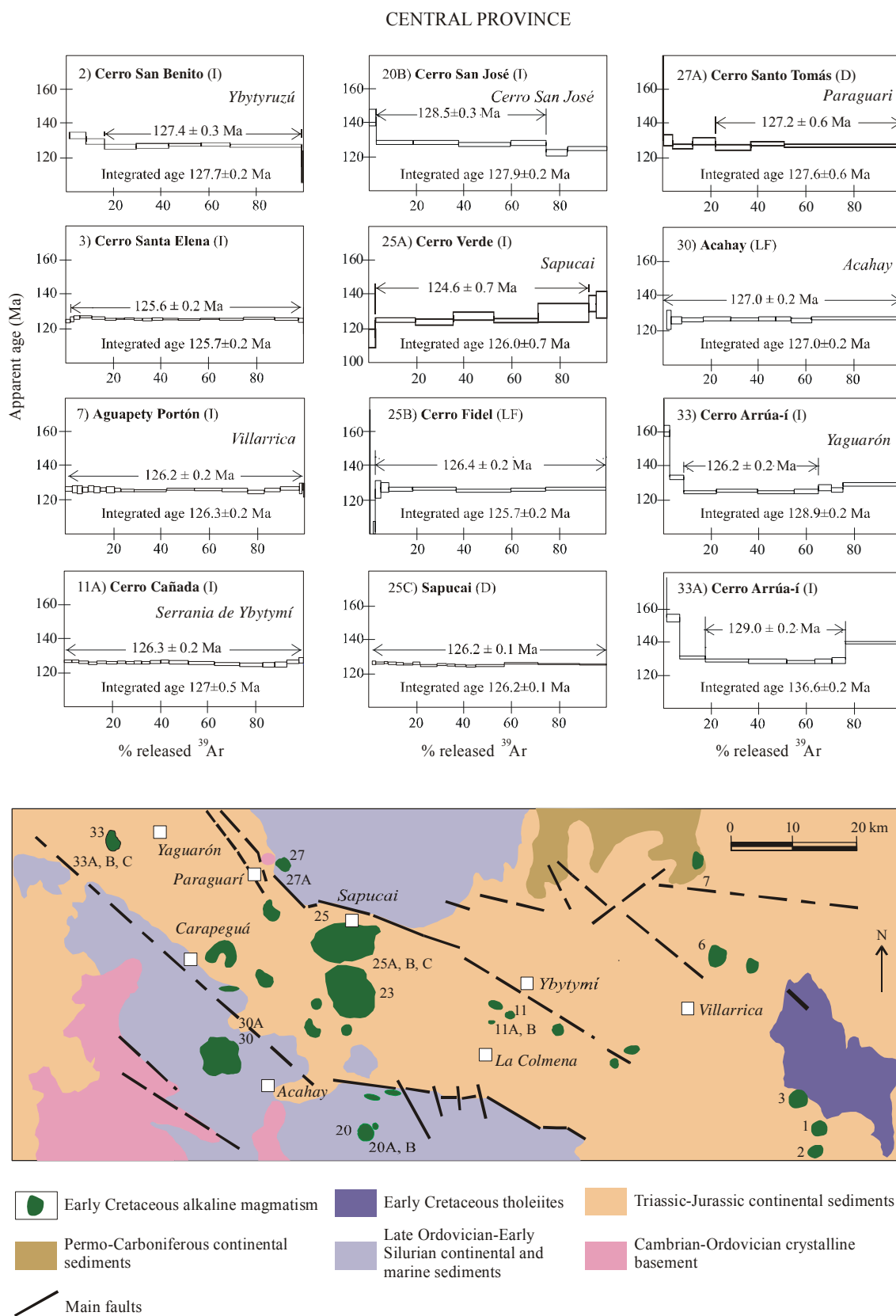


Fig. 5. Representative $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra (best results) for the potassic Central Province rock types and a sketch map showing the location of the samples numbered as in Table 2. I: intrusive; LF: lava flow; D, dyke.

Asunción province

A total of one plateau age and five mini-plateau ages have been obtained on lava flow whole-rock samples from the Na-magmatic Asunción province (Fig. 7). The mini-plateau ages range from 56.0 ± 0.5 to 61.3 ± 0.6 Ma, whereas the sample from the Ñemby ankaratrite yielded a plateau age at 60.7 ± 0.6 Ma. This latter sample yield an isochron age (59 ± 2) with an atmospheric initial argon isotopic ratio. By contrast, no isochron ages were obtained for samples yielding mini-plateau ages. Thus, a Paleocene age is suggested for the Asunción province (average of plateau and mini-plateau ages = 58.7 ± 2.4 Ma) even though it should be noted that the age and duration of the sodic alkaline events is generally less well constrained than for the potassic alkaline events. These Early Cretaceous ages are comparable with those reported for some potassic alkaline complexes along the Cabo Frio Lineament (cf. Thompson *et al.*, 1998).

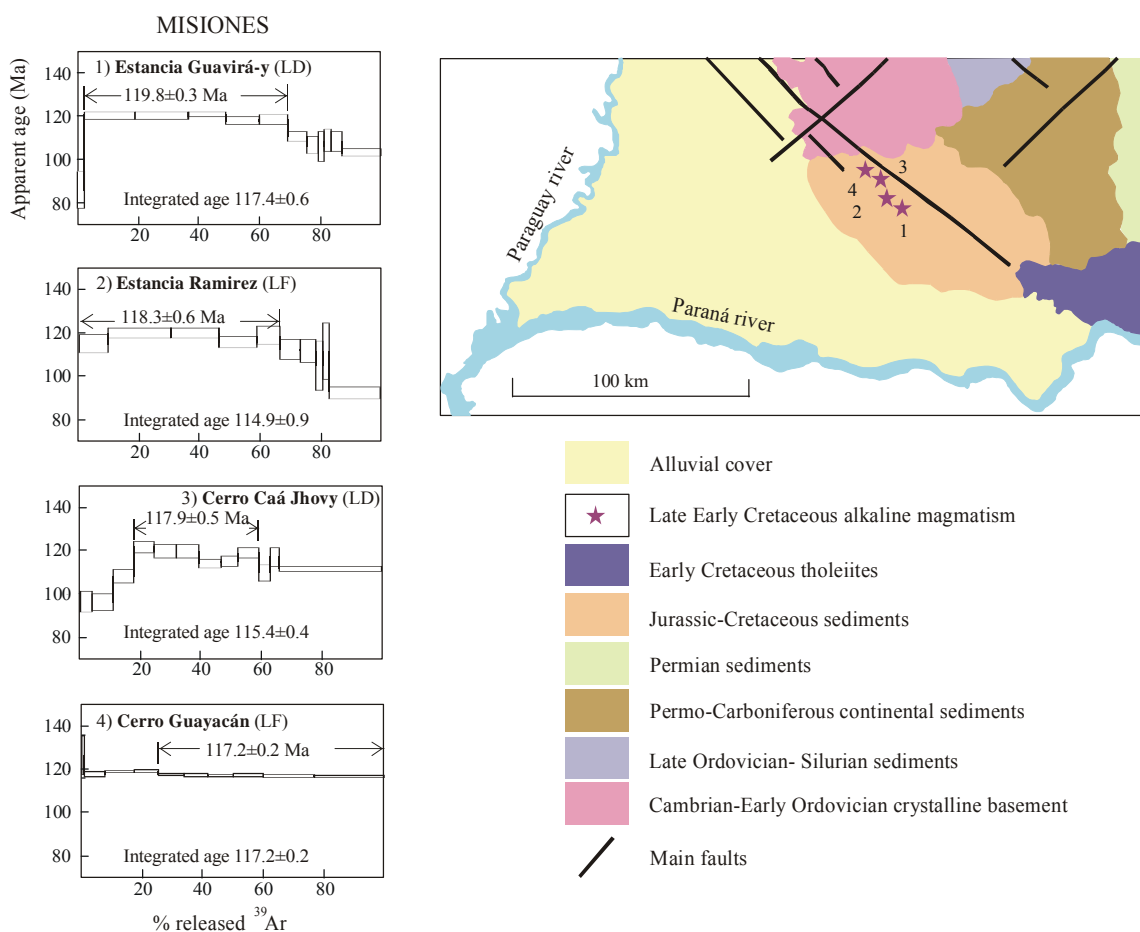


Fig. 6. Representative $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the Misiones Province and sketch map with the location of the samples numbered as in Table 2 (cf. Fig. 2).

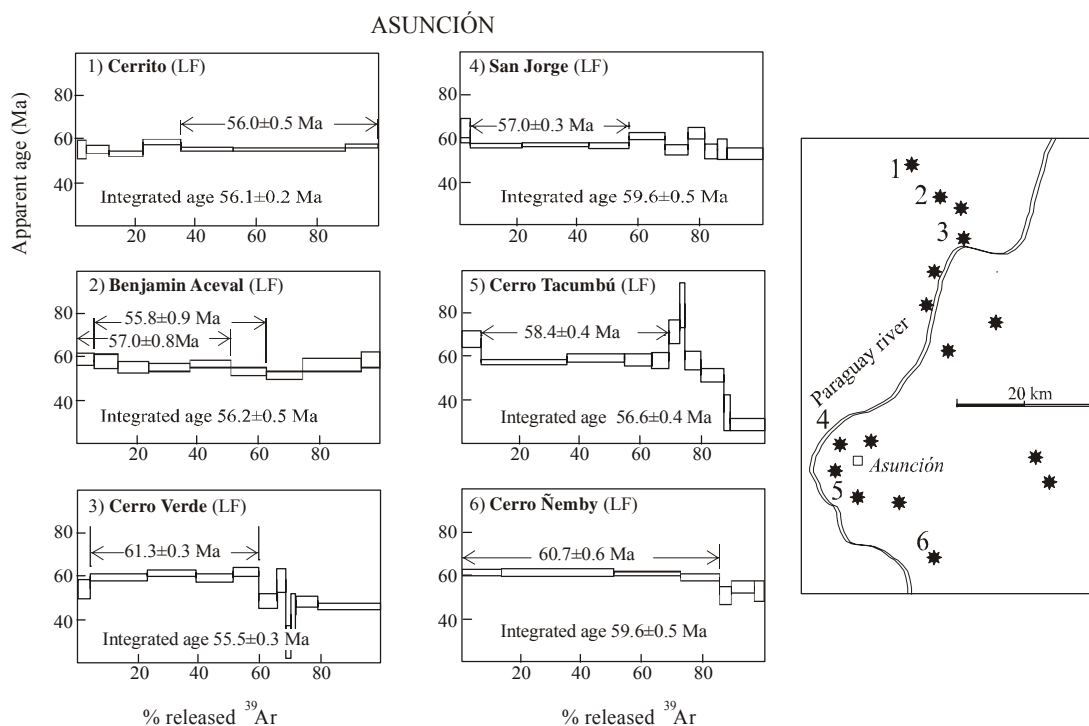


Fig. 7. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the Asunción Province and sketch map showing the location of samples numbered as in Table 2 (cf. Fig. 2). Note the prevailing mini-plateau (see text).

COMPARISON WITH AGES OF VOLCANIC ROCKS FROM THE PARANÁ-ANGOLA-ETENDEKA SYSTEM (PAE)

Continental flood basalts from PAE cover an area of over $1.5 \times 10^6 \text{ km}^2$. The PAE province has two main associated tholeiitic dyke swarms, one trending NW-SE (Ponta Grossa; cf. Fig. 8 and Piccirillo *et al.*, 1990) and the other approximately paralleling the coast, i. e. trending N-S (Florianópolis and Etendeka; Raposo *et al.*, 1998, Erlank *et al.*, 1984) and with ~ENE-WSW attitude (Santos-Rio de Janeiro, Brazil, and Kwanza, Angola; Comin-Chiaramonti *et al.*, 1983, Marzoli *et al.*, 1999). The NW-SE trending Ponta Grossa dykes are confined to South America and are parallel to the Mesozoic rift-controlled basins, e.g. in Paraguay (Riccomini *et al.*, 2005) and in Argentina (Salado and Colorado basins of Hawkesworth *et al.*, 1999, 2000). These basins reflect significant NE-SW extension in the Mesozoic which is not apparent in southern Africa (cf. Hawkesworth *et al.*, 2000), although the Moçamedes Arch may be considered, to some extent, the symmetrical NE-SW expression of the Ponta Grossa Arch (cf. Comin-Chiaramonti *et al.*, 1991).

The $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the PAE basaltic flood tholeiites and Ponta Grossa dyke swarm suggest that tholeiitic peak activity occurred at 133-130 (Renne *et al.*, 1992, 1993, 1996; Turner *et al.*, 1994; Stewart *et al.*, 1996; Ernesto *et al.*, 1999; Hawkesworth *et al.*, 1999; Marzoli *et al.*, 1999; Kirstein *et al.*, 2001). A slightly later generation of tholeiitic magmatism, i.e. 129-119 Ma, is represented by the coast-parallel dyke swarms (Florianópolis, Santos-Rio de Janeiro, Kwanza

and Horingbaai: cf. inset of Fig. 8), indicating a tendency for younger tholeiitic dykes to concentrate towards the continental margins during the final stages of the main immediately preceding the opening of the South Atlantic ocean (cf. Raposo *et al.*, 1998). Notably, the latter younger tholeiitic dykes have an age close to the age of the ASU potassic magmatism (126.4 Ma).

On the other hand, distinct age intervals (K/Ar data, mainly) are apparent in the whole PAE system for the alkaline and alkaline-carbonatite complexes (Comin-Chiaramonti & Gomes, 2005, and references therein; cf. Fig. 8):

- A) Pre-tholeiitic, i.e. 139-137 Ma (Early Cretaceous) potassic alkaline complexes occur in Angola (Moçamedes Arch; Alberti *et al.*, 1999 and references therein), Namibia (Milner *et al.*, 1995) and eastern Bolivia (Velasco complexes, Ar/Ar plateau age Comin-Chiaramonti *et al.*, 2005b).
- B) Syntholeiitic, i.e. 129 ± 2 Ma (Early Cretaceous) potassic alkaline magmatism occurs in Brazil (Santa Catarina State, Ponta Grossa Arch), Uruguay and Angola (Alberti *et al.*, 1999; Ruberti *et al.*, 2005a,b). In Namibia the alkaline rock types slightly post-date (129-123 Ma) the main PAE eruptive phase (Stewart *et al.*, 1996; Peate, 1997; Hawkesworth *et al.*, 1999). These first two events are generally represented by “low-Ti” potassic rocks (cf. Gibson *et al.*, 1995a,b).
- C) Post-tholeiitic, i.e. 109-106 Ma (late Early Cretaceous), potassic magmatism outcrops in Brazil (Ponta Grossa Arch; Ruberti *et al.*, 2005a), whereas Late Cretaceous (95 Ma; Ar/Ar plateau age) sodic magmatism occurs in Angola (Kwanza basin; Marzoli *et al.*, 1999).
- D) Late Cretaceous, i.e. 81 ± 7 Ma alkaline rocks, both of potassic and sodic affinity, outcrop in Brazil (Rio Grande do Sul and Santa Catarina States, Ponta Grossa Arch, Serra do Mar, Alto Paranaíba, Goiás and Mato Grosso States), Bolivia (Candelaria) and Namibia (Comin-Chiaramonti & Gomes, 2005). In particular, the alkaline magmatism from Alto Paranaíba and Santa Catarina districts (Brazil) is represented by “high-Ti” rock types of kamafugitic affinity (cf. Gibson *et al.*, 1995a,b). The spatial distribution of Late Cretaceous alkaline magmatism suggests a close correlation between cratonic blocks (cb) and associated mobile belts (mb), e.g. São Francisco cb / Araçuaí mb, Congo cb / Damara mb, Luis Alves cb / Ribeira-Dom Feliciano mb (cf. Trompette, 1994, Kröner & Cordani, 2003).
- E) Paleocene and Eocene alkaline magmatism is preserved in Brazil (i.e. 61 ± 4 Ma: Cabo Frio Lineament; Comin-Chiaramonti & Gomes, 1995, 2005) and in Namibia (49 Ma: Cooper & Reid, 2000), respectively.

If a comparison is made with the age of the alkaline rocks from Eastern Paraguay, all the age intervals are present, except for the Triassic and Late Cretaceous magmatism, respectively. In particular, the alkaline complexes from symmetrical lineaments of the African counterpart compared with the Paraná basin (cf. Fig. 8), e.g. Moçamedes Arch and Damara belt (northwest

Namibia), display ages similar to the alkaline complexes from Brazil (Ponta Grossa Arch) and Paraguay (ASU graben), respectively (Alberti *et al.*, 1999; Le Roex & Lanyon, 1998, and references therein).

MAIN GEOCHEMICAL CHARACTERISTICS OF MAGMATISM FROM EASTERN PARAGUAY AND COMPARISON WITH MAGMATISM FROM THE PARANA'-ANGOLA-NAMIBIA SYSTEM.

IE (Incompatible Elements) patterns, LILE (Large Ion Lithophile Elements) vs HFSE (High Field Strength Elements) ratios, and Sr-Nd-Pb isotopic compositions indicate that the six magmatic events that occurred in Eastern Paraguay were generated from geochemically distinct (enriched vs. depleted) mantle sources. This section is based on previous work, namely Comin-Chiaramonti & Gomes (1995, 2005), Castorina *et al.* (1997), Comin-Chiaramonti *et al.* (1991; 1997; 1999; 2001), Alberti *et al.* (1999), and references therein. The geochemical data of the Paraguay rocks are compared with those of tholeiitic and alkaline rocks that occurred in the PAE province and in a contiguous region of South America and south-western Africa from the Early Cretaceous to Paleogene (Fig. 8). Some chemical analyses representative of the most “primitive” alkaline rock-types are reported in Appendix.

Incompatible elements

The IE patterns of the Alto Paraguay sodic magmatic rocks (considering the less evolved rocks, i.e. nepheline syenites, SiO₂ = 55 wt% and MgO = 2.5 wt%) largely reflects their differentiated composition (e.g. negative Sr and Ti spikes), yet features like positive Nb-Ta anomalies are most probably primary, i.e. related to the mantle source of the parent magmas (Fig. 9).

The pre- and post-tholeiites potassic alkaline rocks (from Rio Apa-Amambay and ASU, respectively; cf. Figs. 4 and 5) are low-Ti variants, according to Gibson *et al.* (1995a), and display quite similar IE patterns, in general characterized by LILE enrichment and HFSE depletion (Fig. 9A). Notably, high-titanium potassic rocks are typical of Late Cretaceous potassic magmatism in the APIP and Namibia suites which, in contrast, are characterized by HFSE enrichment (cf. Gibson *et al.*, 1995a, b).

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. 9B). In general, the marked Ta-Nb negative spike of the Paraná tholeiitic basalts is similar to that of the potassic alkaline magmas from Eastern Paraguay, but marks a clear difference with the Mesozoic to Cenozoic sodic alkaline rocks from Paraguay and with Ocean Island basalts (OIB) of the southern Atlantic islands of Tristan da Cunha and Trindade (Fig. 9C and D).

In detail, similar to the whole Paraná basin, in Paraguay the high-Ti tholeiites have IE abundances higher than the coeval low-Ti analogues and negative Sr anomaly (cf. Comin-Chiaramonti *et al.*, 1999; 2004). The upper Late Cretaceous (Misiones, SJB) and Paleocene (Asunción) sodic alkaline rocks display almost identical IE patterns. With respect to the potassic alkaline magmatism, the Early Cretaceous and Paleocene sodic events differ, in general, by a marked negative K spike and positive HFSE spikes (Fig. 9C, F), with a general pattern similar to the Tristan da Cunha and Trindade ocean island magmas and, to some extent, also to the Early Cretaceous potassic alkaline mafic rocks from Angola and Namibia (Fig. 9D).

In summary, the IE suggest a common signature for potassic alkaline magmatism from Paraguay and PAE tholeiitic magmas, whereas Paraguay sodic alkaline rocks display similar IE patterns to Atlantic OIBs and African potassic alkaline basalts. Strongly LREE-enriched patterns suggest that Paraguayan potassic and sodic alkaline magmas issued from a garnet-bearing peridotite, yet their mantle source compositions were clearly distinct both in terms of IE composition and mineralogy. As proposed by Comin-Chiaramonti *et al.* (1997), the relative K enrichment of Eastern Paraguay potassic rocks suggests that a K-bearing phase (e.g. phlogopite) was not a residual phase during 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 lower melting degree inferred for the sodic magmatism compared to the potassic (e.g. 4-6% and 6-11% melting, of a garnet mantle, respectively; Comin-Chiaramonti *et al.*, 1997; Velázquez *et al.*, 2006).

Considering “geodynamic indicators” (e.g. Pearce, 1983; Beccaluva *et al.*, 1991), as Nb/Zr vs Th/Zr and Ta/Yb vs Th/Yb (not shown; cf. Fig. 8 of Velázquez *et al.*, 2006), the Misiones and ASU sodic rocks fall in the basalt array from non-subduction settings, i.e. MORB + WPB (cf. Comin-Chiaramonti *et al.*, 1997), along with the data from volcanic rocks of the Argentina Central Rift and Bolivian Ayopaya complex. On the other hand, both SGF high- and low-Ti tholeiites and the ASU potassic rocks fall out of the field for non-subduction related compositions in the same diagrams (cf. Comin-Chiaramonti *et al.*, 1999). Utilizing the ΔNb parameter of Fitton *et al.* (1997), the magmatic rock types from Eastern Paraguay fit the field of Western Usa rift system (Basin + Range and lamproites: Fitton this volume, Fig. 10; cf. also the Appendix), for which it is suggested that the composition of the Early Basin and Range basalts is best explained by mixing with an enriched component, represented by lamproites, in the subcontinental lithosphere.

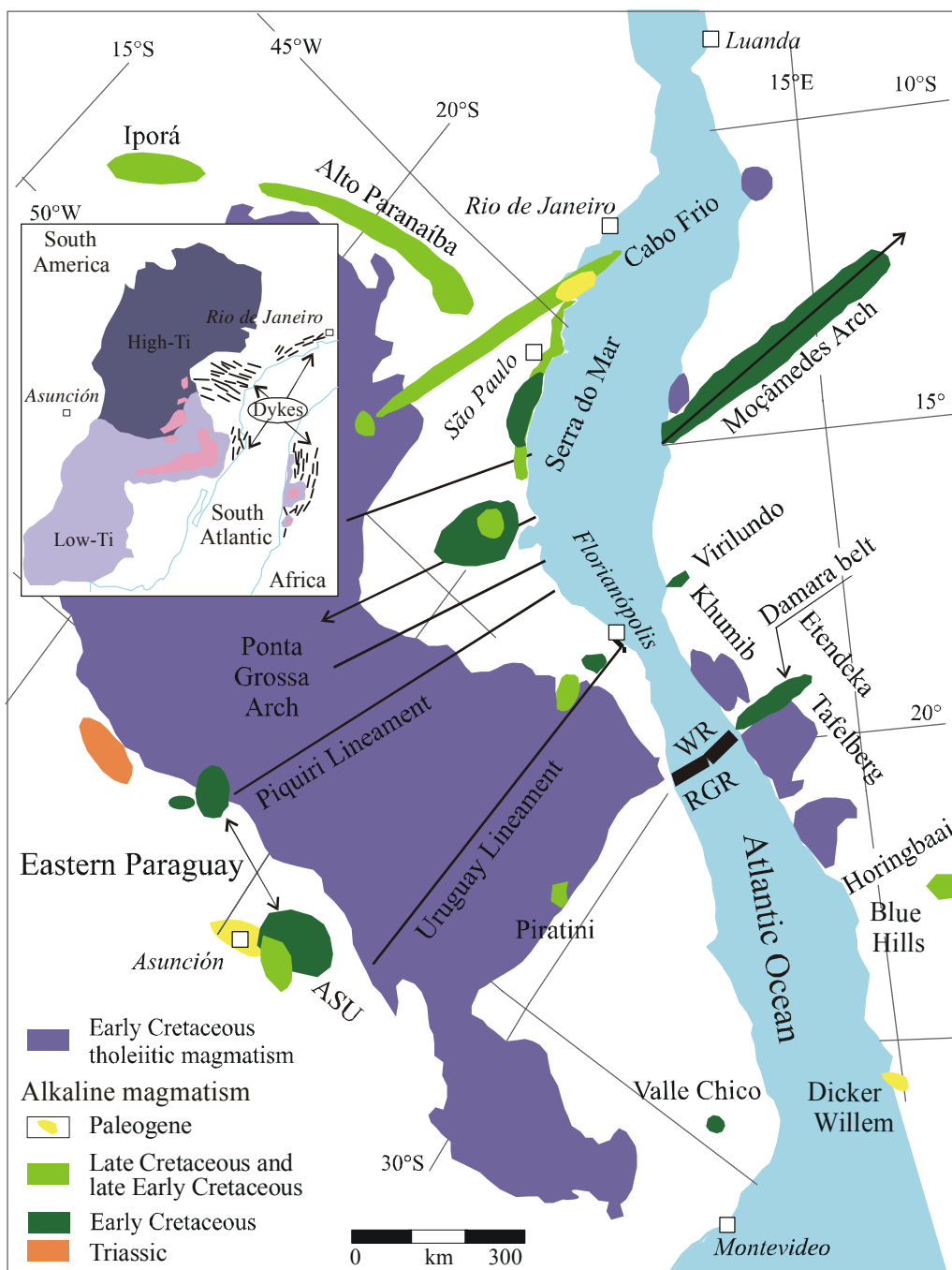


Fig. 8. Sketch map showing the distribution of alkaline occurrences in and around the Paraná-Angola-Etendeka system (modified after Comin-Chiaramonti *et al.*, 1997). RGR and WR, Rio Grande Rise and Walvis Ridge, respectively. The arrows indicate the direction and dip of the main uplift of the Ponta Grossa and Moçamedes Arches. **Inset:** sketch map of the Paraná-Angola-Etendeka system (cf. Piccirillo & Melfi, 1988), where the arrows indicate the occurrences of the main dyke-swarms. The basaltic lavas are subdivided into broad high- and low-Ti groups, and late-stage rhyolites (dotted fields).

Sr-Nd isotopes.

The investigated rocks from Eastern Paraguay cover a wide range of Sr-Nd isotopic compositions (Fig. 10A) defining on the whole a trend similar to the low Nd array of Hart & Zindler (1989) (the “Paraguay array” of Comin-Chiaramonti *et al.*, 1995a,b). Due to the high Sr and Nd content of the most "primitive" alkaline rocks (and associated carbonatites) from Eastern Paraguay, Comin-Chiaramonti *et al.* (1997) suggested that the initial Sr-Nd isotopic ratios of such rocks can be considered to be crustally uncontaminated and, as a result, representative of the isotopic composition of the mantle source(s).

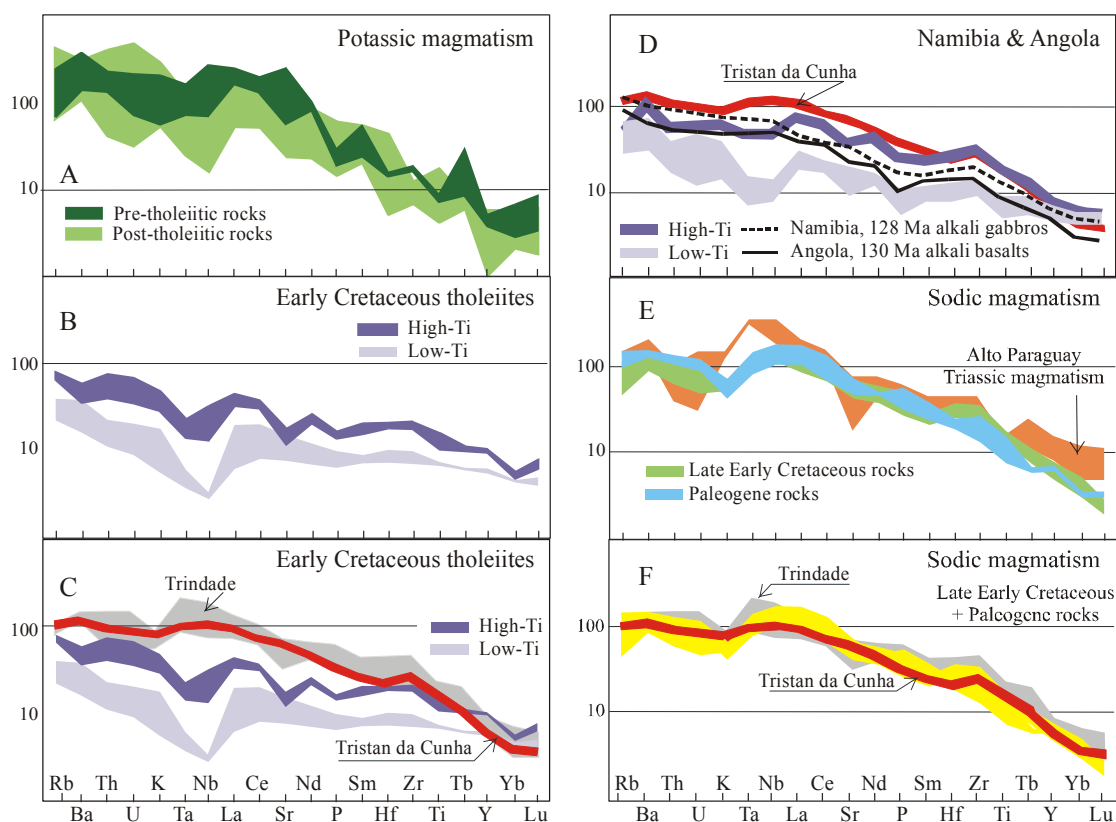


Fig. 9. Eastern Paraguay: incompatible elements (Comin-Chiaramonti & Gomes, 2005 and references therein) normalized to the primitive mantle (Sun & McDonough, 1989) representative of the compositions of the mafic K-alkaline rocks (A) and tholeiites (B), compared with Trindade and Tristan da Cunha basanites (C: Ewart *et al.*, 2004; Le Roex *et al.*, 1990; Marques *et al.*, 1999; Siebel *et al.*, 2000). D: high- and low-Ti "uncontaminated" tholeiitic basalts from Angola and Namibia compared with Namibia alkali gabbros and Angola alkali basalts (Comin-Chiaramonti *et al.*, 1999; Alberti *et al.*, 1999; Ewart *et al.*, 2004) and with Tristan da Cunha basanites. E: Triassic sodic rocks (Alto Paraguay: nepheline syenites with $\text{SiO}_2 = 55$ wt% and $\text{MgO} = 2.5$ wt %), compared with sodic alkaline rocks with upper Late Cretaceous and Paleogene ages from Paraguay (Comin-Chiaramonti & Gomes, 2005). F: sodic mafic magmatism (late Early Cretaceous+Paleogene) compared with the field of Trindade and Tristan da Cunha basanites.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ (Sr_i) and $^{143}\text{Nd}/^{144}\text{Nd}$ (Nd_i) ratios range from the depleted quadrant to the enriched one. The potassic alkaline rocks, both pre- and post-tholeiites, have the highest initial Sr_i and the lowest Nd_i . Including the Cerro Chiriguelo and Sarambì carbonatites (Comin-Chiaramonti & Gomes, 1995), which occur associated with the pre-tholeiitic potassic rocks in northeastern Paraguay, Sr_i and Nd_i range from 0.70636 to 0.70721 and from 0.51194 to 0.51165, respectively. These values are quite distinct from those of the late Early Cretaceous sodic rocks (Misiones: ca. 118 Ma; $\text{Sr}_i = 0.70486 \pm 0.00043$, $\text{Nd}_i = 0.51226 \pm 0.00015$), and the Paleocene sodic rocks (ASU: ca. 60 Ma), which plots within the depleted quadrant ($\text{Sr}_i = 0.70369 \pm 0.00011$, $\text{Nd}_i = 0.51268 \pm 0.00006$) towards the HIMU-DMM mantle components.

In any case, on the basis of the isotopic compositions, it is possible to infer a time related (Early Cretaceous to Paleogene) progressive increase in the role of the depleted mantle domain(s) in the genesis of alkaline magmatism in Eastern Paraguay (Comin-Chiaramonti *et al.*, 1999). On the other hand, the sodic magmatism, including the Alto Paraguay sodic magmatism (Triassic), tend 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. Comin-Chiaramonti *et al.*, 1999).

The Sr-Nd isotopic variation of the Paraguayan alkaline rocks is larger than that of all other PAE alkaline magmatism. In Angola and Namibia, at the easternmost fringe of the Paraná-Etendeka system, Sr_i and Nd_i values for most Early Cretaceous Angolan K-alkaline-carbonatite complexes (Fig. 10B) vary between 0.70321 and 0.70466, and between 0.51273 and 0.51237, respectively, showing on the whole depleted characteristics relative to the Bulk Earth (cf. Alberti *et al.*, 1999). On the other hand, the Early Cretaceous alkaline-carbonatite complexes from Namibia have a similar Sr_i range (0.70351-0.70466), but almost constant Nd_i (0.51250 to 0.51244; Milner & Le Roex, 1996; Le Roex & Lanyon, 1998). Since the Sr-Nd isotopic compositions of these alkaline-carbonatitic magmas are insensitive to crustal assimilation (due to their high Sr and Nd contents; cf. Alberti *et al.*, 1999). Notably, regarding the source region of carbonatites, Bell & Blenkinsop (1989) suggest that their Sr_i and Nd_i data may result from large-scale reservoirs, one corresponding to a lithosphere keel and the other to the asthenosphere.

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. 10C) are generally higher and lower, respectively, than those of the coeval rocks (both sodic and potassic) from Angola and Namibia (cf. Comin-Chiaramonti *et al.*, 1999, Comin-Chiaramonti & Gomes, 2005).

Late Cretaceous potassic alkaline-carbonatitic complexes have the following Sr_i and Nd_i mean values, respectively: Alto Paranaíba (APIP), $\text{Sr}_i = 0.70527 \pm 0.00036$ and $\text{Nd}_i = 0.51224 \pm 0.00006$ (Bizzi *et al.*, 1994; Gibson *et al.*, 1995b, and references therein); Taiúva-Cabo Frio and Serra do Mar, $\text{Sr}_i = 0.70447 \pm 0.00034$ and $\text{Nd}_i = 0.51252 \pm 0.00008$ (Thompson *et al.*, 1998); Lajes, $\text{Sr}_i = 0.70485 \pm 0.00053$ and $\text{Nd}_i = 0.51218 \pm 0.00022$ (Comin-Chiaramonti *et al.* 2002).

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

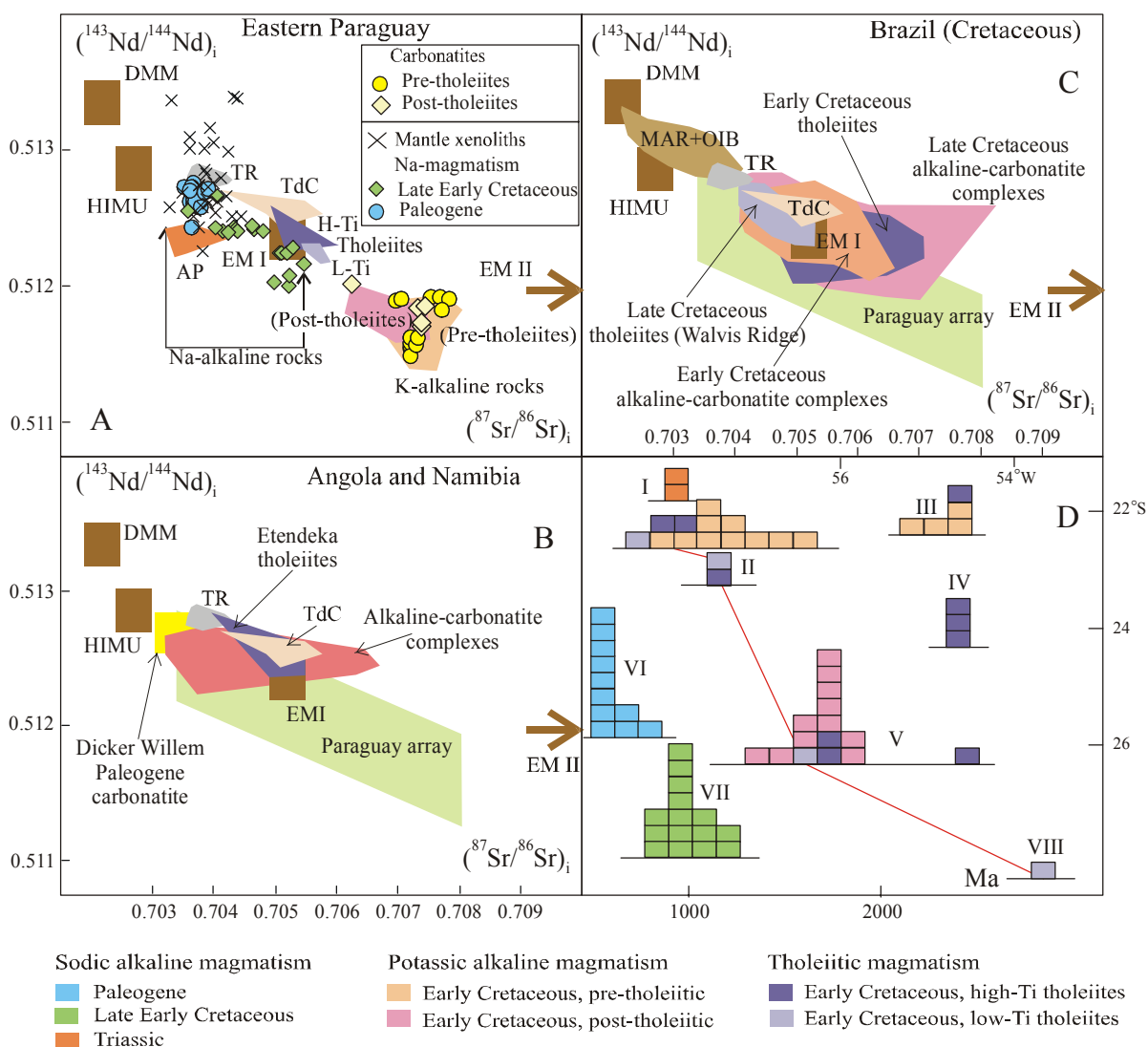


Fig. 10. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ (Sr_i) vs. $^{143}\text{Nd}/^{144}\text{Nd}$ (Nd_i) diagram for magmatic rocks from Eastern Paraguay (A) compared with Angola and Namibia (B) and Brazil (C). AP, Alto Paraguay; TR: Trindade; TdC, Tristan da Cunha; H-Ti and L-Ti, high-Ti and low-Ti tholeiites, respectively. Data source and other symbols as in Fig. 9 and Comin-Chiaromonti *et al.*, 2001. DMM, HIMU, EMI and EMII fields after Zindler & Hart (1986), Hart & Zindler (1989) and Stracke *et al.*, 2005. D: distribution of TDM ages (Ma) in Eastern Paraguay: I, Alto Paraguay; II, Rio Apa; III, Amambay; IV Carayó; V, Sapucaí; VI, Asunción; VII, Misiones; VIII, Encarnación. Colours as in D. Red line joins "L-Ti" tholeiites. Data sources: Comin-Chiaromonti & Gomes, 2005.

Model Ages

Despite uncertainties related to the Sm/Nd fractionation (f) during melting and magma differentiation (cf. Arndt & Goldstein, 1987), Nd model ages (depleted mantle, T^{DM} ; cf. De Paolo, 1988) may give a broad indication of the age of the main enrichment processes which may affected the mantle source(s) of Paraguayan magmas. In general, Paraguayan potassic magmas display T^{DM} comparable to those of the PAE tholeiites and higher than those of sodic magmas. T^{DM} of the potassic alkaline rocks increases from the pre-tholeiitic rocks of North Eastern Paraguay (peaks at 1.1-1.4 Ga, for $f \approx -0.5$ to -0.7 ; Valle-mí, Apa Block, and Amambay), to the post-tholeiitic ASU potasss alkaline complexes and dykes (1.7 Ga, $f \approx -0.4$ to -0.5 ; cf. Fig. 10 D and Appendix; Comin-Chiaramonti *et al.*, 1995a). The sodic alkaline rocks display Upper Proterozoic T^{DM} (0.9 Ga, Alto Paraguay; 0.6 Ga, Na-ASU; 1.0 Ga, Misiones, for $f \approx -0.4$ to -0.5). The younger model ages parallel the Rio Paraguay lineament and characterize the sodic magmatism.

The different geochemical behaviour in the different sectors of the PAE implies also different sources. Utilizing the T^{DM} (Nd) model ages on the whole Paraná-Angola-Etendeka system (cf. Gastal *et al.*, 2005; Comin-Chiaramonti & Gomes, 2005), we observe that (1) the H-Ti flood tholeiites and dyke swarms (cf. inset of Fig. 8) from the Paraná basin, and the Early Cretaceous potassic rocks and carbonatites from Eastern Paraguay mainly range from 0.9 to 1.7 Ga, whereas in Angola and Namibia the Early Cretaceous K-alkaline rocks range from 0.4 to 0.9 Ga; (2) the low-Ti tholeiites display a major T^{DM} variation, from 0.7 to 2.4 Ga (mean 1.6 ± 0.3) with an increase in the model ages from North to South; (3) Late Cretaceous alkaline rocks and associated carbonatites show model ages ranging from 0.6 to 1 Ga, similar to the model age shown by the Triassic to Paleogene sodic alkaline rock types along the Paraguay river. These model ages indicate that some notional distinct "metasomatic events" may have occurred during Paleoproterozoic to Neoproterozoic times as precursor to the alkaline and tholeiitic magmas in the Paraná-Angola-Etendeka system (cf. Comin-Chiaramonti *et al.*, 1995, 1997, 1999, 2004; Alberti *et al.*, 1999).

The T^{DM} (Nd) model ages and mantle heterogeneity are supported in the Paraná basin also by:

(1) Re-Os isotope systematics for the potassic rocks of kamafugitic and kimberlitic affinity (Brazil Alto Paranaíba and Lages) where the Nd model ages cover a similar age range to the Os model ages and suggests different melting depths of heterogeneous lithospheric sources (Carlson *et al.*, 1996; Araujo *et al.*, 2001).

(2) the model of Meen *et al.* (1989; see also Castorina *et al.*, 1996): a veined lithospheric mantle (amphibole/phlogopite-carbonate-lherzolite+CO₂-fluid type III and IV veins of Meen *et al.*, 1989) of Proterozoic age may well account for the magmatism of the Paraná basin.

Pb isotopes

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 *s.l.* components (e.g. EMII; Figs. 11 and 12). To be noted that the tholeiitic flood basalts from Eastern Paraguay and from Angola-Namibia, at the westernmost and easternmost sides of the PAE, respectively, delineate well different fields (cf. Fig. 12).

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

GEOCHEMICAL IMPLICATIONS

The geochemical features of the Paraguay alkaline magmatism have been explained by enrichment processes (e.g. subduction: Hergt *et al.*, 1991, Maury *et al.*, 1992, or volatile-rich small-volume melts derived from the asthenosphere: McKenzie & O’Nions, 1995) occurring in a previously depleted mantle source. Comin-Chiaramonti *et al.* (1997) emphasize the lack of any geological evidence to support subduction processes in the Paraguayan region during Phanerozoic times. They suggest that the enrichment processes were related to small-volume melts in an old lithospheric mantle, possibly affected by a contribution from the previous Transamazonian to Brasiliano cycles.

Similarly, the main differences between low- and high-Ti flood tholeiites 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 (Piccirillo & Melfi, 1988), possibly a veined peridotite where the distribution and frequency of the "metasomatizing" channels determine the different chemical signatures (cf. Comin-Chiaramonti & Gomes, 2005).

The Sr-Nd isotopic variations of the alkaline rocks from Eastern Paraguay (Fig. 10A) may be explained: a) by generation from distinct portions of a large- and small-scale heterogeneous lithospheric mantle source, where 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 a depleted mantle component (DMM- or HIMU-like components).

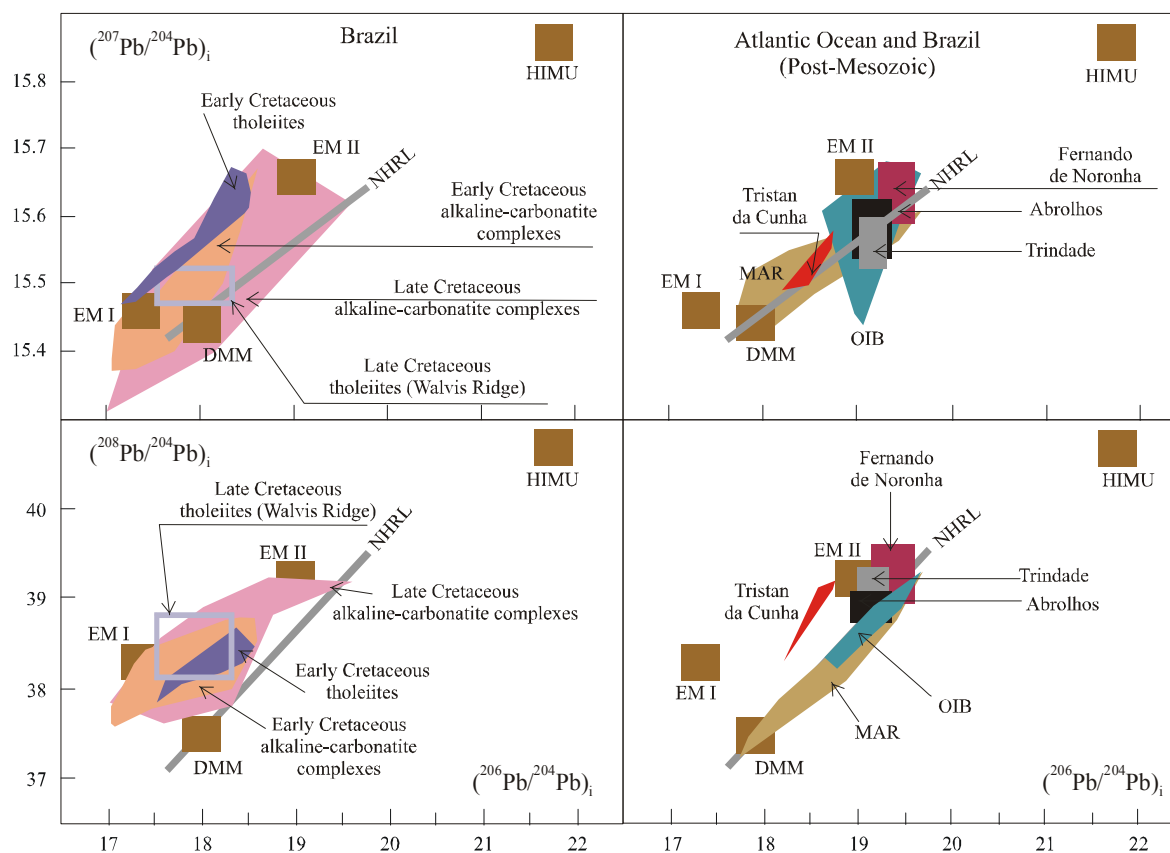
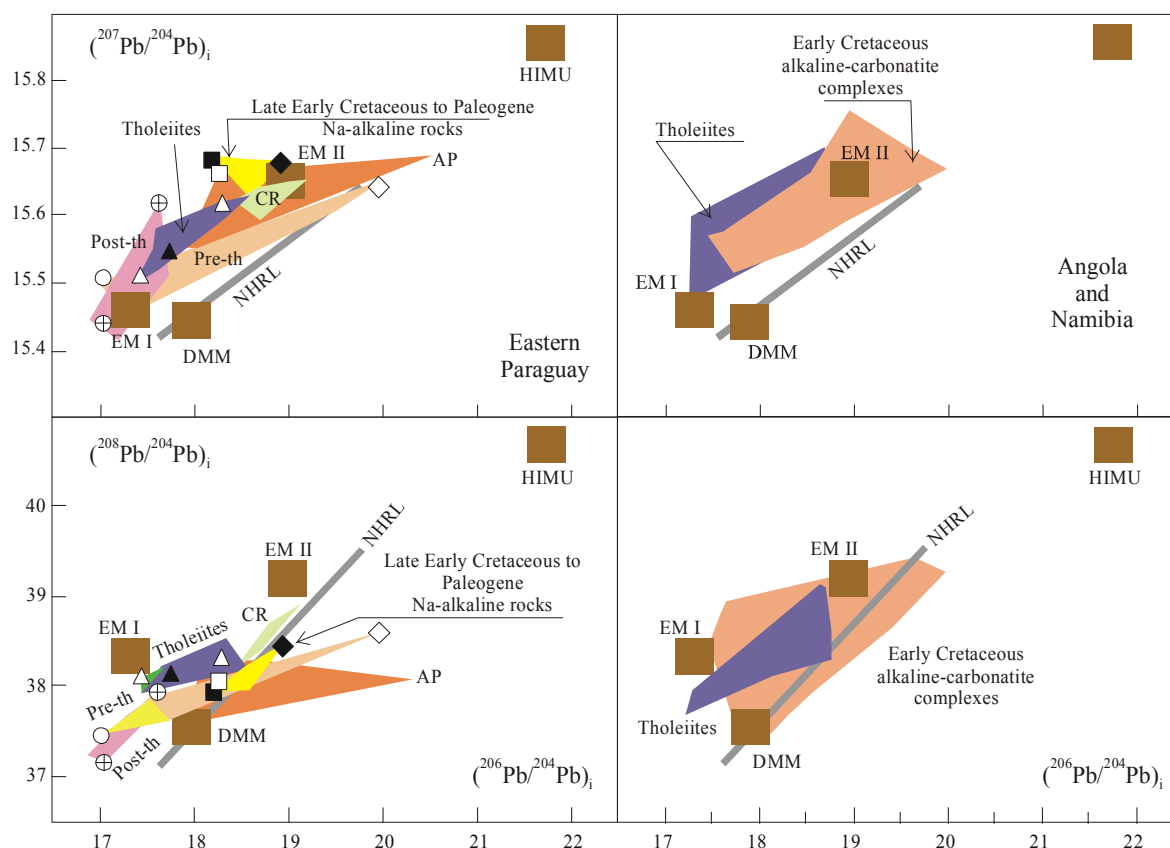
Le Roex & Lanyon (1998) Thompson *et al.* (1998) and Ewart *et al.* (2004) postulated that Early Cretaceous alkaline-carbonatitic and tholeiitic magmatism from northwestern Namibia and Late Cretaceous alkaline and alkaline-carbonatitic magmatism from Alto Paranaíba-Serra do Mar (southern Brazil) would reflect variable contributions from the asthenospheric mantle

components related to the Tristan da Cunha and Trindade plumes. On the contrary, Comin-Chiaramonti *et al.* (1997a, 1999, 2004), Castorina *et al.* (1997), Alberti *et al.* (1999) suggested that the alkaline and alkaline-carbonatitic magmatism in the PAE originated from lithospheric mantle sources without appreciable participation of plume-derived materials.

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

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

Hawkesworth *et al.* (1986) interpreted the Etendeka (Namibia) high-TiO₂ (HTZ) tholeiitic basalts as resulting from melting of a Proterozoic lithospheric mantle, which, in the case of the Walvis Ridge (WR2 basalts, cf. Richardson *et al.*, 1982), was floating inside the oceanic asthenosphere during the opening of the South Atlantic. Alternatively, the elemental and isotopic signature of the HTZ basalts could be related to contamination of oceanic mantle by ancient subcontinental lithospheric mantle. In summary, the isotopic signature of the Early and Late Cretaceous alkaline-carbonatite complexes of the PAE reflects ancient heterogeneities preserved in the subcontinental lithospheric mantle.



□ Alto Paraguay ◇ Valle-mí: K-basanite ○ Amambay: K-tephrite △ Low-Ti tholeiitic basalt
 ▲ Valle-mí: H-Ti tholeiitic andesibasalt ⊕ K-alkaline: post-tholeiitic ■ Misiones ◆ ASU

Fig. 11. $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (initial ratios) for rock types from the PAE.. NHRL (North Hemisphere Reference Line) after Hart (1984) and Hart *et al.*, 1986, 1992; 132 Ma Geochron after Ewart *et al.* (2004); CR, "Central Rift" from NW Argentina after Lucassen *et al.* (2002). Other data source, **Eastern Paraguay**: Comin-Chiaramonti *et al.* (1991, 1995, 1996, 1997, 2001), Comin-Chiaramonti & Gomes (1995; 2005), Castorina *et al.* (1997), Marques *et al.* (1999).; symbols (cf. Appendix): open square, Alto Paraguay; open diamond, Valle-mí; open circle, Amambay; open and full triangles, low- and high-Ti tholeiites, respectively; crossed circles, post-tholeiitic potassic rocks; full square, Misiones; full diamond, ASU sodic magmatism; **Angola and Namibia**: Milner & Le Roex (1996), Le Roex & Lanyon (1998), Gibson *et al.* (1999), Harris *et al.* (1999), Ewart *et al.* (2004, and references therein), Cooper & Reid (1998), Smithies & Marsh, 1998, Alberti *et al.* (1999), Kurzslaukis *et al.* (1999); **Brazil, Lower Cretaceous**: Toyoda *et al.* (1995), Huang *et al.* (1995), Walter *et al.* (1995), Garda *et al.* (1995), Marques *et al.* (1999), Gibson *et al.* (1999), Andrade *et al.* (1999a), Comin-Chiaramonti *et al.* (2002a, b; Comin-Chiaramonti & Gomes, 2005), Ruberti *et al.* (2002); **Brazil, Upper Cretaceous**: Bellieni *et al.* (1990), Bizzi *et al.* (1994, 1995), Toyoda *et al.* (1994), Meyer *et al.* (1994), Gibson *et al.* (1995a,b, 1997, 1999), Carlson *et al.* (1996), Thompson *et al.* (1998); **Atlantic Ocean**: *Walvis Ridge*, Richardson *et al.* (1982); *Rio Grande Rise*, Gamboa & Rabinowitz (1984); *Mid Atlantic Ridge (MAR)*, Hamelin *et al.* (1984), Ito *et al.* (1987), Fontignie & Shilling (1997); *OIB*, Halliday *et al.* (1988; 1995); *Tristan da Cunha*, Le Roex (1985), Le Roex *et al.* (1990), Ewart *et al.* (2005); *Trindade*, Marques *et al.*, (1999b), Siebel *et al.* (2000); **Brazil, Paleogene**: *Serra do Mar*, Thompson *et al.* (1998), Bennio *et al.* (2002); *Abrolhos*, Fodor *et al.* (1989); *North-eastern Brazil*, Fodor *et al.* (1998); *Fernando de Noronha*, Gerlach *et al.* (1987). DMM, HIMU, EMI and EMII are approximations of mantle end-members taken from Hart & Zindler (1989) and Hart *et al.* (1992). In all the diagrams the Rio Grande Rise basalts (not shown) plot in the same field as Walvis Ridge samples.

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 (cf. Fig. 1) in Archean-Proterozoic times. In this context, considering the important differences in terms of trace elements patterns and of Sr-Nd-Pb isotopic composition, the role of the Tristan da Cunha plume claimed by Ewart *et al.* (2004) is not apparent (cf. Figs 9 to 12). Therefore, we believe, as documented by Ernesto *et al.* (1999; 2002), that the hypothesis of a mantle plume origin for PAE magmatism is not compelling, with the caveat that mantle plumes may represent thermal perturbations.

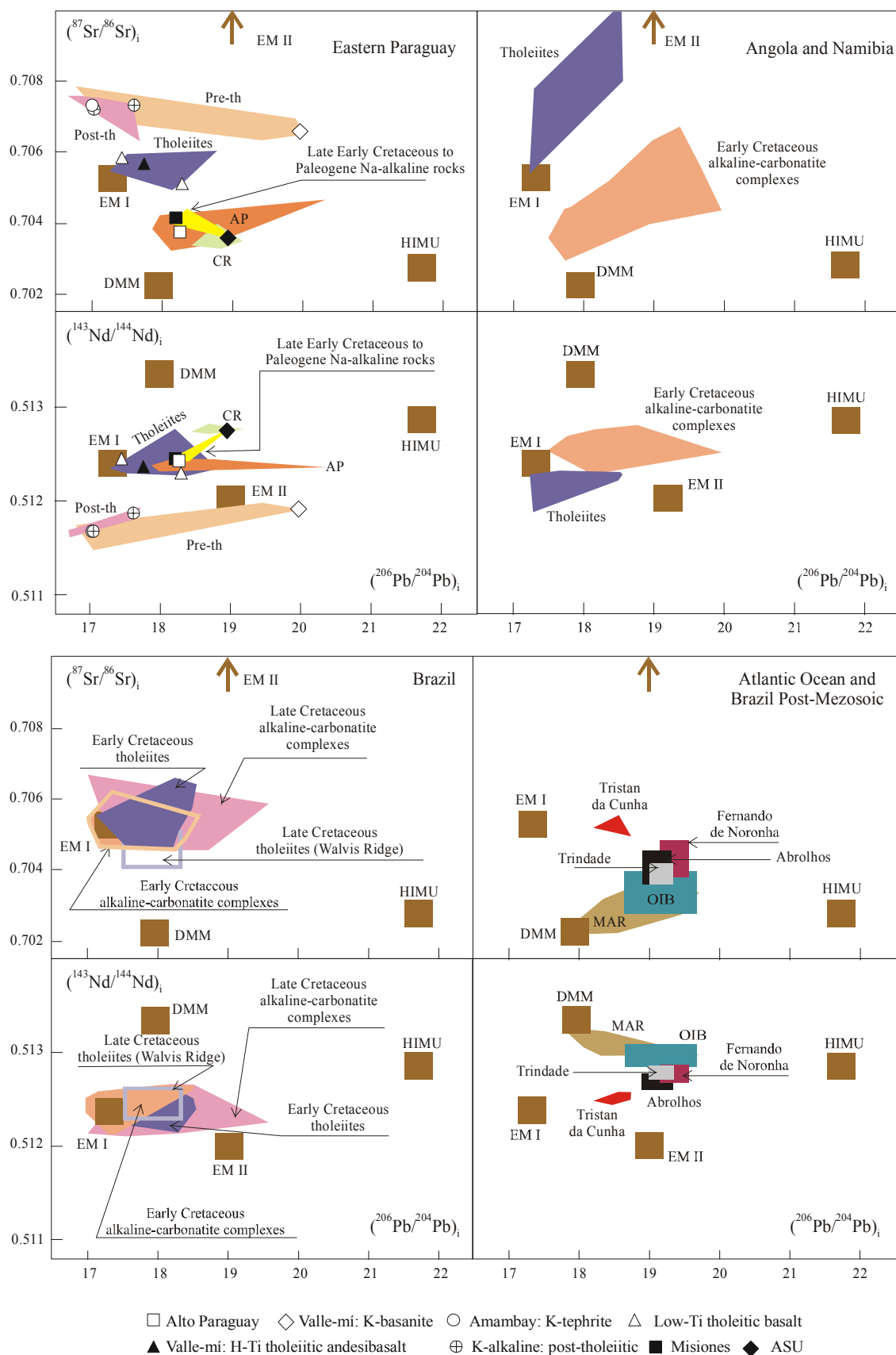


Fig. 12. Sr_i and Nd_i vs $^{206}\text{Pb}/^{204}\text{Pb}$ (initial ratios). Symbols and data source, as in Fig. 11.

GEODYNAMIC IMPLICATIONS

The geodynamic evolution of Western Gondwana in the Early Cretaceous reflects the amalgamation processes which affected the region at least back to the time of the Brasiliano cycle, both at the Atlantic and Pacific systems. The Brasiliano cycle developed between ~890 to 480 Ma in a diacronic way, creating the final arrangement of the basement of the South American platform (Brito Neves *et al.*, 1999; Mantovani *et al.*, 2005, and references therein). During the Lower Ordovician a mosaic of lithospheric fragment linked by several (accretionary, collisional) Neo-Proterozoic mobile belts amalgamated to form Gondwana (Unrug, 1996). After the amalgamation, the Gondwana supercontinent accumulated Paleozoic and Mesozoic sediments. Concomitantly, it continuously laterally accreted on its western borders by successive orogenic belts, in the Lower Paleozoic and in the Permian-Triassic, until the formation of Pangea (Cordani *et al.*, 2000, 2003). The main cratonic fragments, descending from ancestors of Pangea, were reworked, such as the Amazonia, Rio Apa, Arequipa-Antofalla and Rio de La Plata cratons. Smaller ancient crustal blocks at the present-day Paraguay boundaries, were continuously reworked (Kroener & Cordani, 2003). In this context, the magmatism was driven by the relative extensional regimes derived by relative movements of the ancient blocks. For example, Alto Paraguay Middle Triassic alkaline magmatism occurred at the boundaries between the Rio Apa and Arequipa-Antofalla blocks and reveals extensional events at ~240 Ma, probably induced by counterclockwise and clockwise movements (North and South, respectively) hinged at latitude ~20° S (cf. Prezzi & Alonso, 2002).

The general geodynamic situation of Paraguay and neighbouring countries can be pictured by the present-day earthquakes typology combined with paleomagnetic and geological evidence. Earthquakes mechanisms (Berrocal & Fernandes, 1995) highlight the distribution of the earthquakes with hypocentres > 500 km and < 70 km (Fig. 13). Deep earthquakes coincide with the inferred location under Paraguay of the subducting Nazca plate (cf. Fig. 2). In particular, the depths of lithospheric earthquakes together with paleomagnetic results, delineate different rotational paths at about latitude 18-20° S, roughly corresponding to the Chaco-Pantanal basin, indicating extensional subplate tectonics at the Andean system (Randall, 1998).

Also crucial to the genesis of PAE magma types is the link with the geodynamic processes which promoted the opening of the South Atlantic. According to Nürberg & Müller (1991), sea-floor spreading in the South Atlantic at PAE latitude started at ~125-127 Ma (Chron M4). North of the Walvis-Rio Grande ridges (latitude >28°), the onset of oceanic crust would be younger (~113 Ma; Chang *et al.*, 1988).

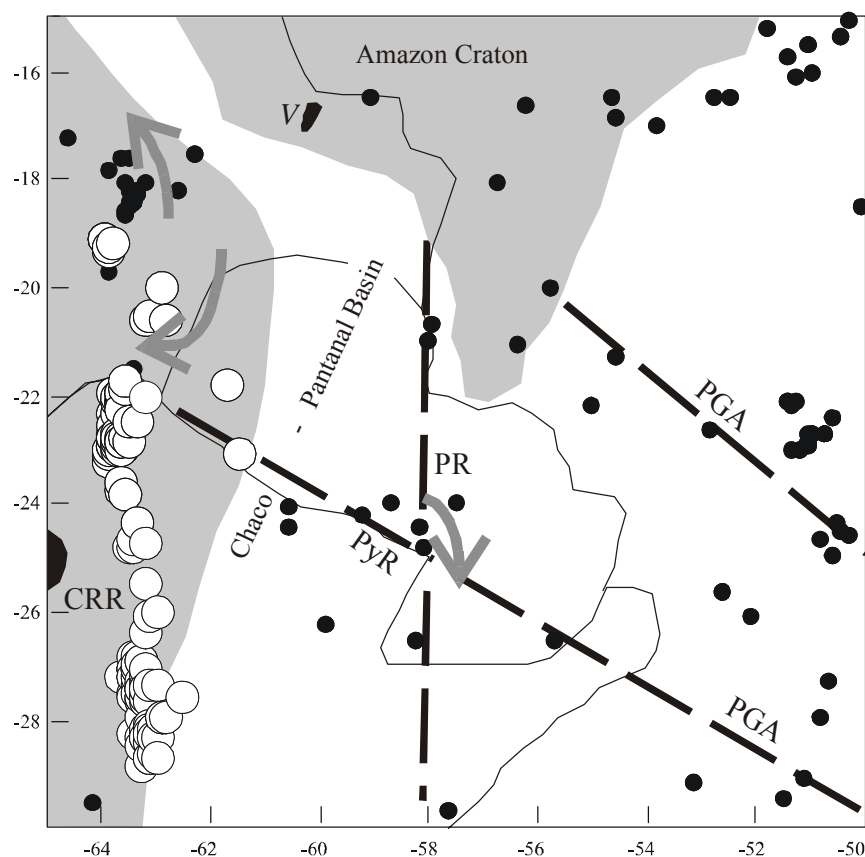


Fig. 13. Earthquakes distribution in Paraguay and neighbouring regions. Open and full circles, earthquakes hypocenters with depths > 500 and < 70 km, respectively (cf. Berrocal & Fernandes, 1995). Black lines indicate extensional lineaments: PGA, Ponta Grossa arch; PR and PyR, Paraguay and Pylcomaio lineaments, respectively. For reference Velasco (V) and Central rift (CRR) alkaline complexes, NW-Argentina (140 and 90 Ma, respectively) are also shown. The dark gray lines with arrow delineate the rotational subplate trends (after Randall, 1998 and Comin-Chiaramonti & Gomes, 1995).

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 analogs emplaced during advanced stages of Africa-South America continental separation.

The origin of alkaline-carbonatitic magmatism in terms of plate tectonics is currently debated. Various models have been proposed involving deep mantle plume/hot spots (up to 16; Stefanick & Jurdy, 1984), or shallow thermal anomalies (Holbrook & Kelemen, 1993). Whatever the temperature, size, depth of origin and number of hot spots, the plume model cannot account for the worldwide occurrence of alkaline-carbonatitic magmatism (see Smith & Lewis, 1999 for a discussion). Gibson *et al.* (1999) suggested that the Late Cretaceous alkaline-carbonatitic magmatism of Lages, located more than 1000 km South of the postulated head of the Trindade plume, was induced by “impressive” southward channeling of high-temperature melts away from the thick keels of the São Francisco craton. This model does not account for occurrences of Late

Cretaceous potassic alkaline rocks from Rio Grande Arch (e.g. Piratini), nor for the mechanical barriers formed, e.g., by the Ponta Grossa Arch and by Piquiri and Uruguay lineaments (“second order plate boundaries”, i.e. intraplate boundaries in line with the Paraná Province, the Rio Grande and the Wavis Ridge > Compare. also Ponta Grossa and Moçamedes lineaments, according to Comin-Chiaramonti & Gomes, 1995. According to the interpretation of remote sensing data along the South American second-order boundary, Unternehr *et al.*, 1988, suggest important dextral displacement between the two South American domains across this boundary).

A more convincing model for the South Atlantic is that proposed by Smith & Lewis (1999). The forces acting on plates which move at differential angular velocity and the presence of volatile-rich mantle sources (“wetspots”) would drive the rifting to occur parallel to the pre-existing (e.g. N-S) sutures corresponding to the “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 (cf. Frimmel and Fölling, 2004 for a discussion). Intraplate alkaline and alkaline-carbonatitic magmatism occurred where “second order plate boundaries” (e.g. the Alto Paranaíba, Ponta Grossa-Moçâmedes Arches, the Uruguay lineament and the Damara Belt; cf. Unternehr *et al.*, 1988) intersect the axis of major rifting, possibly related to the erosion and cycling of continental lithospheric mantle towards the ridge axis.

In southern Brazil, alkaline and alkaline-carbonatitic magmatism is concentrated in regions with positive geoid anomalies (Molina & Ussami, 1999) that may be related to dense very deep materials. Moreover, the different westward angular velocity of lithospheric fragments in the South American plate, as defined by “second order plate boundaries”, as well as the different rotational trends at latitude 19-20° (cf. Fig.13), may favor decompression and melting at different times of variously metasomatized (wet-spots) portions of the lithospheric mantle with variable isotopic signatures (cf. also Turner *et al.*, 1994; Comin-Chiaramonti *et al.*, 1999). The combined presence of even small amounts of water and carbon dioxide in the upper mantle may lower the melting temperature even by some hundred degrees (see Thybo, 2006, for a discussion).

This scenario could explain the presence of Late Cretaceous to Paleogene sodic magmatism in the PAE (cf. Fig. 8), even at the longitude of Eastern Paraguay, where there is evidence for active rifting structures (Comin-Chiaramonti *et al.*, 1992, 1999). In this case, thermal perturbations may be channeled along the “second order plate boundaries”, as suggested also by earthquake hypocenters in South America (cf. Fig. 13 and Berrocal & Fernandes, 1995).

CONCLUDING REMARKS

1. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages show that distinct magmatic events took place in Eastern Paraguay since the Middle Triassic in areas strongly characterized by extensional tectonics. The first event occurred during the Anisian (Middle Triassic) and was of sodic affinity. After a magmatic hiatus

of about 100 Ma, during the Early Cretaceous, potassic alkaline magmatism pre- and post-dated the emission of the Paraná Basin flood tholeiites. Since the late Early Cretaceous to Paleogene, only sodic magmatism has occurred in Paraguay. The Sr-Nd-Pb isotopic data indicate two main mantle components could have been involved in the Cretaceous to Paleogene magmatism in Eastern Paraguay: an extreme and heterogeneous EMI component which is prevalent in the Cretaceous K-alkaline magmatism, and a depleted component, which appears important in the sodic magmatism in the Middle Triassic, late Early Cretaceous and Paleogene.

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

3. The potassic suites (pre- and post tholeiitic) are characterized by strongly fractionated REE “Ta-Nb-Ti anomalies”. In contrast, slight positive anomalies for Ta and Nb are observed in the sodic rock.

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

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

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

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

9. Any hypothesis involving mantle plume activity (Tristan da Cunha, TC, plume) at the margin of the Paraná Basin is constrained by distinct lithospheric mantle characteristics and by paleomagnetic results (see Ernesto et al., 2002). The latter authors demonstrate by paleomagnetic reconstruction: A) Paraná-TC system, assuming this hot-spot is a fixed point in the mantle,

indicates that the TC plume was located ~800 km south of the Paraná Magmatic Province (PMP). Therefore, plume mobility would be required in order to maintain the PMP-TC relationships. B) Assuming that TC was located in the northern portion of the PMP (~20° from the present TC position), the plume migrated southward from 133-132 Ma (main volcanic phase in the area) to 80 Ma at a rate of ~40mm/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 Ma in the North). C) 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.

This does not preclude that thermal perturbations from the asthenosphere may have triggered magmatic activity in the lithospheric mantle in the Eastern Paraguay.

10. It is proposed that variously isotopically enriched sources implied by the potassic magmas derived from a depleted lithospheric mantle, pervasively invaded by IE-C-H rich fluids. These are expected to have promoted crystallization of K-rich phases (e.g. phlogopite) in a pristine peridotite, where they developed a veined network variously enriched in LILE and LREE under various redox conditions. The newly formed veins (“enriched component”) and peridotite matrix (“depleted component”) underwent different isotopic evolutions with the time, depending on their parent/daughter ratio (cf. Comin-Chiaramonti *et al.*, 1995). This model may be extended to the Paraná flood tholeiites and to high- and low-Ti potassic magmatism from southeastern Brazil, Angola and Namibia.

11. Isotopically distinct magmas were generated following two main “enrichment” events of the subcontinental upper mantle estimated at 2.0-1.4 Ma and 1.0-0.5 Ga (Comin-Chiaramonti *et al.*, 1997, 1999). This would have preserved isotopic heterogeneities over a long period of time, pointing to a non-convective lithospheric mantle beneath different cratons or intercratonic regions.

12. The occurrence of sodic and potassic magmatism in the Paraná Basin implies appropriate lithospheric sources to generate also the flood tholeiites. Therefore, any hypothesis of an asthenospheric plume origin is not required, with the caveat that it might provide a thermal perturbation and/or a decompressional environment, and possible sources of Precambrian plume melts to contaminate the lithosphere.

13. The over-simplified model of mantle plumes is not satisfactory for explaining most continental flood basalts and recurrent intraplate alkaline magmatism, and therefore, following Ernesto *et al.* (2002), alternative thermal sources may be found in the mantle with no implication of material transfer from the core or lower mantle to the lithosphere. Besides the indications from geoid anomalies, the existence of long lived thermal or compositional anomalies in the mantle have already been demonstrated by velocity distribution models based on seismic tomography,

using both P- and S-waves (e.g. Zhang & Tanimoto, 1993; Li & Romanonicz, 1996; Van der Hilst *et al.*, 1997; Liu *et al.*, 2003).

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

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APPENDIX. Selected analyses of the main "primitive" alkaline rock-types from Eastern Paraguay (after Comin-Chiaramonti *et al.*, 1999 and Comin-Chiaramonti and Gomes, 1995, 2005). $(\text{La}/\text{Ta})_{\text{N}}$: normalized ratios to the primitive mantle of Sun and Mc Donough (1989). TDM are calculated assuming the following values for the depleted mantle: $^{143}\text{Nd}/^{144}\text{Nd} = 0.513151$ and $\text{Sm}/\text{Nd} = 0.2188$ (Faure, 1986). $f_{\text{Sm}/\text{Nd}} = [(^{147}\text{Sm}/^{144}\text{Nd})_{\text{Sample}} - (^{147}\text{Sm}/^{144}\text{Nd})_{\text{CHUR}}] / (^{147}\text{Sm}/^{144}\text{Nd})_{\text{CHUR}}$ (DePaolo, 1988).

	ALTO PARAGUAY	VALLE- MÍ	AMAMBAY	VALLE- MÍ	VALLE- MÍ	CENTRAL REGION	CENTRAL K-ASU	CENTRAL K-ASU	MISIONES	ASUNCION
Sample	RP-232	VM-3	SA-94	ST-1	VM-2	3006	77-PS245	D159-PS9	01A	3209
Rock-type	Na- Nepheline syenite	K- Basanite	K-Tephrite	L-Ti Tholeiitic basalt	H-Ti Tholeiitic basalt	L-Ti Tholeiitic basalt	K B-P Ijolite	K AB-T Trachybasalt	Na- Ankaramite	Na- Mela- nephelinite
SiO ₂ wt%	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 ₂ O 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 ₂ O	6.42	1.38	2.92	2.52	3.04	2.19	3.34	2.29	4.03	5.80
K ₂ O	4.35	1.61	6.36	0.74	1.24	0.33	5.41	5.72	1.82	1.46
P ₂ O 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
Cr ppm	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
Age (Ma)	241	139	139	133	133	133	126	126	118	60
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
T _{DM} (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 ₂ O ₃ /FeO	0.56	0.47	0.22	0.17	0.22	0.22	0.33	0.33	0.23	0.69
Mg#	0.51	0.72	0.59	0.56	0.42	0.55	0.71	0.68	0.66	0.69

