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Early Cretaceous–Tertiary magmatism in Eastern Paraguay (western Paraná basin): geological, geophysical and geochemical relationships

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Abstract

Structural characteristics of Eastern Paraguay, at the westernmost side of the Paraná basin, show that the tectonics in the region is extensional. This tectonics controlled the emplacement of the alkaline rocks in Early Cretaceous–Tertiary times. Major structures are NW-trending zones of tectonic subsidence, i.e. the 'Asunción–Sapucai–Villarrica' and 'Amambay' grabens of the central and northeastern regions of Eastern Paraguay, respectively. Early Cretaceous potassic magmatism is widespread in the 'gravity lows', and predates the tholeiitic Early Cretaceous magmatism in the northern areas, whereas in central Paraguay it postdates the tholeiitic flood basalts. Sodic alkaline rocks (late Early Cretaceous–Tertiary) are widespread in cratonized areas of the La Plata Craton. The Early Cretaceous uncontaminated potassic rocks (and tholeiites) have geochemical features of 'subduction type' (e.g. Ta–Nb negative anomaly), while the contrary occurs for the closely associated younger sodic magmatism. This implies different mantle sources consistently with Sr–Nd isotopes which are Rb–Nd enriched and depleted for the potassic and sodic rocks, respectively. T_{DM}(Nd) model ages point to two notional distinct metasomatic events occurred in Middle and Late Proterozoic times. A contribution of asthenospheric melts from Tristan da Cunha Plume is not appreciable. We suggest that the source(s) of the recurrent

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potassic magmatism and interposed tholeiitic event may not be easily accounted for by the Tristan da Cunha plume hypothesis.

1. Introduction

The Paraná–Etendeka Igneous Province (PEIP) is characterized by Early Cretaceous flood tholeiites and dyke swarms, associated with alkaline rocks of Early and Late Cretaceous ages, respectively. The Eastern Paraguay region, located at the westernmost fringe of the Paraná basin, is of special interest because: (1) it was the site of tholeiitic and alkaline magmatism; (2) the alkaline rocks are related to block-faulted systems; (3) the Early Cretaceous potassic alkaline complexes and dykes were emplaced both before and after the flood tholeiites; and (4) the younger (mainly Late Cretaceous–Tertiary) sodic rocks are closely related in space to the potassic analogues.

The paper aims at discussing (1) the relationships between tectonics and magmatic activity on the basis of field and geophysical data and (2) the most important geochemical and Sr–Nd isotopic features of the tholeiitic and alkaline magmas, relevant to constraining the nature of source mantle in PEIP, through the review of the available data.

2. Geological setting

Eastern Paraguay has a complex block-faulted structure (Fig. 1). The Precambrian–Early Palaeozoic basement mainly occurs in two structural highs, the 'Caacupú High' in the south and the 'Apa High' in the north, respectively. Smaller basement outcrops are also present in the 'Asunción High', while isolated blocks may be found at the western side of the Asunción–Sapucai–Villarrica (ASV) graben.

2.1. Precambrian–Ordovician: 'Caacupú High' and 'Apa High'

The 'Caacupú High' (Fig. 1) is considered to be the northernmost exposure of the Rio de La Plata Craton (Fulfaro, 1996). Three main zones were proposed by Kanzler (1987): (1) a southern zone ('Tebicuary Complex') composed of ortho- and paragneisses, migmatites, amphibolites, schists and metarhyolitic dykes of Early Proterozoic age; (2) a central zone composed of low-grade metamorphosed conglomerates, sandstones and siltstones ('Paso Pindó Group'), and granites, rhyolites, granodiorites, quartzites, gneisses, amphibolites and marbles ('Villa Florida Group') of Middle Proterozoic age; and (3) a northern zone composed of Late Proterozoic granites, rhyolites and associated pyroclastic rocks. The whole area was affected by the 'Brasiliano Cycle' during the Late Proterozoic–Early Ordovician (576–480 Ma; Kanzler, 1987).

The 'Apa High' (Fig. 1) is formed by Precambrian crystalline rocks and represents the southernmost tip of the Amazonia Craton (Fulfaro, 1996). The most ancient stratigraphic unit is the 'Apa Basal Complex', consisting of Early Proterozoic gneisses, granites and

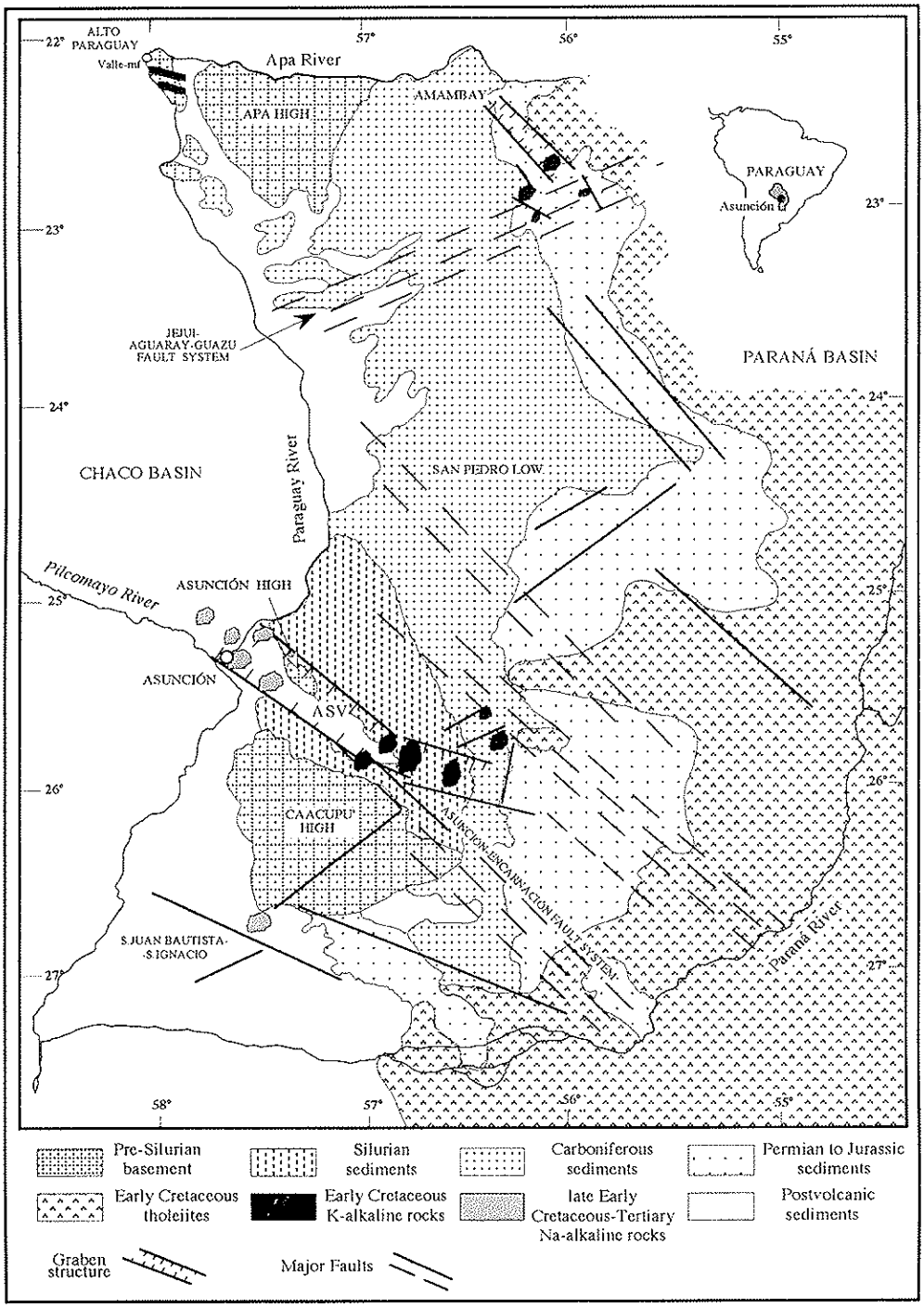

Fig. 1. Geological sketch-map of Eastern Paraguay modified after Hutchinson (1979), Wiens (1982), Livieres and Quade (1987) and Kanzler (1987). ASV = Asunción-Sapucai-Villarrica graben (cf. Fig. 3 for details).

metasediments (Hutchinson, 1979; Projecto PAR-83/005, 1986; Occidental Company, 1987). The Middle Proterozoic 'San Luis Group' rests unconformably on the 'Apa Basal Complex' and includes a volcano-sedimentary sequence made of low-grade metamorphic sandstones, conglomerates, phyllites, granites and pyroclastic rocks. Cambro-Ordovician limestones ('Itapucú-mí Group') are widespread in the western part of the Apa High.

2.2. Silurian-Cenozoic

The Silurian and Devonian sediments of Eastern Paraguay were deposited in basins subjected to a convergent margin regime, whereas those of Carboniferous-Permian age were deposited in a cratonic basin (Gohrbandt, 1992). The Palaeozoic–Mesozoic sediments have a

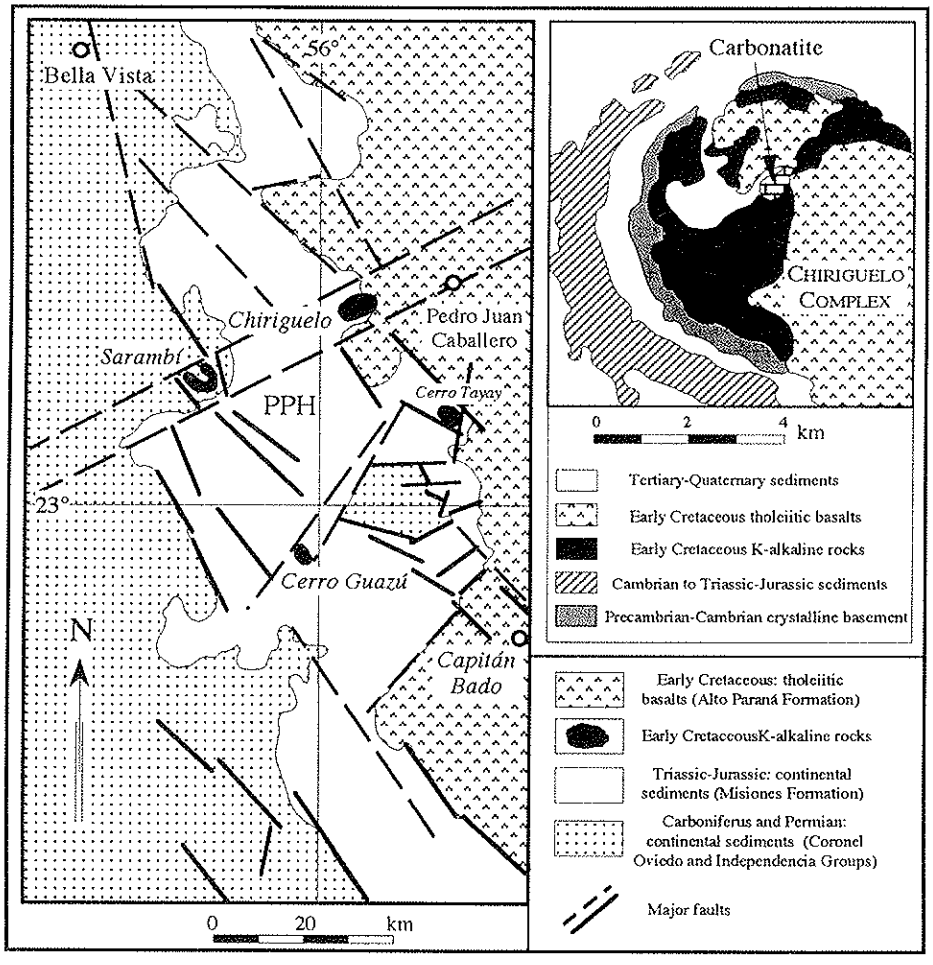

Fig. 2. Geological sketch-map of the Amambay area, modified after Wiens (1986). Inset: Chiriguelo alkaline–carbonatitic complex (cf. Censi et al., 1989).

total thickness ranging from less than 100 m on structural highs to almost 6000 m in the 'San Pedro Low', located between the 'Caacupú and 'Apa Highs' (Fig. 1).

Geological studies (Eckel, 1959; Fulfaro, 1996; Putzer, 1962; Wiens, 1982, 1986) show that Eastern Paraguay is cut by two sets of major faults, i.e. an older, NE-trending set (e.g. Jejui–Aguaray–Guazu fault zone), and a younger NW-trending set (Fig. 1), inherited from the Precambrian basement. The latter tectonic trend defines NW-trending grabens or fault-controlled basins that formed in Late Mesozoic times in response to NE–SW extensional tectonics active to Upper Tertiary times (Comin-Chiaramonti et al., 1992; DeGraff et al., 1981; Hegarty et al., 1996; Livieres and Quade, 1987). This tectonic regime allowed the intrusions of the NW–SE dykes in the Asunción–Sapucai–Villarrica graben.

Since Early Mesozoic times, Eastern Paraguay was the site of voluminous alkaline and tholeiitic magmatic activity (Fig. 1). The older alkaline rocks occur in NE Paraguay and are represented by (1) the Permo-Triassic (250–240 Ma; Gomes et al., 1996) ring complexes of nepheline syenites to alkaline granites and their effusive analogues of the Alto Paraguay Province (discussed elsewhere), and (2) the Late Jurassic–Late Cretaceous (c. 145 Ma;

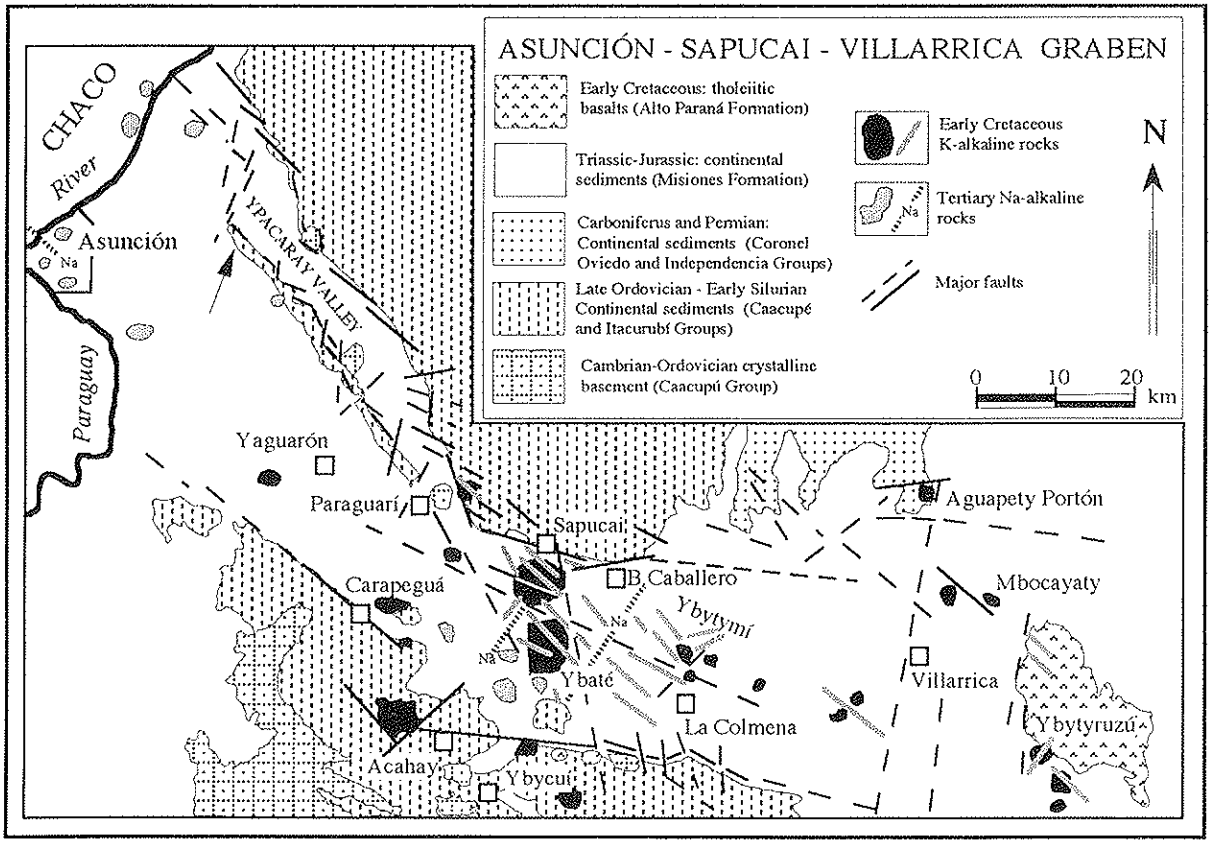

Fig. 3. Main geological–tectonical characteristics of the Asunción–Sapucai–Villarrica graben with the location of K- and Na-alkaline complexes and dykes, and flood tholeiites.

Velázquez et al., 1996; Comin-Chiaramonti et al., 1997; Renne et al., 1997) alkaline potassic complexes with carbonatites (e.g. Chiriguelo, Fig. 2) and dykes (e.g. Valle-mí, Fig. 1) which predate the Paraná flood tholeiites (137–132 Ma; Renne et al., 1992, 1997; Turner et al., 1994; Stewart et al., 1996) in the 'Apa High' and Amambay regions (Figs. 1 and 2). The Eastern

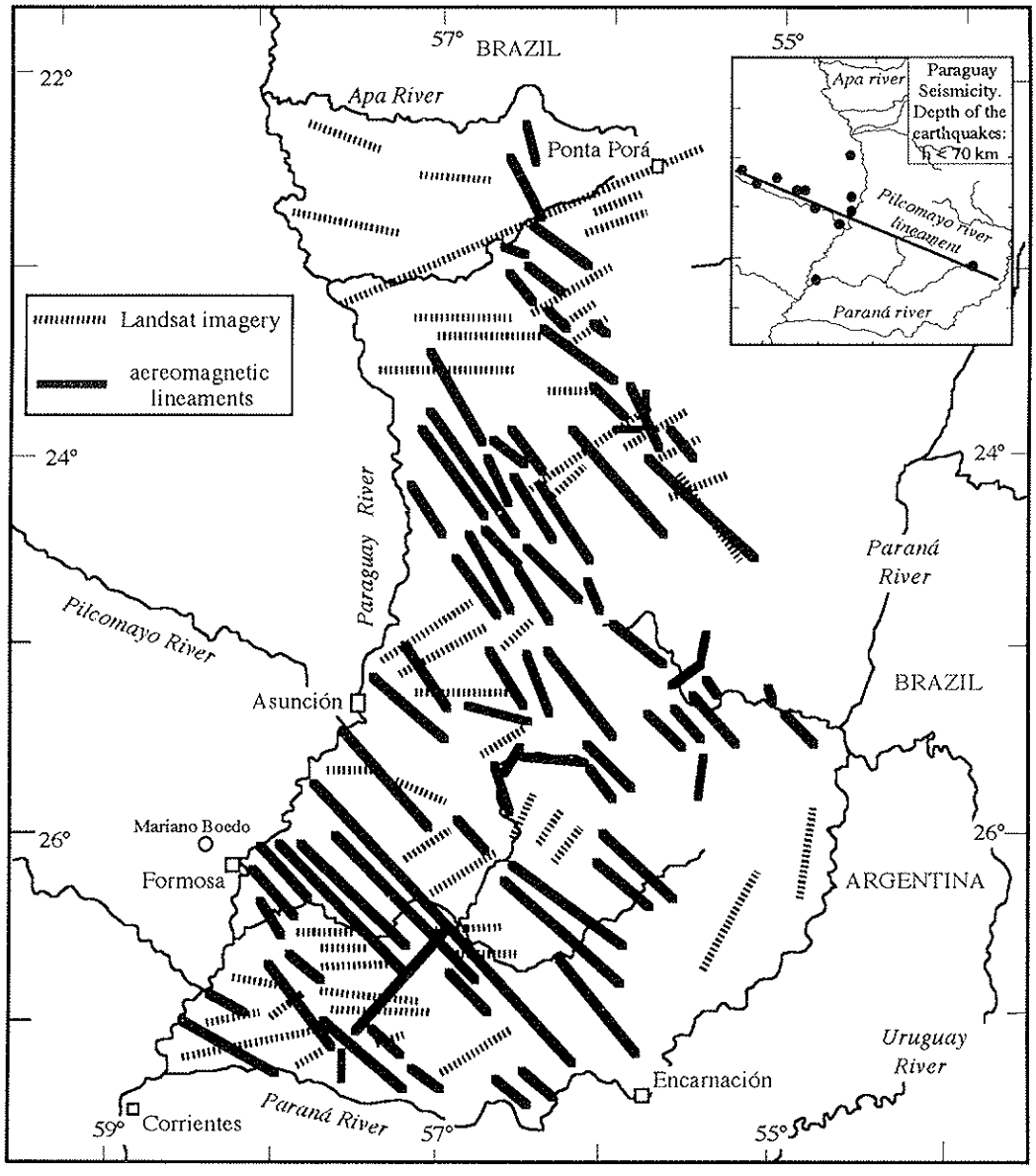

Fig. 4. Landsat and aeromagnetic lineaments in Eastern Paraguay. The NW-trending aeromagnetic anomalies were interpreted by Druecker and Gay (1987) due to tholeiitic dykes which are virtually absent in the field. The only NW-dyke swarm outcrops in the Asunción–Sapucaí–Villarrica graben (cf. Fig. 3) are represented by potassic alkaline rocks. Inset: distribution of earthquakes, depth < 70 Km (Berrocal and Fernandes, 1996).

Paraguay tholeiites are represented by both high-Ti and low-Ti stratoid flows (Bellieni et al., 1986) and rare NW-trending high-Ti and low-Ti dykes (Comin-Chiaramonti et al., 1995).

The younger alkaline rocks are exclusive to SE Paraguay (Fig. 1) and postdate the Paraná flood tholeiites. They are concentrated in the Asunción–Sapucai–Villarrica (ASV) graben (Figs. 1 and 3), and locally at San Juan Bautista (Fig. 1). The Early Cretaceous event (128–126 Ma; Velázquez et al., 1996) of this magmatic activity is represented by more than two hundred potassic NW-trending dykes, as well as potassic complexes, sometimes with carbonatites, and lava flows occurring in the ASV graben. By contrast, the Early/Late Cretaceous (112–93 Ma; Comin-Chiaramonti et al., 1993) event of San Juan Bautista and that of Late Cretaceous to Oligocene age (70–32 Ma; Comin-Chiaramonti et al., 1997) of the ASV graben (Asunción township; Petrini et al., 1994) is represented by sodic plugs and dykes which sometimes contain spinel-peridotite mantle xenoliths. Carbonatites are exclusively associated with the potassic rocks (Castorina et al., 1997). In general, the main occurrences of alkaline rocks are along NW-trending grabens (Liveres and Quade, 1987) with the intrusions often located at the intersections of the NW- and SE-trending faults.

Some small outcrops of sedimentary rocks above the Paraná flood tholeiites ('Alto Paraná Formation'), consist of aeolian sandstones (Late Cretaceous 'Acaray Formation', corresponding to the 'Bauru Group' in Brazil).

Since Late Cretaceous, the Cenozoic of Eastern Paraguay is marked by a strong uplift, indicated by the presence of Eocene–Oligocene fanglomerates ('Patiño Formation', Ypacaray Valley) and by fission track ages on apatites from Triassic sandstones (mainly < 70 Ma; Hegarty et al., 1996).

3. Geophysical data

The aeromagnetic survey (ANSCHUTZ Co., 1981; Druecker and Gay, 1987) shows that the linear magnetic anomalies occurring throughout Eastern Paraguay mainly trend N40–45W (Fig. 4). These anomalies have been interpreted as reflecting Early Cretaceous tholeiitic dyke swarms (Druecker and Gay, 1987). Landsat lineaments mainly trend NE–EW and would essentially reflect tectonic lineaments of the basement (DeGraff, 1985). Since field evidence does not support the existence of NW-trending dyke swarms, it seems possible that most magnetic anomalies correspond to Precambrian tectonic lineaments (cf. Ussami et al., 1994 for the Ponta Grossa Arch dykes, Brazil). It should be noted that the present seismic activity (earthquakes with depth < 70 km) indicates that the NW-trending Precambrian fault system lasted to Quaternary times, i.e. NW Pilcomayo lineament (inset of Fig. 3; Berrocal and Fernandes, 1996).

The Bouguer gravity map (Fig. 4) consists of NW-trending gravity highs and lows that represent shallow to exposed basement and sedimentary basins, respectively. The boundaries between the gravity highs and lows are generally marked by steep gradients that reflect abrupt basement offsets along faults, or gradual basement offsets by multiple faults, or basement dip changes by crustal warping. A secondary set of NE-trending gravity anomaly subdivides the dominant NW trending features in gravity highs and lows related to block-faulting tectonics.

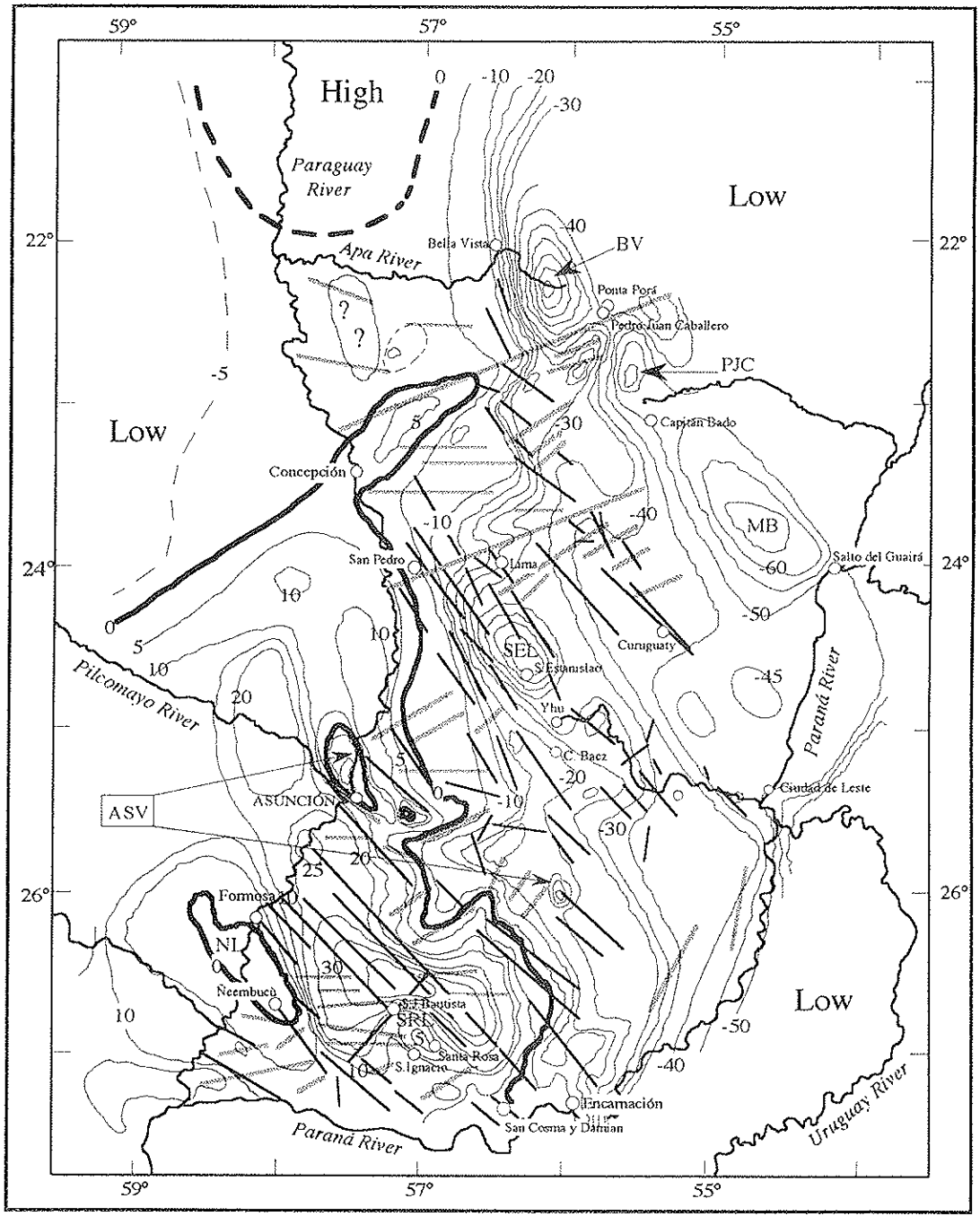

Fig. 5. Bouguer gravity map of Eastern Paraguay (gravity interval: 5 mgal) and arrangement of aeromagnetic and Landsat lineaments (cf. Fig. 4). Gravity lows: BV = Bella Vista, PJC = Pedro Juan Caballero, MB = Mbacarayú (Amambay region); SEL: San Estanislao (formerly San Pedro); NL and SRL: Ñeembucú and Santa Rosa relative gravity lows, respectively. Bold curve: Bouguer zero isoplethe.

In general, the zero mGal contour approximately marks the boundary between the Amazonia Craton to the North and the La Plata Craton to the South.

The gravity lows and highs parallel the dominant NW attitude of the magnetic lineaments, with the alkaline and tholeiitic rocks associated to gravity lows. The Amambay (Fig. 2) and Sapucai-Villarrica (Fig. 3) rift structures are of particular importance as Paraná basalt volcanism occurred here before and after the alkaline potassic magmatism, respectively.

3.1. Asunción–Sapucai–Villarrica graben (ASV)

Asunción–Sapucai–Villarrica graben (Fig. 3) represents the most apparent rift structure in Eastern Paraguay. It is characterized by a relative gravity low trending N30–45W near Asunción township. In this general area, the graben is nearly symmetrical and defined by major faults along each margin (DeGraff et al., 1981; Bitschene, 1987). Geology and gravity data indicate that ASV graben extends up to 100 km from Asunción into the Chaco basin (Figs. 1 and 5). The ASV graben turns to a N80W trend between Paraguarí and Villarrica townships and is marked by a gravity low anomaly which increases eastwards.

It should be noted that while the Tertiary sodic rocks mainly occur in an area characterized by gravity highs, the Early Cretaceous potassic rocks occur in a gravity low belt (Figs. 3 and 5). Notably, the emplacement of most alkaline potassic complexes are related to block faulting. Near Villarrica township (Fig. 3), the ASV structure is poorly defined, but the tectonic control of alkaline intrusions is still apparent. The alkaline intrusions at Aguapety Portón and Mbocayaty townships, north of Villarrica, outcrop along faults with southeastern blocks displaced downward, consistently with gravity data. East of Villarrica, a NS-trending fault bounds the western flank of the Ybytyruzú hills, close to several alkaline intrusions (Bitschene, 1987).

3.2. Amambay tectonic depression (AMA)

The Amambay region is defined by three main gravity lows (i.e. Mbaracayú, Pedro Juan Caballero and Bella Vista), aligned N40–45W, and extending at least 300 km from Salto del Guairá to Bella Vista township (Fig. 5). The AMA rift belt varies in width from about 40 to 70 km, although its width is not well constrained by gravity data in the south. The belt was also affected by NE-trending tectonic lineament (Livieres and Quade, 1987).

The Amambay tectonic belt is poorly defined by surface geology due to the cover of Paraná flood tholeiites and the overlying Late Cretaceous Acaray sandstones. The southwestern margin of this tectonic zone roughly coincides with the southwestern edge of the Serra Geral flood tholeiites and with the easternmost margin of the Permian outcrops.

The Mbacarayú gravity low is 150 km long and 70 km wide. Gravity values indicate a total subsidence of about 1800 m. Gravity values near Salto del Guairá suggest that the northeastern margin of the basin is faulted and that the basin terminates along a NE-trending fault near the same town.

The Pedro Juan Caballero gravity low (PJC) may be considered the northwesterly extension of Mbacarayú analogue. PJC trends nearly N–S for 70 km and it is about 35 km wide. Gravity values point to about 1300–2600 m of subsidence.

The Bella Vista gravity low (BV) is about 80 km long and 50–60 km wide with gravity values indicating about 2600–4900 m subsidence. The NNW-trending western margin of the basin is marked by gravity gradients that are among the steepest observed in Eastern Paraguay and are related to faulting. Most of the estimated 4900 m of subsidence along the western margin of the basin is attributed to the Bella Vista fault zone which trends N10W near Bella Vista and N30–35W near the Sarambí alkaline complex (Fig. 2).

The Ponta Porá High (PHH) trends N35E and has been recognized as a tectonic feature that controlled the emplacement of alkaline magma in the Amambay alkaline province (Livieres and Quade, 1987). The tectonic PPH ends to the NE at Pedro Juan Caballero against a gravity low in neighbouring Brazil.

All known alkaline-carbonatite complexes and dykes of the Amambay Province are located within or on the boundaries of the Ponta Porá High where this crosses the Amambay tectonic depression. The Sarambí complex lies exactly at the intersection of the Bella Vista fault zone, while the Chiriguelo complex forms a strongly updoming structure (inset in Fig. 2; Censi et al., 1989) cropping out close to a possible fault zone along the northeastern margin of the Bella Vista basin. Both the Cerro Guazú and the Cerro Tayay potassic plugs (Comin-Chiaramonti and Gomes, 1996) occur along the inferred fault that bounds the southeastern margin of the PPH (Fig. 2).

The Ponta Porá High lies along a major gravity lineament that trends N55–60E in Eastern Paraguay and in the northern Chaco basin, west of the Paraguay River (Fig. 5). This trans-Paraguayan gravity lineament probably marks a structural zone related to older Precambrian tectonic events in the area.

4. Early Cretaceous–Tertiary magmatic rocks

The voluminous potassic rocks in Eastern Paraguay occurred prior to (c. 145 Ma) and later (128–126 Ma) than the extrusion of the Paraná flood basalts (137–132 Ma). Therefore, the Eastern Paraguay potassic rocks may serve to test out the validity of the hypothetical 'Tristan da Cunha' mantle plume in the genesis of the Brazilian Early Cretaceous magmas in the Paraná-Etendeka Province. Early Cretaceous alkaline magmatism in Eastern Paraguay is moderately to strongly potassic, spanning from alkali basalt to trachyte and from basanite to phonolite and their intrusive analogues (Comin-Chiaramonti and Gomes, 1996). The late Early Cretaceous–Tertiary sodic rocks include ankaratrites, nephelinites and phonolites (Comin-Chiaramonti et al., 1991, 1997).

4.1. Geochemistry

Major and trace element data for the alkaline rocks from Eastern Paraguay are given in Comin-Chiaramonti and Gomes (1996) and in Comin-Chiaramonti et al., (1997).

Multi-elemental diagrams, normalized to the primitive mantle of Sun and McDonough (1989), show that the potassic rocks (pre- and post-tholeiites) from Eastern Paraguay (Fig. 6A) and the low- and high-Ti Paraná tholeiites (Fig. 6B) are characterized by a pronounced Ta–Nb negative anomaly. On the other hand, the sodic rocks (late Early Cretaceous–Tertiary) in

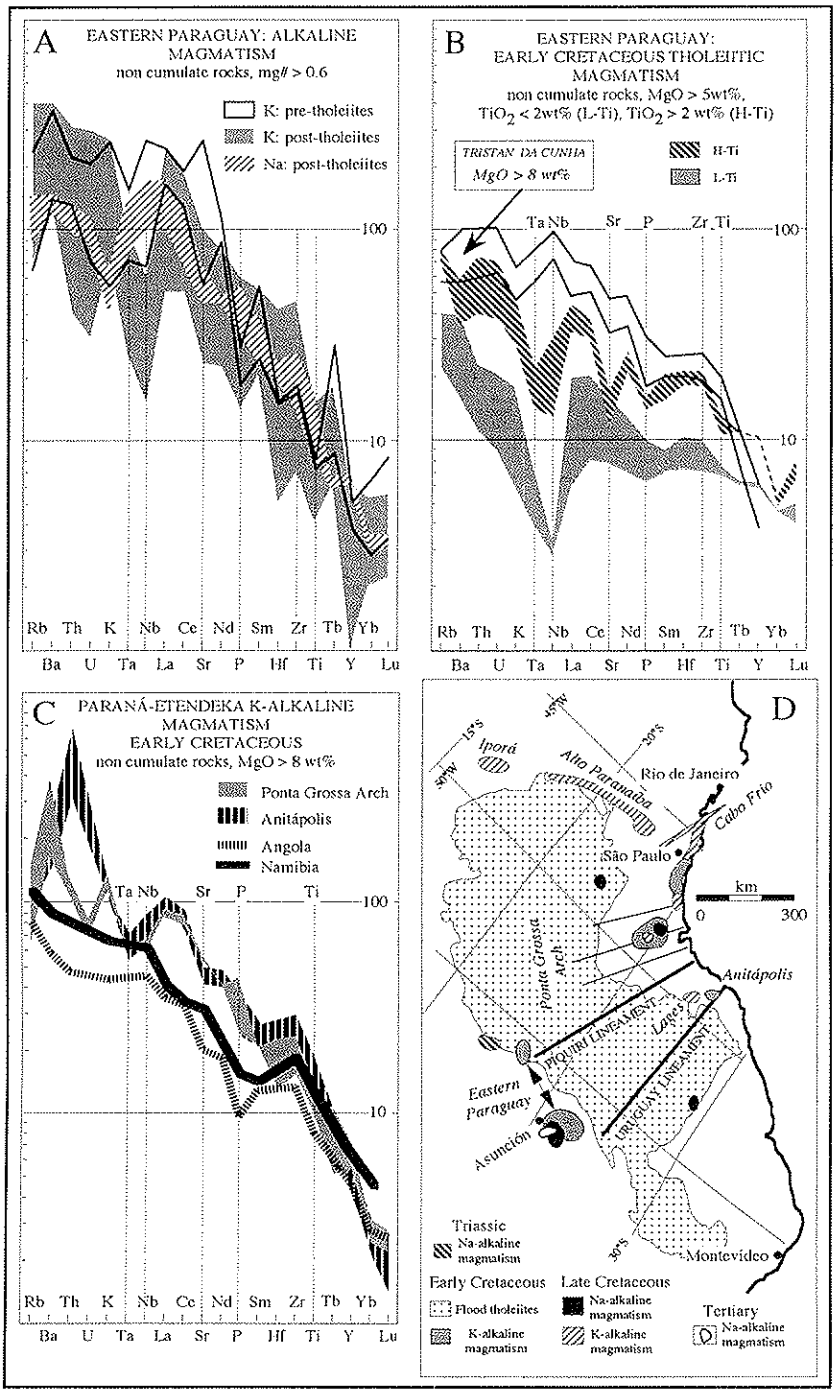

Fig. 6. Multi-elemental diagrams normalized to primitive mantle (Sun and McDonough, 1989). *Eastern Paraguay*: (A) potassic and sodic alkaline magmatism and (B) low- (<2 wt%) and high-TiO_2 (>2 wt%) Paraná flood tholeiites. (C) *Potassic alkaline magmatism* in eastern Paraná basin (Ponta Grossa Arch and Anitápolis), Angola and Namibia. (D) Distribution of the alkaline and tholeiitic magmatism in the Paraná basin. Data sources: Piccirillo and Melfi (1988), Le Roex et al. (1990), Coltorti et al. (1993), Comin-Chiaramonti and Gomes (1996), Comin-Chiaramonti et al. (1995, 1997), Milner and Le Roex (1996), Le Roex and Lanyon (1998).

Eastern Paraguay show a positive Ta–Nb anomaly (Fig. 6A). Notably, the potassic rocks (Early Cretaceous) from the eastern side of the Paraná basin (e.g. Ponta Grossa and Anitápolis, 129–130 Ma; Fig. 6C) are also characterized by a Ta–Nb negative anomaly. The potassic rocks from Angola and Namibia belonging to the Paraná-Etendeka Igneous Province instead show (Fig. 6C) a slight positive Ta–Nb anomaly (Coltorti et al., 1993; Le Roex and Lanyon, 1998).

In general, the Early Cretaceous potassic rocks from Eastern Paraguay are distinct from the Angola–Namibia analogues, suggesting distinct mantle sources. Multi-elemental patterns from Tristan da Cunha rocks (Fig. 6B) are different from those for the Early Cretaceous alkaline and tholeiitic rocks from the Paraná basin, indicating that the Tristan plume geochemical signature is not easily appreciable in the whole alkaline-tholeiitic magma system from the Paraná basin (Comin-Chiaramonti et al., 1997). Moreover, in Eastern Paraguay the Early Cretaceous potassic rocks, both pre- and post Paraná tholeiites, are very close in terms of major and trace element concentrations.

4.2. Sr–Nd isotopes

Sr–Nd isotopes for the Early Cretaceous potassic rocks (Comin-Chiaramonti et al., 1997) from Eastern Paraguay revealed that the crustally uncontaminated rocks plot in the enriched quadrant with $\epsilon^t(Nd) < -10$ and $\epsilon^t(Sr) > +24$ (Fig. 7A). Instead, the low- and high-Ti tholeiites span from the enriched quadrant towards the depleted quadrant relative to the Bulk Earth, while the Tristan da Cunha volcanics plot in the enriched quadrant (Fig. 7A and B). The late Early Cretaceous–Tertiary sodic rocks of Eastern Paraguay are isotopically shifted towards Sr–Nd depleted quadrant, trending to the N-MORB field (Fig. 7D). Fig. 7C shows that the Early Cretaceous potassic rocks from Eastern Paraguay are isotopically distinct from the Brazil–Namibia–Angola analogues, suggesting distinct mantle sources. It should be stressed that the Tristan da Cunha volcanics plot in the field of the Early Cretaceous Paraná-Etendeka magma system, except the potassic rocks from Eastern Paraguay.

In summary, the Early Cretaceous potassic rocks from Eastern Paraguay, outpouring prior to and later than the emplacement of the Paraná flood tholeiites, are geochemically and isotopically distinct from the modern Tristan da Cunha magma. On the other hand, part of Paraná tholeiites tend to be similar to Tristan da Cunha volcanics in their Sr–Nd isotope compositions, but different in terms of geochemical features (Fig. 6B).

5. Discussion and conclusions

Geological and geophysical evidence indicates that the Mesozoic–Tertiary block faulting tectonics in Eastern Paraguay is extensional and responsible for NW-trending grabens (Asunción–Sapucai–Villarrica, ASV, and Amambay), fault systems (Jejui–Aguaray–Guazu and Asunción–Encarnación) and fault-controlled sedimentary basins (e.g. San Pedro) (Fig. 1). This type of tectonics, reflecting basement lineaments, controlled the emplacement of both the alkaline magmas in Eastern Paraguay, and that in the eastern Paraná basin (Fig. 6).

The Early Cretaceous potassic rocks of Amambay and Alto Paraguay regions predated the

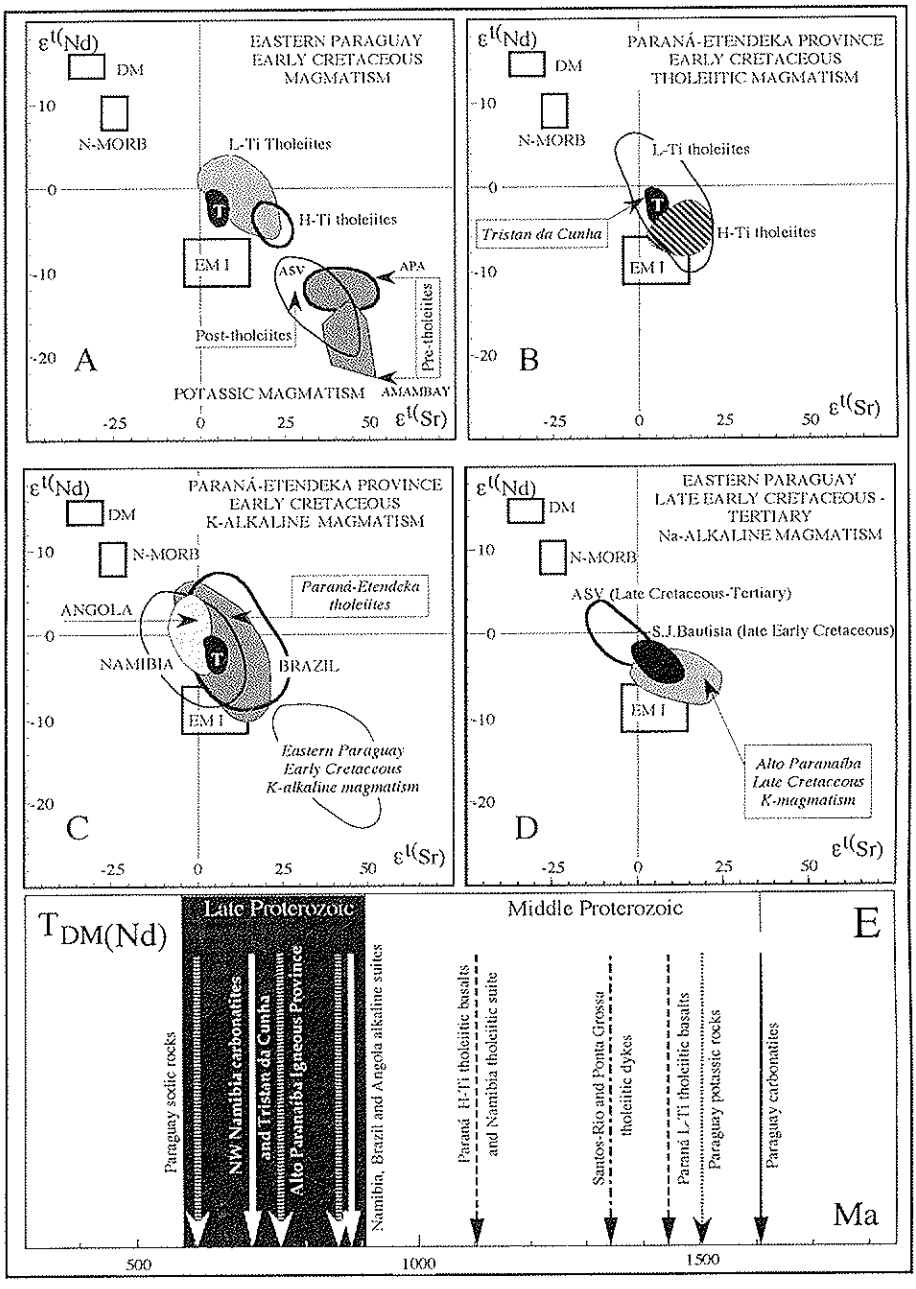

Fig. 7. $\varepsilon^t(Sr)$ vs $\varepsilon^t(Nd)$ relationships (A–D), and T_{DM} (Nd) model ages (E; DM, depleted mantle: $^{143}Nd/^{144}Nd = 0.513151$, $^{147}Sm/^{144}Nd = 0.2188$) for the magmatic rocks for Eastern Paraguay and Paraná-Etendeka Province. *Early Cretaceous*: (A) Eastern Paraguay magmatism, (B) tholeiitic magmatism in the Paraná-Etendeka Province, and (C) potassic alkaline magmatism in the Paraná-Etendeka Province, and (D) *late Early Cretaceous–Tertiary* sodic alkaline magmatism in Eastern Paraguay (Comin-Chiaramonti et al., 1991, 1993). The distribution of the Late Cretaceous potassic alkaline magmatism from Alto Paranaíba Igneous Province (Gibson et al., 1995, APIP, cf. Fig. 6D) is shown for comparison. (E) mean model ages for the tholeiitic and alkaline-carbonatitic rocks of the Paraná-Etendeka Province. Abbreviations: DM, N-MORB and EMI after Hart and Zindler (1989); T, Tristan da Cunha (Le Roex et al., 1990); other source data as in Fig. 6.

Paraná flood tholeiites, while the rocks from the ASV graben postdated the flood tholeiites. The sodic rocks are virtually confined to ASV graben (Late Cretaceous–Tertiary), and locally to the San Juan Bautista (late Early Cretaceous).

The Early Cretaceous potassic rocks from northern and southern Eastern Paraguay, show virtually the same composition both for major and trace elements. These rocks, and the associated Paraná tholeiites, are characterized by a pronounced Ta–Nb negative anomaly and by Th/Zr vs Nb/Zr and Th/Yb vs Ta/Yb relationships (cf. Comin-Chiaramonti et al., 1997) which indicate a subduction setting (Pearce, 1983; Beccaluva et al., 1991). However, strong geological and geophysical evidence indicates that the Paraguay potassic rocks are related to extensional tectonics. Similar geochemical characteristics are also shown by the Early Cretaceous potassic complexes from the eastern Paraná basin (e.g. Ponta Grossa Arch, Anitápolis). By contrast, the coeval potassic rocks from Angola and Namibia show a slight positive Ta–Nb anomaly and plot in the 'non-subduction field' of the magmatic-tectonic diagrams.

The late Early Cretaceous–Tertiary magmatic rocks of Eastern Paraguay are distinct for their sodic nature. They are characterized by Ta–Nb positive anomaly and by Th–Zr–Nb–Ta–Yb relationships typical of the 'non-subduction' setting. It should be noted that similar geochemical features are also shown by the Late Cretaceous alkaline rocks from northern Paraná basin (Alto Paranaíba; Gibson et al., 1995) which, on the contrary, are strongly potassic.

In general, the geochemical data indicate that the magmatism of the Paraná-Etendeka Province requires heterogeneous source mantle, supported also by Sr–Nd isotopes (Fig. 7). The Early Cretaceous potassic rocks from Eastern Paraguay have $\epsilon^t(Sr)$ and $\epsilon^t(Nd)$ ranging from +25 to +50 and from −10 to −24, respectively. Instead, the coeval potassic rocks from Brazil, Angola and Namibia are distinct in showing, on the whole, $\epsilon^t(Sr) = +25$ to −15, and $\epsilon^t(Nd) = -10$ to +6, similar to the Paraná tholeiites. The younger sodic rocks in Eastern Paraguay are isotopically slightly enriched or depleted with respect to the Bulk Earth and overlaps the fields of the potassic rocks from Brazil (Early and Late Cretaceous), and Angola and Namibia (Early Cretaceous).

The subduction geochemical 'signature' of the Early Cretaceous magmas in the Paraná basin is related to extensional tectonics, suggesting that it is a primary mantle source characteristics. According to Comin-Chiaramonti et al. (1997) this mantle signature may be related to 'metasomatic processes' which variably affected the source mantle in ancient times.

The genesis of the alkaline magmatism from Eastern Paraguay requires relatively high melting degrees (4–11%; Comin-Chiaramonti et al., 1997). Therefore, we can assume that Sm/Nd of the source was not substantially modified during melting, and that the $T_{DM}(Nd)$ model ages may represent those of the 'metasomatic events'.

$T_{DM}(Nd)$ model ages (Fig. 7E) of the flood tholeiites and dykes (Ponta Grossa Arch and Santos–Rio de Janeiro) from Paraná and Etendeka, and the Early Cretaceous potassic roks and carbonatites from Eastern Paraguay range from 1.1 to 1.6 Ga. By contrast, the Early Cretaceous potassic rocks and carbonatites from eastern Paraná basin, Angola and Namibia, as well as the younger sodic and potassic rocks of Paraguay and Alto Paranaíba, respectively, yielded 0.6–0.9 Ga. Note that Tristan da Cunha modern volcanics yielded 0.7 Ga. These model ages indicate that two notional distinct metasomatic events may have occurred during Middle

and Late Proterozoic times as precursors to the alkaline and tholeiitic magmas in the Paraná-Etendeka Igneous Province. Finally, it should be noted that the Late Proterozoic model ages refer to Early and Late Cretaceous alkaline rocks mostly characterized by Ta–Nb positive anomaly, independently from their sodic or potassic nature. This suggests that the Middle and Late Proterozoic 'metasomatic events' were chemically distinct.

In summary, the alkaline and tholeiitic magmatism in Eastern Paraguay appears to be related to the lithospheric mantle, and the contribution of asthenospheric components derived from the hypothetical Tristan da Cunha mantle plume is not appreciable in terms of geochemistry and Sr–Nd isotopes. The source(s) of the recurrent potassic magmatism and interposed tholeiitic event may not easily accounted for the plume hypothesis. We suggest that the main role of this plume may have been to promote the melting of the overlying lithospheric mantle.

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