Cretaceous Na-Alkaline Magmatism from the Misiones Province (Paraguay): Its Relationships with the Paleocene Na-Alkaline Analog from Asunción and Geodynamic Significance

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ABSTRACT

Alkaline (sodic) volcanic rocks, i.e., ankaratrites-melanephelinites, basanites-tephrites, and phonolites, dated at 119 Ma and similar in composition to the 60-Ma plugs of the Asunción Province, occur in Eastern Paraguay and belong to the Misiones Province. The age relationships confirm that the youngest volcanic events in Eastern Paraguay, at the central westernmost side of the Paraná basin, are represented by alkaline rock types of sodic affinity emplaced in late Early Cretaceous and Paleocene times. This sodic magmatism contrasts with the Early Cretaceous alkaline (potassic) magmatism of the region, and it is associated in space and time with the Paraná basin tholeiites. Geological and geophysical results for Eastern Paraguay indicate transtensional tectonics, with a NE-SW regional extensional stress field. The geochemistry and Sr-Nd-Pb isotope systematics are consistent with a lithospheric mantle source(s) enriched in incompatible elements by metasomatic processes. Nd model ages suggest that these probably occurred during Meso- and/or Neoproterozoic times and may be regarded as precursors of both alkaline and tholeiitic magmas in Eastern Paraguay. Potential parents for the alkaline (sodic) liquids have been modeled in terms of small degrees of mantle partial melting. Multielemental plots of calculated mantle sources for these liquids from Asunción and Misiones contrast with the analog mantle sources for the Paraguayan alkaline (potassic) suite, confirming the view that popular geodynamic markers of this type remain implausible indicators of subduction. Our results support the view that the magma genesis and the emplacement of the alkaline magmatism in southeastern Paraguay, and even in northwestern Argentina and Bolivia, is related to and probably driven by reactivation of preexisting lithospheric discontinuities in the various South American blocks, which promoted local decompression melting of previously enriched mantle sources.

Online enhancement: appendix.

Introduction

The opening of the South Atlantic Ocean generated one of the most prominent continental provinces of flood basalts (the Paraná-Angola-Etendeka Province), as well as the continental breakup and complex rift systems associated with distinctive alkaline magmatism. The latter occurred along and across the passive margins of South America and Africa (fig. 1). Structural and geochronological data show that many of the alkaline occurrences along the western and eastern borders of the Paraná basin are linked to extensional tectonics (Riccomini et al. 2005). On the basis of apatite fission track analysis, Hegarty et al. (1996) suggested that the present topography and drainage pattern in Eastern Paraguay could be controlled by a kilometer-scale uplift beginning some time between 90 and 80 Ma. Consequently, Eastern Paraguay represents a crucial

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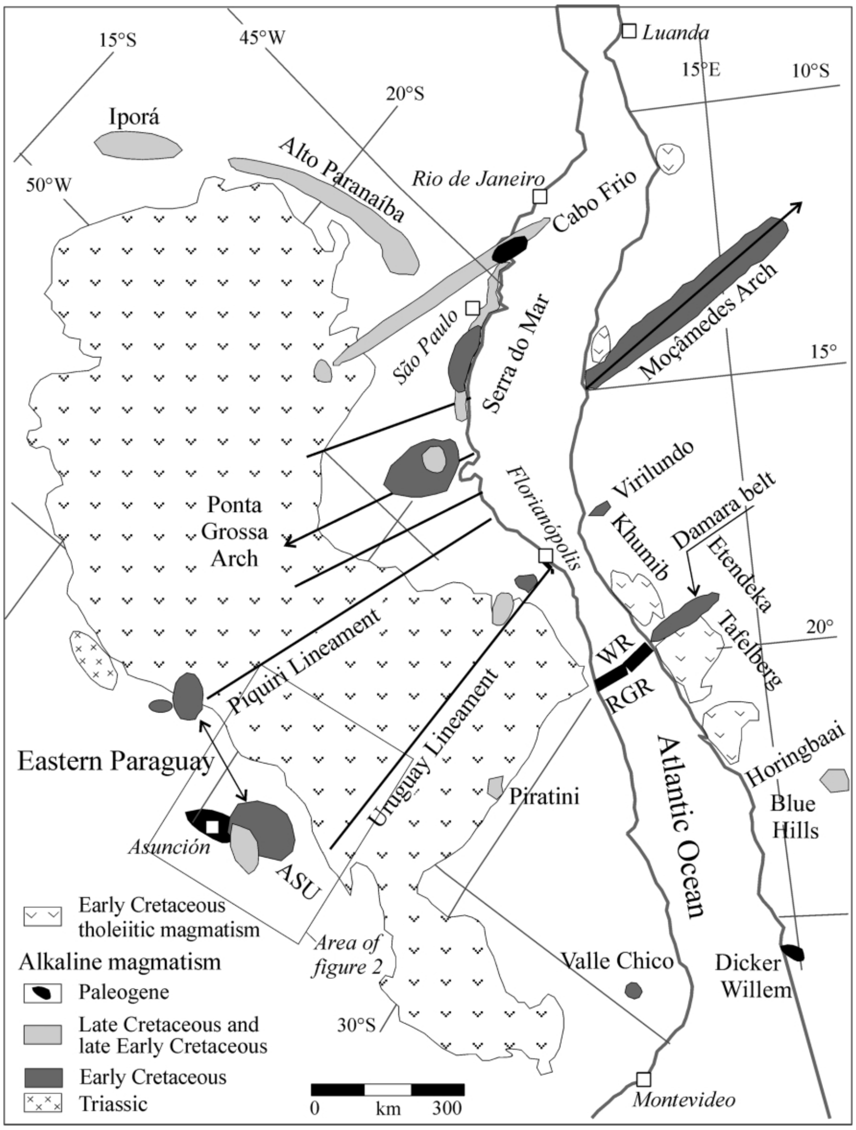

Figure 1. Sketch map showing the distribution of the alkaline occurrences around the Paraná-Angola-Namibia Early Cretaceous flood tholeiites (Comin-Chiaramonti et al. 1997, modified). RGR = Rio Grande Rise, and WR = Walvis Ridge. Geological time scale according to Gradstein et al. (2004).

area for investigating the geodynamic significance of the widespread magmatism located between the compressional Andean and extensional Atlantic systems. A generalized NE-SW-trending crustal extension, combined with right-lateral strike-slip motion (Riccomini et al. 2002), probably associated with the propagation of the Early Cretaceous breakup phase, was the tectonic regime dominant in Eastern Paraguay. NW-SE fault trends, paralleling the dominant orientation of Mesozoic alkaline and tholeiitic dikes, reflect this type of structure (Comin-Chiaramonti et al. 1992, 1997, 1999; Riccomini et al. 2001). The resulting structural pattern controlled the development of grabens or half-grabens as a response to NE-SW-directed extension and evolution during Neogene times (see Comin-Chiaramonti and Gomes 1996).

From the beginning of the Cretaceous, five main magmatic events occurred (Comin-Chiaramonti et al. 1999): (1) alkaline (potassic) carbonatitic complexes and dikes in northern Eastern Paraguay, from the Rio Apa and Amambay areas (139 ± 1 Ma, i.e., Valanginian, according to Gradstein et al. 2004), which predate the Paraná flood basalts (Serra

Geral Formation, SGF); (2) SGF flood tholeiites and dikes (133 ± 1 Ma, i.e., Hauterivian; Renne et al. 1992; Turner et al. 1994); (3) alkaline (potassic) complexes and dikes (128–126 Ma, i.e., Barremian; Comin-Chiaramonti and Gomes 1996, 2005) with subordinate silico-carbonatite flows and dikes, widespread mainly in the Asunción-Sapucai-Villarica graben (ASU of Comin-Chiaramonti et al. 1997, 1999); (4) alkaline (sodic) complexes, plugs, and dikes (119 ± 2 Ma, i.e., Aptian; Velázquez et al. 2004), occurring mainly in Misiones Province (San Juan Bautista region); (5) alkaline (sodic) complexes, plugs, and dikes (60 ± 2 Ma, i.e., Danian-Selandian, Paleocene, according to recent Ar/Ar ages of Gomes et al. 2004), cropping out near the city of Asunción, at the western side of the ASU. The Early Cretaceous alkaline magmatism, both pre- and post-tholeiites, is moderately to strongly potassic, spanning the compositional ranges from alkali basalt to trachyte and from basanite to phonolite and their intrusive equivalents (Comin-Chiaramonti and Gomes 1996; Comin-Chiaramonti et al. 1997). Early Cretaceous tholeiitic rock types are mainly basalts and andesibasalts (nomenclature according to De La Roche 1986), both including high- and low-Ti suites (Bellieni et al. 1986; Piccirillo and Melfi 1988; Comin-Chiaramonti and Gomes 1996). Late Early Cretaceous and Paleocene sodic rocks (ankaratrites, nephelinites, tephrites, and phonolites) are both characterized by mantle xenoliths, ranging from spinel lherzolites to dunites (Comin-Chiaramonti et al. 2001 and references therein).

In this article, we illustrate some peculiar aspects (geological, geophysical, and geochemical) of the late Early Cretaceous sodic magmatism occurring in the Misiones Province, southeastern Paraguay, compared with the better-known sodic magmatism of the Asunción area (see Comin-Chiaramonti et al. 1986, 1991, 2001). These aspects will help in understanding the significance of the sodic alkaline magmatism in the westernmost side of the Paraná-Angola-Namibia system.

Geological Setting of the Southern Provinces from Eastern Paraguay

Proterozoic–Early Paleozoic basement, sedimentary basins, and taphrogenetic events form the main geological features of the region (fig. 2). The basement (Caacupú high) is composed of metamorphic (gneisses, migmatites, amphibolites, metarhyolites, quartzites, and metasediments) and magmatic rocks (granites, rhyolites, and associated pyroclastites) of Mesoproterozoic age (Cordani and Sato 1999).

The whole area was affected by the trailing end of the Brasiliano cycle, i.e., from Late Neoproterozoic to Early Ordovician (576–480 Ma; Kanzler 1987). During Paleozoic times, an important regional subsidence and extensive sedimentation occurred: (1) Ordovician-Devonian continental deposits, i.e., conglomerates, sandstones, fossiliferous shales with thin intercalations of argillaceous beds, typical of fluvial and coastal marine environment, deposited in basins subjected to a convergent margin regime (Gohrbandt 1992; Almeida et al. 2000); (2) Carboniferous-Permian glacial deposits, i.e., conglomerates, tillites, and diamictites; (3) Permian continental transgressive deposits, including sandstones, siltstones, and shale beds (Harrington 1950; Eckel 1959; Gohrbandt 1992; Orué 1996).

At the time of Gondwana breakup, the widespread SGF covered most of western Eastern Paraguay (both high- and low-Ti stratoid flows and sills and rare NW-trending high- and low-Ti dikes; see Bellieni et al. 1986; Piccirillo and Melfi 1988; Comin-Chiaramonti et al. 1995), along with alkaline magmatism, aged both at pre- and postdrift times (Comin-Chiaramonti et al. 1997, 1999). The whole Cretaceous magmatism was preceded by aeolian sedimentation (Misiones Formation, corresponding to the Brazilian Botucatu Group; see Fúlfaro 1996). Some small outcrops of sedimentary rocks, covering the Paraná flood tholeiites (Alto Paraná Formation, corresponding in Brazil to the SGF), consist of aeolian sandstones (Late Cretaceous Acaray Formation, corresponding in Brazil to the Bauru Group; see Fúlfaro 1996). Since the Late Cretaceous, Eastern Paraguay has been characterized by a strong uplift, indicated by the presence of Paleocene fanglomerates (Patiño Formation, Ypacaray Valley) and also supported by fission track ages of apatites from Silurian sandstones (mainly <70 Ma; Hegarty et al. 1996).

The most recent alkaline rocks, i.e., late Early Cretaceous and Paleocene (119 and 60 Ma, respectively, according to Gomes et al. 2004; Velázquez et al. 2004), are restricted to southeastern and central Eastern Paraguay, respectively (fig. 2), and are concentrated in the Misiones and Asunción provinces (see Comin-Chiaramonti et al. 1999). The Misiones sodic magmatic rocks occur between the towns of San Juan Bautista and San Ignacio as small plugs and dikes and are tectonically associated with the Santa Rosa graben (Velázquez et al. 2002). It should be stressed that Paleocene sodic magmatism, with characteristics very similar to that of Misiones, oc-

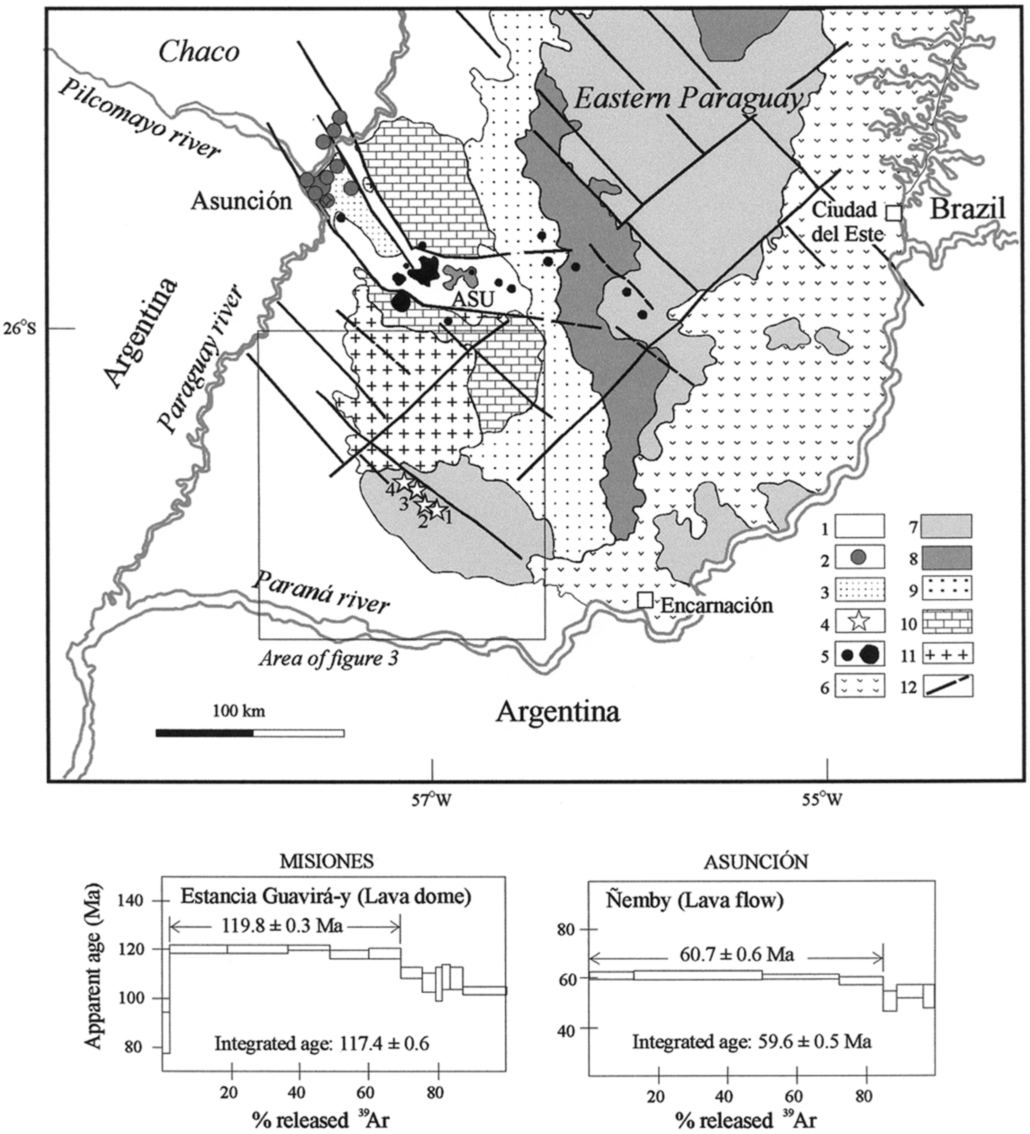

Figure 2. Eastern Paraguay. *Top*, generalized geological map of the southeastern region (Comin-Chiaramonti et al. 1997; Velázquez et al. 1998, modified). Key: *1*, Quaternary alluvial cover; *2*, Paleocene (~60 Ma) alkaline sodic intrusions (Asunción Province); *3*, Cenozoic sedimentary rocks of the Patiño Formation; *4*, late Early Cretaceous (ca. 119 Ma) alkaline sodic intrusions (Misiones Province); *5*, Early Cretaceous (128–126 Ma) alkaline potassic intrusions (Central Province); *6*, Early Cretaceous (133 Ma) flood tholeiites (Alto Paraná Formation, corresponding to the Brazilian Serra Geral Formation); *7*, Early Cretaceous eolian sediments (Misiones Formation); *8*, Permian sediments of the Independencia Group; *9*, Carboniferous-Permian sediments of the Coronel Oviedo Group; *10*, Ordovician-Silurian sedimentary rocks of the Caacupé and Itacurubi groups; *11*, Proterozoic basement; *12*, main faults. ASU = Asunción-Sapucai-Villarica graben. *Bottom*, two $^{40}Ar/^{39}Ar$ ages of rock types from the Misiones (Velázquez et al. 2004; *left*) and Asunción (Gomes et al. 2004; *right*) provinces, as an example. It should noted that from a geographical point of view, the Paraguay is subdivided into two main regions, i.e., the Chaco Paraguayo (west) and Eastern Paraguay.

curs also near the city of Asunción, 180 km NNW of the late Early Cretaceous analogs (fig. 2).

Geophysical and Structural Data

Aeromagnetic surveys covering Eastern Paraguay (Anschutz 1981) show that the linear magnetic anomalies occurring throughout Eastern Paraguay mainly trend N 40°–45° W. These anomalies are thought to reflect the attitude of Early Cretaceous tholeiitic dikes (Druecker and Gay 1987). Landsat imagery displays mainly NW-SE and E-W lineaments reflecting the basement tectonic structures (see DeGraf 1985; Comin-Chiaramonti et al. 1999). Since the field evidence does not support the presence of NW-trending tholeiitic dike swarms (Comin-Chiaramonti et al. 1995, 1997, 1999; Comin-Chiaramonti and Gomes 1996), it seems likely that most magnetic anomalies may correspond to Precambrian tectonic lineaments (see Ussami et al. 1991). It should be noted that the present-day seismic activity, i.e., earthquakes with depths of <70 km, indicates that the NW-trending Precambrian fault systems are still active (e.g., Pilcomayo lineament; see Berrocal and Fernandes 1996).

The Bouguer gravity map shows NW-trending gravity highs and lows representing shallow to exposed basement and sedimentary basins, respectively, as clearly indicated by, e.g., the Asunción graben system of figure 2 (see Velázquez et al. 1998; Comin-Chiaramonti et al. 1999). The boundaries between the gravity highs and lows are generally marked by steep gradients that reflect abrupt basement offsets along faults, gradual basement offsets caused by multiple faults, or basement dip changes caused by crustal warping. A secondary set of NE-trending anomalies subdivides the dominant NW-trending features in gravity highs and lows related to block-faulting tectonics. The gravity low and highs parallel the dominant northwestward attitude of the magnetic lineaments, whereas the alkaline outcrops are associated with the gravity lows. In general, the zero amplitude on the Bouguer anomaly contour map approximates the boundary between the Amazon craton to the north and the La Plata craton to the south (see Comin-Chiaramonti et al. 1999).

The aeromagnetic anomalies from the Misiones Province (Aerial Geophysics 1980) exhibit two types of contour patterns (fig. 3). The first is characterized by a NW-trending alignment of positive anomalies of short wavelength, with amplitudes varying from 4700 to 5100 nT. These anomalies are interpreted as successive interchanges among the primary polarities in areas of differentiated magnetization, induced by a remaining structure of deep source. The second shows nonlinear contours and wide lateral variation: these asymmetric anomalies are largely influenced by the regional distribution of the Early Cretaceous sedimentary cover overlying the crystalline basement.

Field data indicate that the linear positive anomalies of short wavelength represent faults and fractures locally intruded by magmatic alkaline bodies. Coincident with the aeromagnetic positive anomaly, prominent gravimetric negative anomalies are also registered in the San Ignacio region (fig. 4), contrasting with a positive anomaly in the San Juan Bautista area. The Bouguer anomalies (Photo Gravity 1991) picture NW-trending elliptical forms, where laterally the gradients vary abruptly, reaching zero in the center. These anomalies are interpreted as areas of important subsidence filled by low-density materials or, alternatively, as multiple faulting zones (Swain 1992; Comin-Chiaramonti et al. 1999). It is important to note that the negative anomalies coincide with the sedimentary rocks of the Misiones Formation and, in part, with the faults that controlled the alkaline intrusions of Cerro Caá Jhovy and Cerro Guayacán. A circular anomaly is also clearly seen in the Asunción region and has been interpreted as the result of tectonic subsidence (Riccomini et al. 2001), given the strong amplitudes of low gradient (about up to −25 mGal). Finally, it should be stressed that the sodic alkaline magmatism from the Misiones Province occurs between the San Ignacio trough and the San Juan Bautista high, in a similar fashion as the Asunción analog is displaced between the Asunción trough and the Pilcomayo high (fig. 4).

Classification and Nomenclature

The classification of the Misiones rock types was made on petrochemical basis (for the analytical techniques, see the appendix, available in the online edition or from the *Journal of Geology* office), and the adopted nomenclature follows the R_1-R_2 diagram of De La Roche (1986; fig. 5), as in most previous articles on the Paraná basin (e.g., Piccirillo and Melfi 1988; Comin-Chiaramonti and Gomes 1996, 2005; Comin-Chiaramonti et al. 1997, 1999). The chemical results, considered representative of the sodic alkaline rocks (Estancia Guavirá-y, plug; Estancia Ramirez, dikes; Cerro Guayacán, plug; Cerro Caá Jhovy, plug; see figs. 2, 3) are given in tables A1 and A3; all tables are available in the online edition or from the *Journal of Geology* office.

Petrography

Estancia Guavirá-y. Rock types range from ankaratrites to melanephelinites with mg# (mg# = $Mg/[Mg + Fe^{2+}]$, assuming $Fe_2O_3/FeO = 0.20$) between 0.60 and 0.65. The textures are typically porphyritic, with clinopyroxene and olivine pheno- and/or microphenocrysts set in a hypocrystalline groundmass made up of glass, clinopyroxene, olivine, opaques, and foids. Clinopyroxene displays compositions ranging from phenocrysts, $Wo_{50}En_{44}Fs_6$ (mg# of 0.87), to microphenocrysts and groundmass, $Wo_{50}En_{41}Fs_9$-$Wo_{50}En_{39}Fs_{10}$ (mg# of

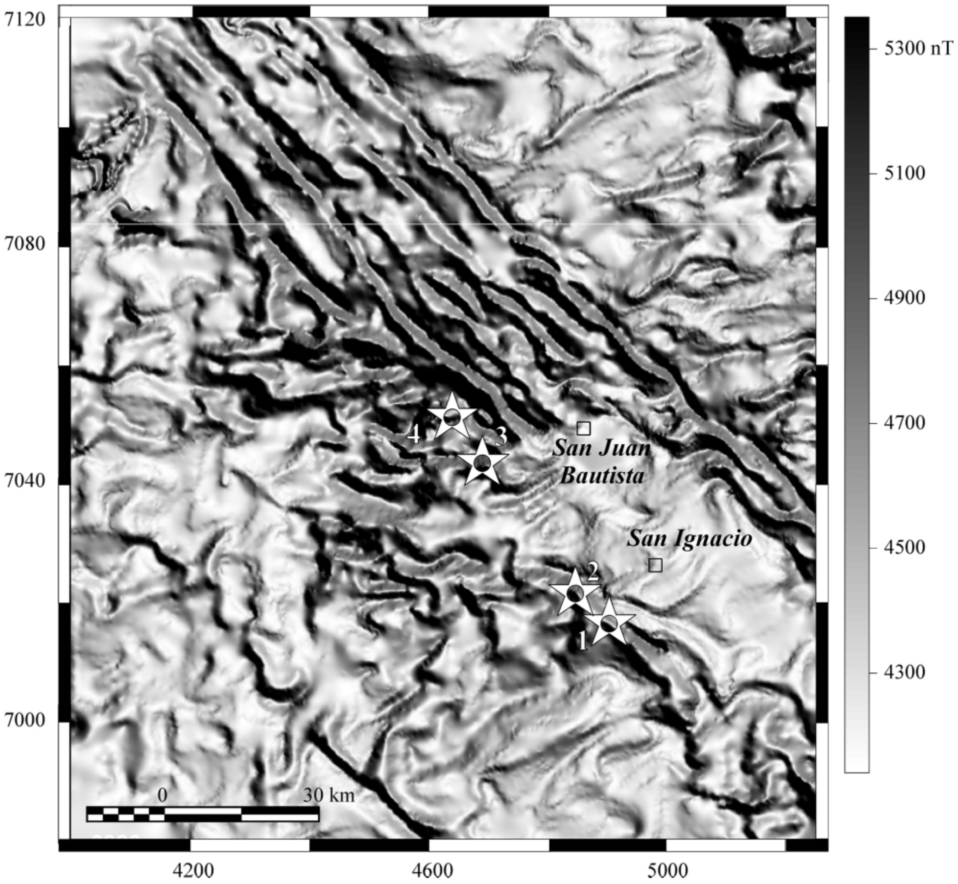

Figure 3. Aeromagnetic map encompassing the Misiones Province and surrounding area (Aerial Geophysics 1980; nT = nanotesla) and showing the sodic alkaline occurrences. *1*, Estancia Guavirá-y; *2*, Estancia Ramirez; *3*, Cerro Caá Jhovy; *4*, Cerro Guayacán.

0.82–0.80). Olivine has an mg# of 0.83–0.80 in pheno- and/or microphenocrysts (in equilibrium with a liquidus having an mg# of 0.62–0.57, roughly corresponding to the mg# of the host rock), and some core compositions have a higher mg# (up to 0.93); olivine microlites show an mg# around 0.78. Opaques are Ti-magnetite, 64 mole% ulvöspinel, sometimes with Cr-spinel core. Foids are nepheline with a kaliophilite (Kp) component of up to 18 wt% (Comin-Chiaramonti et al. 1992).

It should be noted that olivines from the Asunción ankaratrites-nephelinites have an mg# of 0.89–0.85 (phenocrysts), 0.82–0.77 (microphenocrysts), or 0.76–0.74 (groundmass). Opaques are Ti-magnetite, 64 mole% ulvöspinel, and foids are nepheline with a Kp component of 17–20 wt% (Comin-Chiaramonti et al. 1991).

Clinopyroxene and orthopyroxene megacrysts (a few millimeters to 10 cm across, mg# of 0.93) are widespread and occur in close association with dunitic mantle xenoliths and xenocrystic debris (see Comin-Chiaramonti et al. 1992, 2001); megacrysts and debris have the same crystallographic characteristics as the mineral phases of the associated xenoliths (Comin-Chiaramonti et al. 1992, 2001). Equilibration temperatures and pressures (calculated according to Mercier 1980; Nimis 1995; Nimis and Taylor 2000) of these spinel peridotite xenoliths (similar to the Asunción analogs; see Comin-Chiaramonti et al. 1991, 2001) vary between 944° and 1051°C and between 14 and 22 kbar, respectively. In addition, the isotopic temperatures ($\delta^{18}O$), calculated according to Kyser et al. (1981), are around 970°–1070°C (Comin-Chiaramonti et al. 2001). It should be stressed here that, according to the Comin-Chiaramonti et al. (1991) model, assuming a diameter of 45 cm, representing the size of the largest xenoliths, a density of 3.3 g cm^{-3} and a depth of about 70 km (roughly corresponding to the garnet-spinel transition facies), the transport of the xenoliths to the surface (calculated following Spera 1984) occurred in less than 10 h, testifying to the

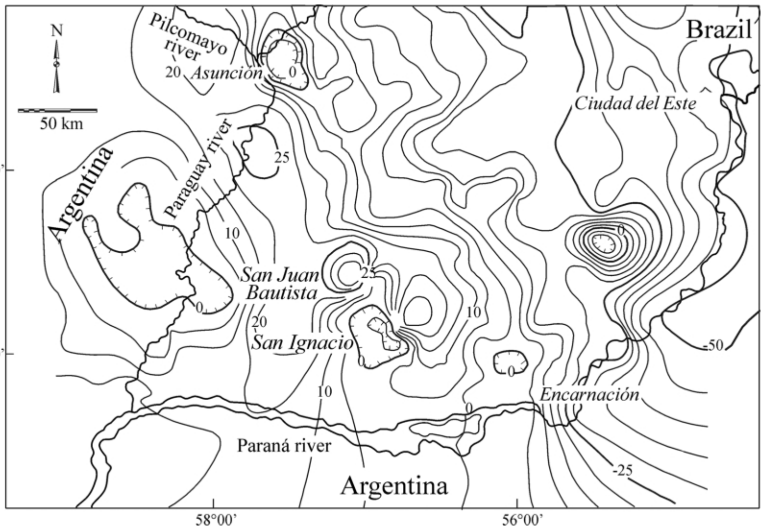

Figure 4. Bouguer gravity map for southeastern Paraguay (gravity contour, 5 mGal; reduction density, 2.67 g cm^{-3}; data source: Photo Gravity 1991; see Comin-Chiaramonti et al. 1999).

high energy of ascending magma, the strong decompressional environment, and a volatile-rich propellent.

Estancia Ramirez. The rock types are mainly tephrites (mg# of 0.52–0.50) and nephelinites (mg# of 0.51–0.48). Texture is microporphyritic, with clinopyroxene ($Wo_{53}En_{40}Fs_7$; mg# of 0.85), olivine (mg# of 0.74), and Ti-magnetite (60 mole% ulvöspinel) microphenocrysts set in a hypohyaline groundmass characterized by microlites of olivine (mg# of 0.70),

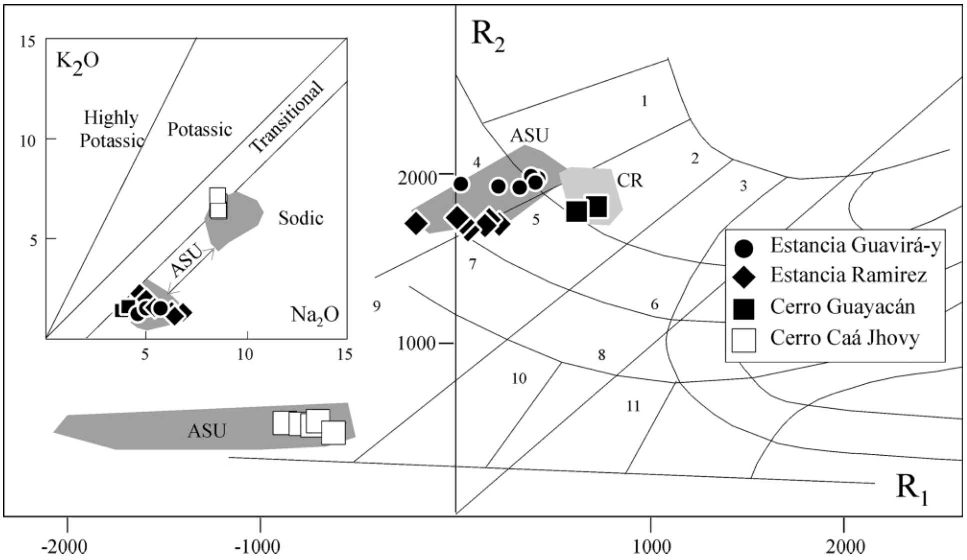

Figure 5. Compositional variation for the Misiones rocks in terms of De La Roche's (1986) diagram; $R_1 = 4Si - 11(Na + K) - 2(Fe + Ti)$, $R_2 = 6Ca + 2Mg + Al$. Numbers correspond to the fields of De La Roche's nomenclature: *1*, ankaratrite; *2*, basanite; *3*, alkali basalt; *4*, nephelinite; *5*, tephrite; *6*, trachybasalt; *7*, phonotephrite; *8*, trachyandesite; *9*, phonolite; *10*, trachyphonolite; *11*, trachyte. Shown for comparison are Na-mafic rock types carrying spinel-lherzolite xenoliths from the Asunción region (ASU) and the Argentina Central Rift (CR), northwestern Argentina, lat ~26°W, age ~90 Ma (data sources: Comin-Chiaramonti et al. 1991; Comin-Chiaramonti and Gomes 1996; Lucassen et al. 2002). *Inset*, Na_2O versus K_2O (wt%) diagram (see Comin-Chiaramonti and Gomes 1996).

opaques (58 mole% ulvöspinel), and foids (nepheline, Kp component of about 12 wt%).

Cerro Guayacán. The rocks are basanites with relatively constant compositions (mg# of 0.61), with olivine (mg# of 0.84), clinopyroxene ($Wo_{48}En_{44}Fs_8$; mg# of 0.85), and Mg-biotite phenocrysts set in a holocrystalline groundmass made up of clinopyroxene ($Wo_{46}En_{43}Fs_{11}$; mg# of 0.80), olivine (mg# of 0.80–0.78), zoned plagioclase (An_{80-60}), Ti-magnetite, biotite, and nepheline.

Cerro Caá Jhovy. The plug is made of peralkaline phonolites that have a porphyritic texture with alkali feldspar phenocrysts ($Or_{44}Ab_{55}$) and Ti-magnetite microphenocrysts (71 mole% ulvöspinel) set in a glassy matrix containing clinopyroxene (10 mole% of acmitic component) and alkali feldspar microlites.

Geochemistry

Major elements and CIPW norms (table A1) show the general undersaturated character of the alkaline rocks from the Misiones Province, i.e., normative nepheline ranging from 13% to 27% and leucite up to 8.4% in the ankaratrite-melanephelinite from Estancia Guavirá-y. The Na_2O/K_2O ratios range between 2.2 and 5.5 in the mafic rocks and between 1.2 and 1.3 in the felsic variants and plot in the main range of the Na-alkaline rocks from the Asunción Province (see fig. 5). The variation diagrams, assuming MgO as differentiation index, display trends that are consistent with fractional crystallization (table A1; fig. 6). However, mass balance calculations, from less to more evolved rock types, in general give unrealistic results (i.e., both removal and addition of phases) or results with ΣR^2 (sum of the squares of the residual) $\gg 1$. The best result was obtained assuming sample 557 from Estancia Guavirá-y as a parent liquid (mg# of 0.63, Cr and Ni at 301 and 125 ppm, respectively) and the nephelinite SI-2 from Estancia Ramirez (mg# of 0.51, Cr and Ni at 34 and 36 ppm, respectively) as a derivative magma. In this case, mass balance calculations (major elements) require separation of olivine, clinopyroxene, nepheline, Ti-magnetite, and apatite (6, 27, 17, 6 and 1 wt%, respectively; $\Sigma R^2 = 0.12$). On the other hand, for the incompatible trace elements, calculated/observed ratios (using the partition coefficients according to Bristow 1984) display random ranges between 1.0 and 7.7 (table A2). Thus, the geochemical evidence points to the existence of independent parental magmas or to other processes, such as crustal contamination or assimilation and fractional crystallization (AFC; see below).

Comparison with the Asunción Province (ASU) shows that the ASU sodic mafic rock types are characterized, for the same MgO content, by higher SiO_2, P_2O_5, Cr, Ni, and Nb; the felsic variants display higher Sr and Ba and early K_2O (fig. 6). Notably, the sodic rock types from other rift structures, i.e., the Cretaceous Central Rift of NW Argentina (~90 Ma; Lucassen et al. 2002) and even the central Andes Ayopaya alkaline-carbonatite complex (Bolivia, 98–101 Ma; Schultz et al. 2004), are chemically similar to the Misiones and ASU Na-alkaline rock types (fig. 6).

The Misiones incompatible elements, normalized to the primitive mantle (fig. 7*A*), have a systematic Ta-Nb-La-Ce positive bump in the mafic rock types and patterns overlapping those of the Na-mafic analogs from the ASU. It should also be stressed that the Misiones mafic rocks, in spite of their sodic affinity and geological environment, also overlap the patterns of the Tristan da Cunha and Trindade basanites (fig. 7*B*) and even the patterns of the Argentina Central Rift and Ayopaya (Bolivia) analogs (fig. 7*C*). The peralkaline phonolites from Cerro Caá Jhovy show negative spikes for Ba, Sr, P, and Ti and positive ones for Th-U-K, La, Ta-Nb, and Hf-Zr (fig. 7*D*), similar to the Paleocene ASU felsic analogs. All the mafic specimens are similarly enriched in rare earth elements (REEs; fig. 7*E*) and exhibit subparallel light REE (LREE) and heavy REE (HREE) trends (La/Sm_C 3.6–4.2; Tb/Lu_C 1.9–2.7), similar to those in rocks from the ASU, the Argentina Central Rift, and Ayopaya (fig. 7*E*, 7*F*). The felsic rocks show U-shaped patterns with a very steep LREE to intermediate REE profile (La/Sm_C 24.4) and HREE enrichment ($Tb/Lu_C = 0.62$). The Eu/Eu* negative anomaly is significant only in the peralkaline phonolites.

Considering the geodynamic indicators (e.g., Pearce 1983; Beccaluva et al. 1991), such as Nb/Zr versus Th/Zr and Ta/Yb versus Th/Yb (fig. 8), the Misiones and ASU sodic rocks fall in the basalt array from nonsubduction settings, i.e., MORB+WPB (mid-ocean ridge basalt plus within-plate basalt; see Comin-Chiaramonti et al. 1997), along with the data from volcanic rocks of the Argentina Central Rift and Bolivian Ayopaya complexes. 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 (see Comin-Chiaramonti et al. 1999).

Sr-Nd Isotopes. Selected Sr and Nd isotopic compositions of representative samples from Cretaceous to Paleocene magmatic rocks and of the basement from Eastern Paraguay are given in table A3.

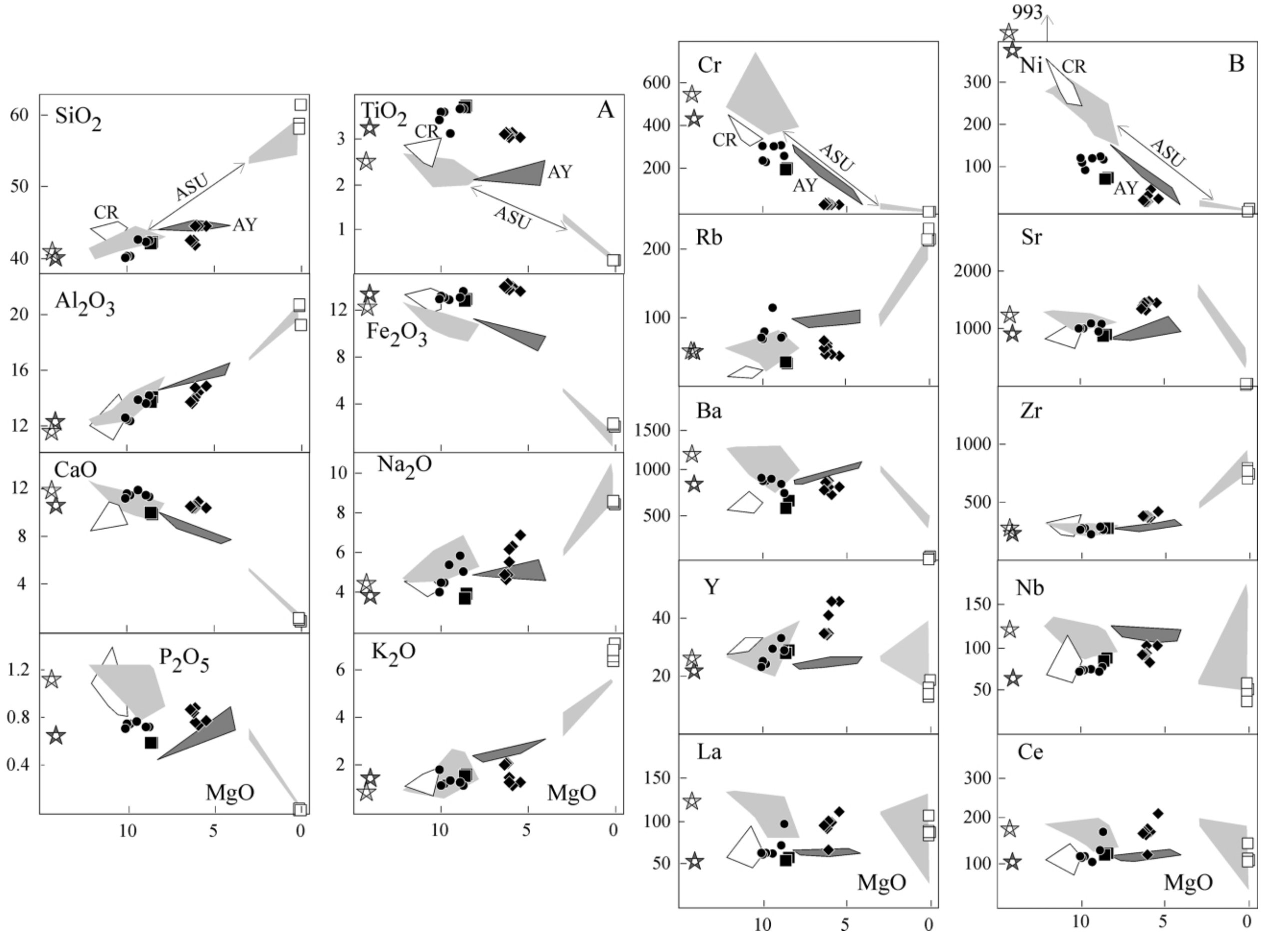

Figure 6. Variation diagrams, assuming MgO (wt%) as the differentiation index, for major (wt%) and trace elements (ppm; *A* and *B*, respectively) for the rock types from the Misiones Province. Symbols are as in figure 5; stars indicate calculated sources (see table A4). *Light gray field*, compositional variation of the Na-alkaline rocks from Asunción Province (data sources: Comin-Chiaramonti et al. 1991; Comin-Chiaramonti and Gomes 1996). Additional fields reported for comparison are (*CR*) the Argentina Central Rift (Lucassen et al. 2002) and (*AY*) sodic mafic and intermediate rock types from Bolivian alkaline-carbonatite complex of Ayopaya (101–98 Ma; Schultz et al. 2004).

The time-integrated isotope ratios for the Misiones volcanics (118.5 Ma) display two main groups: Estancia Guavirá-y–Cerro Guayacán, initial $^{87}Sr/^{86}Sr$ (Sr_i) = 0.70430–0.70473 and initial $^{143}Nd/^{144}Nd$ (Nd_i) = 0.51242, and Estancia Ramirez-Cerro Caá Jhovy, Sr_i = 0.70517–0.70523 and Nd_i = 0.51226–0.51206. On the other hand, the time-integrated isotope ratios for Asunción rock types (60 Ma) have Sr_i = 0.70367 ± 0.00011 and Nd_i = 0.51269 ± 0.00005.

Because of the high Sr and Nd contents of the mafic alkaline rocks, it is reasonable to assume that Sr-Nd isotope compositions have not been significantly affected by crustal contamination (see below). Therefore, Sr_i and Nd_i compositions of the rock types from Estancia Guavirá-y–Cerro Guyacán (and ASU Na-alkaline rocks) may be considered pristine and, as a result, representative of the isotopic composition of their mantle source (see Comin-Chiaramonti et al. 1997). The Sr-Nd isotopic variations (fig. 9) may be explained (1) by distinct portions of a large- and small-scale heterogeneous lithospheric mantle source, where the small-scale heterogeneity is required for the variations in the Sr_i and Nd_i ratios for each magmatic event, or (2) in terms of mixing by involving an enriched-mantle component with a potassic alkaline isotopic signature (extreme enriched-mantle isotopic [EM I] composition for subcontinental lithospheric mantle?) and depleted-mantle component(s) like depleted MORB mantle (DMM) and/or high-μ (HIMU). The latter component appears to be

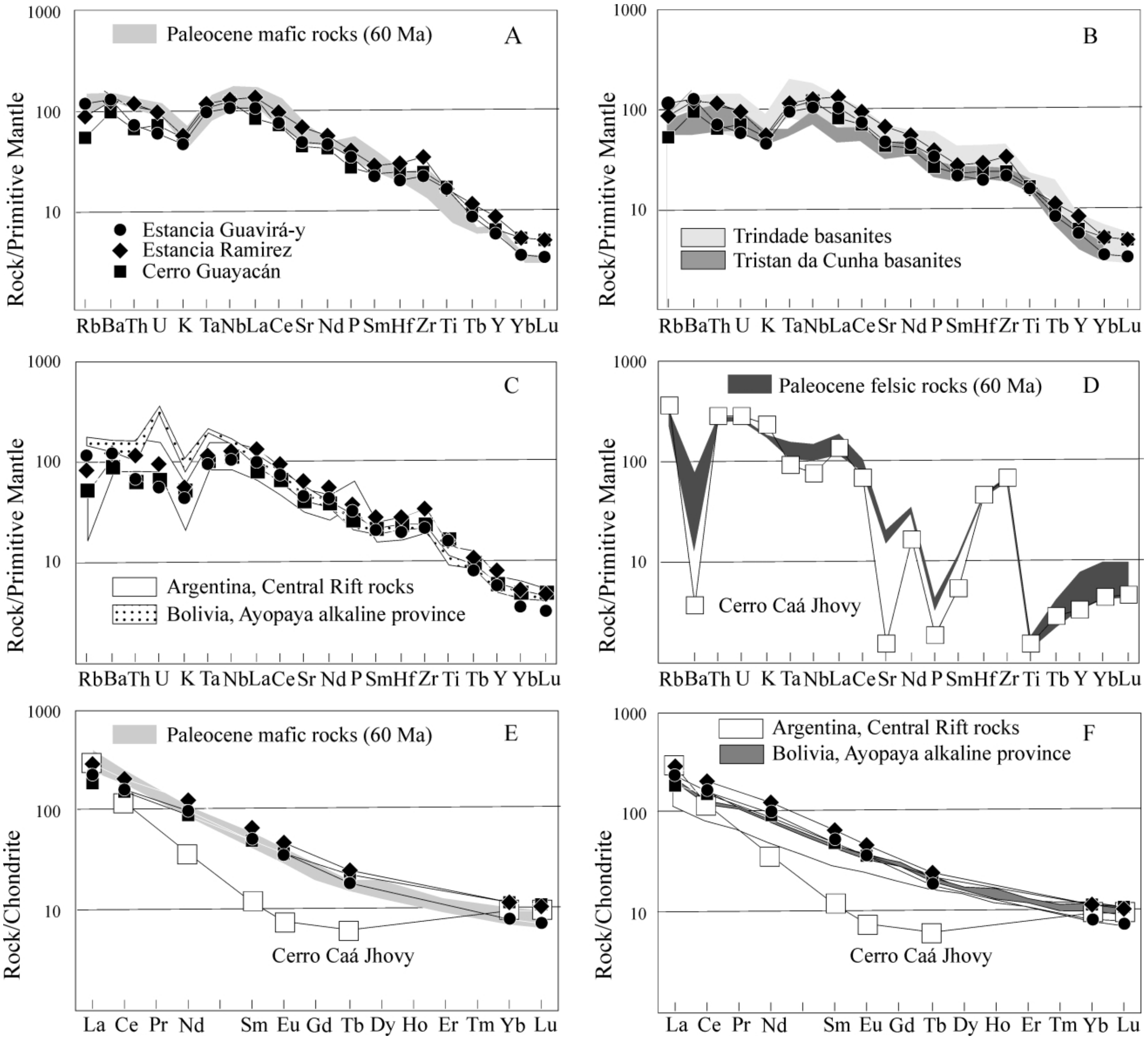

Figure 7. *A*, *B*, Incompatible elements normalized to the primitive mantle (Sun and McDonough 1989) for average compositions of the mafic alkaline rocks from the Misiones Province compared with the field of the ASU analogs (*A*) and the fields of the Tristan da Cunha and Trindade basanites (*B*). *C*, Average spidergram for the Misiones mafic rocks compared with the analogs from Argentina Central Rift and Bolivian Ayopaya complex (Lucassen et al. 2002; Schultz et al. 2004). *D*, Average multielemental diagram for the peralkaline phonolites from Cerro Caá Jhovy compared with the felsic rocks from the Asunción Province. *E*, *F*, REE, chondrite normalization (Boynton 1984). Data sources: this article; Le Roex 1985; Le Roex et al. 1990; Comin-Chiaramonti et al. 1991; Comin-Chiaramonti and Gomes 1996; Le Roex and Lanyon 1998; Marques et al. 1999*b*; and Siebel et al. 2000.

important in the Argentina Central Rift (Lucassen et al. 2002) and even in the Ayopaya alkaline-carbonatite complex in the Bolivian central Andes, the petrologically most exotic expression of large-scale Mesozoic rifting along the western South American continent (Schultz et al. 2004). It is inferred (fig. 9) that depleted-mantle domain(s) progressively played a major role in the genesis of alkaline magmatism in Eastern Paraguay from late Early Cretaceous up to Paleocene times (Comin-Chiaramonti et al. 1999). Notably, the Sr_i and Nd_i of the "uncontaminated" tholeiites (both high- and low-Ti) appear intermediate between the values for potassic and sodic rocks.

Nd Model Ages. Studies of the initial $^{143}Nd/^{144}Nd$ ratios from Precambrian terrains suggest that the

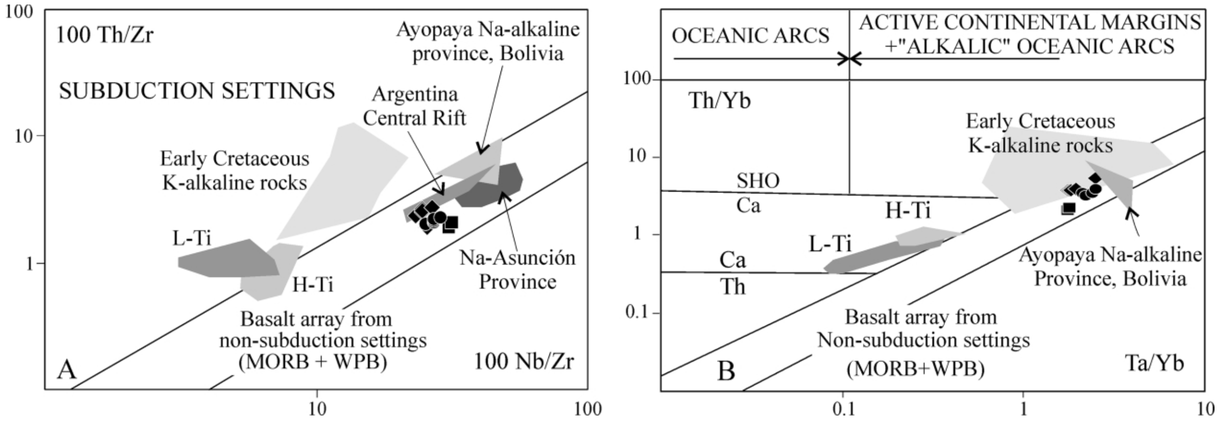

Figure 8. Tectonic characterization using 100Th/Zr versus 100Nb/Zr (Beccaluva et al. 1991; *left*) and Th/Yb versus Ta/Yb ratios (Pearce 1983; *right*). Symbols and data sources are as in figure 7.

mantle that supplied continental crust (as in the Paraná-Angola-Namibia system; see Comin-Chiaramonti et al. 1999) has evolved since earliest time with Sm/Nd ratios greater than that of the chondritic uniform reservoir (CHUR; see DePaolo 1981; Faure 1986). For this reason, model ages for the continental crust are usually calculated with reference to the depleted-mantle reservoir (DM: $^{143}Nd/^{144}Nd = 0.513151$, $^{147}Sm/^{144}Nd = 0.2188$; Faure 1986) rather than the CHUR. The isotopic and/or temporal overlapping of different igneous rocks (i.e., high- and low-Ti tholeiites, K- and Na-alkaline rocks and carbonatites) cannot be accidental and points to sampling of ancient reservoirs formed at the same time from the same subcontinental upper mantle (SCUM). Whatever the implication, i.e., heterogeneity induced by recycled crust in the mantle (Menzies 1990; Weaver 1991), occurrence of variably veined material in the SCUM (Meen et al. 1989), or both, it is clear that magma genesis involved ancient lithospheric mantle reset at well-defined isotopic ranges.

Although the Nd model ages (depleted mantle, T^{DM}; see DePaolo 1981) have little real meaning because they do not reflect exactly the ages of the sources, being a function of the Sm/Nd fractionation (f) during the melting and magma differentiation (see Arndt and Goldstein 1987), the Paraguay rock types may be roughly monitored by the T^{DM} for an estimate of the time when a main "metasomatic" event may have occurred, or, rather, a record of an average series of events.

The T^{DM} relative to the pretholeiitic K-alkaline rocks display two main peaks, at 1.1 Ga ($f \approx -0.5$; Valle-mí, Apa Block) and 1.6 Ga ($f \approx -0.7$; Amambay), similar to those of the associated carbonatites. The post-tholeiitic K-alkaline complexes and dikes from ASU ($f \approx -0.4$ to -0.5) show a mean T^{DM} of 1.7 Ga (Comin-Chiaramonti et al. 1995). The high-Ti tholeiitic basalts have T^{DM} ranging from 0.9 to 1.4 Ga ($f \approx -0.3$ to -0.4). On the other hand, the low-Ti tholeiites display model ages ranging from 0.7 to 2.8 Ga ($f \approx -0.5$), with model ages increasing from north to south and from west to east. The sodic rocks display mean T^{DM} values of 0.6 (Na-ASU) and 1.0 Ga (Misiones), for $f \approx -0.4$ to -0.5. The youngest ASU model ages are similar to those shown by the Argentina Central Rift rocks and rocks from the Bolivian Ayopaya complex (0.5 Ga), corresponding to the ages of the Brasiliano cycle in southern Paraguay (see Kanzler 1987).

These model ages indicate that some notional distinct series of metasomatic events may have occurred during Paleoproterozoic to Neoproterozoic times (1.8–0.6 Ga) as a precursor to the alkaline and tholeiitic magmas in Eastern Paraguay (see Comin-Chiaramonti et al. 1995, 1997, 1999), and they are also supported by the plumbotectonic model of Hawkesworth et al. (1986) for the Paraná tholeiites and by Re-Os systematics for the Alto Paranaíba kamafugites (Carlson et al. 1996; Araújo et al. 2001). This conclusion is distinct from the proposal by Gastal et al. (2005), who suggest that the major events of metasomatism in the region took place mainly during the Neoarchean-Paleoproterozoic.

Lead Isotopes. Pb isotopes are believed to discriminate between DMM and HIMU components (see "Mantle components" review of Bell and Tilton [2001]). For this purpose, lead isotopic compositions have been calculated on four selected late Early Cretaceous and Paleocene rocks from southeastern Paraguay (table A4) and compared with the

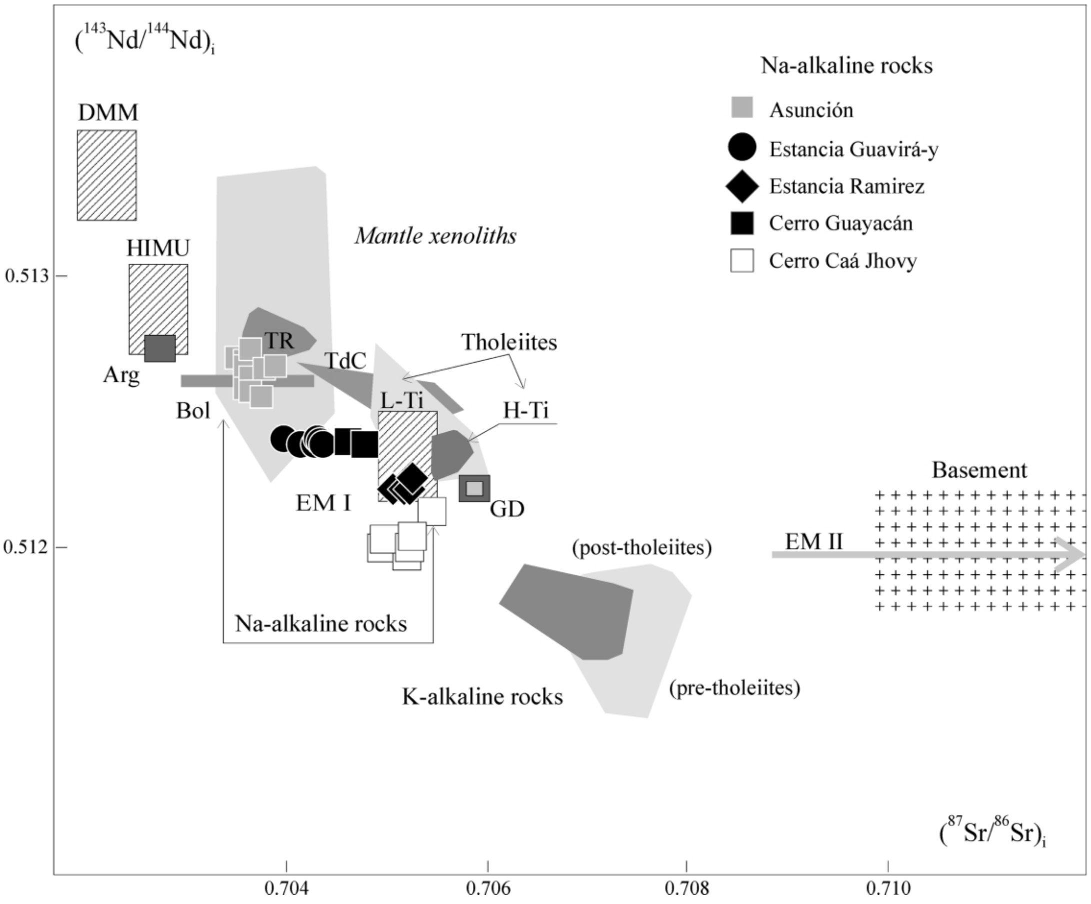

Figure 9. Initial ^{87}Sr/^{86}Sr (Sr$_i$) versus ^{143}Nd/^{144}Nd (Nd$_i$) diagram for the late Early Cretaceous and Paleocene magmatic rocks from Eastern Paraguay. The carbonatites from Eastern Paraguay plot in the same fields as the K-alkaline rock types (see Comin-Chiaramonti et al. 1999). GD = glassy drop isotopic composition from clinopyroxenes of the Ñemby mantle xenoliths. Argentina Central Rift (*Arg*) and the Bolivian Ayopaya complex (*Bol*) are shown for comparison. Data sources and symbols are as in figure 7 and Comin-Chiaramonti et al. (1997, 2001). DMM, HIMU, EM I, and EM II fields after Zindler and Hart (1986) and Hart and Zindler (1989).

whole magmatism from Eastern Paraguay, following Antonini et al. (2005).

The initial Pb isotope compositions of both pre- and post-tholeiitic K-magmatism for the most "primitive" rock types show ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb of 16.888–17.702, 15.433–15.620, and 37.156–37.915, respectively. The initial lead isotope ratios of the tholeiitic Paraguayan rocks generally agree with those of the Brazilian equivalents reported by Marques et al. (1999*a*); the Paleozoic basement rocks (Brasiliano cycle; ~500 Ma; see table A3 of Antonini et al. 2005) overlap the field of the Eastern Paraguay tholeiites, so the latter might partly reflect interaction with crustal material. The sodic alkaline rocks (Misiones and ASU) have different Pb isotopic compositions and differ from the potassic rock types: the Cretaceous potassic rock types are characterized by initial Pb compositions (^{206}Pb/^{204}Pb = 18.211, ^{207}Pb/^{204}Pb = 15.628, and ^{208}Pb/^{204}Pb = 37.963) approaching those of the Cretaceous low-Ti tholeiites of southern Paraná (see Marques et al. 1999*a*), whereas the Paleocene sodic rock types (^{206}Pb/^{204}Pb = 18.964, ^{207}Pb/^{204}Pb = 15.678, ^{208}Pb/^{204}Pb = 38.484) appear shifted toward the HIMU field (fig. 10), overlapping the Argentina Central Rift equivalents.

Petrogenesis

Possible Crustal Contamination. Relatively high Sr initial isotope compositions of the rock types from Estancia Ramirez and Cerro Caá Jhovy (i.e., ≥0.705; average 0.70520 ± 0.00014), coupled with the unlikely derivation of the felsic rocks through

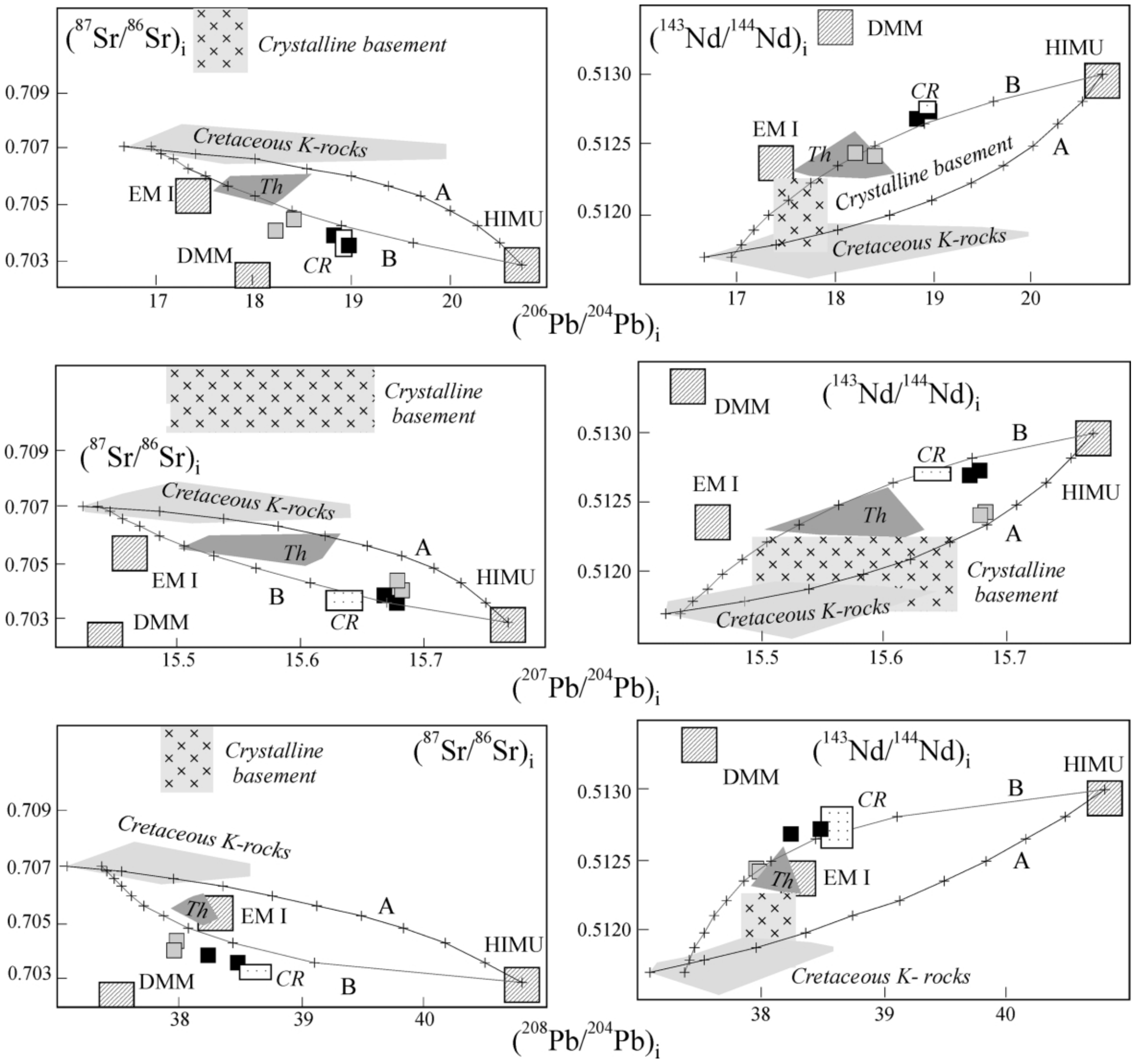

Figure 10. Isotopic mixing curves (*A*, *B*) between HIMU and potassic magmas from Early Cretaceous potassic rocks (ECK, Eastern Paraguay), computed using the following isotopic compositions: HIMU (St. Helena; Chaffey et al. 1989): $^{87}Sr/^{86}Sr = 0.70282$, Sr = 650, $^{143}Nd/^{144}Nd = 0.5130$, Nd = 40, $^{206}Pb/^{204}Pb = 20.73$, $^{207}Pb/^{204}Pb = 15.77$, $^{208}Pb/^{204}Pb = 40.80$, U = 1.44, Th = 3.88, Pb = 4, $\mu = 24.4$, $\kappa = 2.78$; ECK *A*: $^{87}Sr/^{86}Sr = 0.7070$, Sr = 1300, $^{143}Nd/^{144}Nd = 0.5117$, Nd = 60, $^{206}Pb/^{204}Pb = 16.672$, $^{207}Pb/^{204}Pb = 15.422$, $^{208}Pb/^{204}Pb = 37.10$, U = 1.47, Th = 6.38, Pb = 2, $\mu = 23.09$, $\kappa = 4.80$; ECK *B*: $^{87}Sr/^{86}Sr = 0.7070$, Sr = 1300, $^{143}Nd/^{144}Nd = 0.5117$, Nd = 60, $^{206}Pb/^{204}Pb = 16.945$, $^{207}Pb/^{204}Pb = 15.434$, $^{208}Pb/^{204}Pb = 37.369$, U = 2.40, Th = 9.10, Pb = 15, $\mu = 9.8$, $\kappa = 3.8$. Black and gray squares are for Estancia Guavirá-y and Asunción Na-mafic rocks, respectively. Crosses on curves represent 10% steps of mixing. DMM, HIMU, and EM I components after Hart and Zindler (1989). Crossed areas represent the crystalline basement at 119 Ma (see Antonini et al. 2005); dotted areas (*CR*) represent the Argentina Central Rift, after Lucassen et al. (2002).

a simple fractionation process, point to a possible mixing with crustal components or to AFC processes (DePaolo 1981). The data suggest that at least two sources were involved in the production of the Misiones magmas: one characterized by mantle isotopic ratios (i.e., $Sr_i < 0.705$) and the other with crustal geochemical signatures, i.e., high in radiogenic Sr. In this frame, the mafic samples may represent the result of contamination or mixing processes between mantle-derived magmas and crustal materials (e.g., HIMU and EM I or K-ASU types, respectively). Simple mixing calculations (fig. 11*A*) show that the Estancia Ramirez samples may represent a mixing between a parent liquid represented by the Estancia Guavirá-y ankaratrites and ~8% of lower crust (i.e., amphibolites of table A3); on the other hand, the felsic rocks may represent mixing with ~30% of upper crust (meta-

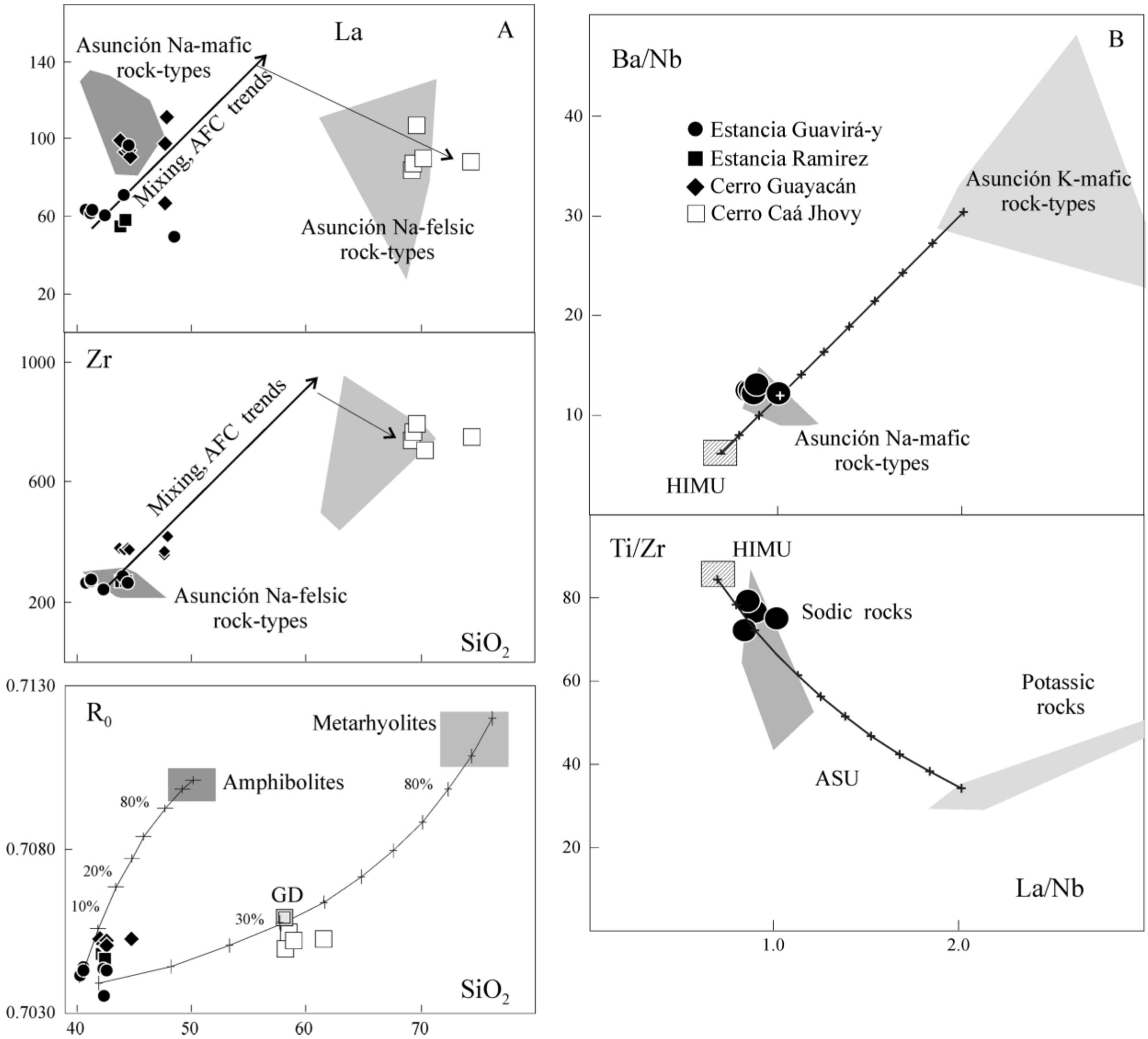

Figure 11. *A*, La, Zr, and R_i (initial $^{87}Sr/^{86}Sr$ ratio) versus SiO_2, showing the possible AFC and mixing paths for the Misiones Na-alkaline rocks. Symbols are as in figure 9; GD = glassy drop from clinopyroxenes of the mantle xenoliths from Ñemby melanephelinites. *B*, La/Nb versus Ba/Nb and Ti/Zr mixing curves between HIMU and potassic magma from ASU (Asunción-Sapucai-Villarica graben; see fig. 2). Only the samples with mg# > 0.61 (Estancia Guavirá-y) are plotted. Crosses represent 10% steps of mixing. HIMU field after Hart and Zindler (1989).

rhyolites of table A3). Moreover, the HIMU component appears dominant in the generation of the sodic magmatism. Notably, the mixing between K-ASU (which may be considered a more Sr-radiogenic extension of EM I) and HIMU-like magmas also appears to be consistent with reproduction of some critical ratios of incompatible elements (IEs) of the sodic magmatism, e.g., Na/Nb, La/Nb, and Ti/Zr (fig. 11*B*). It should be noted that, although only two Sr-Nd-Pb isotopic analyses are available for the Proterozoic basement of the southeastern Paraguay (table A3), the isotopic ratios may be considered to be in the same ranges as those of similar Precambrian rocks from the Rio de la Plata craton and even rocks from the southwestern coast of Africa (see Babinski et al. 1997; Jung et al. 2001; Iacumin et al. 2001; Teixeira et al. 2002; Saalmann et al. 2005).

Mantle Source(s). Most Misiones mafic ankaratrites are relatively evolved in comparison with expected primary compositions (e.g., mg# > 0.65, Ni > 235 ppm). Possibly primary melts (e.g., mg# ~ 0.72) in equilibrium with olivine $Fo_{89–90}$ are expected to have fractionated olivine, clinopyroxene, and Cr-spinel (sp) at or near the mantle source and certainly did so during its rise to the surface. Melting models (Comin-Chiaramonti et al. 1991, 1992, 1997) suggest that it is unlikely that the associated spinel peridotite xenoliths represent solid partial melting residua after the generation of the ASU and Misiones Na-alkaline primary magmas.

Neglecting the effects of polythermal-polybaric fractionation on the chemistry of the fractionates, we calculated crystal fractions to restore the Misiones (Estancia Guavirá-y) and ASU (see Comin-Chiaramonti et al. 1997) parental compositions to possible near-primary melts in equilibrium with their sources (table A5; the mg# of these calculated parent magmas is 0.72–0.73). Mass balance calculations, starting from peridotites with different proportions of garnet and/or phlogopite (Erlank et al. 1987; whole-rock and mineral compositions in table A6), indicate that the primary melt compositions can be derived from relatively high melting degrees, i.e., ~5% of an anhydrous garnet peridotite or 4%–6% of a phlogopite-bearing peridotite (table A7), with phlogopite as residual phase. The calculated primary melts have high abundances in IEs and relatively high LREE/HREE ratios, requiring mantle sources that were enriched in IEs long before the melting process (see Menzies and Wass 1983), e.g., through Meso- and Neoproterozoic metasomatic events (see "Nd Model Ages").

Trace-element concentrations in the hypothetical mantle sources considered here (table A5) were calculated (batch melting) on the basis of the estimated melting degrees (table A7) and using the partition coefficients of McKenzie and O'Nions (1991), Comin-Chiaramonti and Gomes (1996), and Comin-Chiaramonti et al. (1997). The multielemental plots for the calculated mantle sources, normalized to the primitive mantle of Sun and McDonough (1989), highlight a significant enrichment of the most incompatible elements, while the least incompatible elements (mainly from Ti to Lu) would have concentrations similar to or less than those of primitive mantle (fig. 12). Notably, the patterns of the mantle sources of the Paraguayan K-alkaline rocks are characterized by negative Ta-Nb-Ti and positive Ba and Sm spikes (not shown; see Comin-Chiaramonti et al. 1997), i.e., a subduction-related signature (see fig. 8). On the other hand, the patterns of the mantle sources of both the Asunción and Misiones Na-alkaline mafic rocks are distinct in their positive Ta-Nb and Zr and negative U-Th-K and Sm spikes.

It seems, therefore, that the genesis of the Asunción sodic magmatism, coupled with tholeiitic and potassic magmatism, is dominated by small-scale heterogeneous mantle (lithospheric vs. homogenizing effects of the asthenospheric mantle), as also supported by the occurrence of spinel peridotite xenoliths from the Asunción and Misiones ankaratrites and melanephelinites (Comin-Chiaramonti et al. 1986, 1991, 1992, 2001). The more striking feature of the spinel peridotite xenoliths, mainly represented by harzburgite dunite variants, is the relative abundance of blebs and spongy clinopyroxenes; i.e., they are rich in glassy blebs and drops. The latter (up to 7.5% of the whole host clinopyroxene) show variable composition but are systematically enriched in K, Rb, Sr, Ba, and LREEs (see Demarchi et al. 1988; Comin-Chiaramonti et al. 2001). Notably, the geochemical features of the glassy blebs and drops fit those of a material rich in a phlogopite-like component (see McKenzie and O'Nions 1991: Ti = 4796 ppm and K = 78,786 ppm).

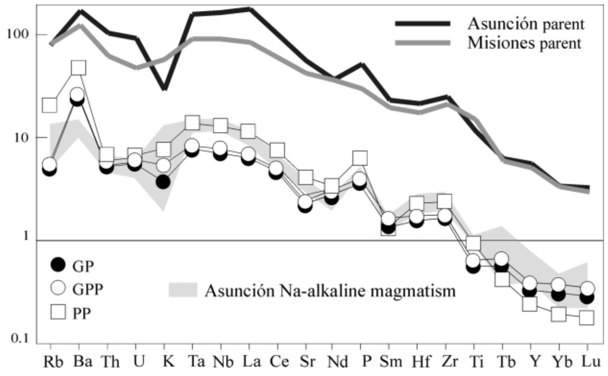

Figure 12. Calculated concentrations of incompatible elements normalized to the primitive mantle of Sun and McDonough (1989) for the mantle source of Misiones and Asunción in equilibrium with calculated parental liquids. GP = garnet peridotite, GPP = garnet-phlogopite peridotite, and PP = phlogopite peridotite of tables A6 and A7.

The metasomatic processes responsible for IE enrichment in the mantle may be attributed to fluids/melts related to subduction processes (e.g., Hergt et al. 1991; Maury et al. 1992) or to volatile-rich small-volume melts from the asthenosphere that would have veined the overlying lithospheric mantle at different depths and times (e.g., Menzies and Hawkesworth 1987; Foley 1992*a*, 1992*b*). In general, the high concentrations of the most incompatible elements in all the Eastern Paraguay alkaline rocks, including Sr-Nd isotope compositions that reflect those of lithospheric mantle sources, suggest that the effects of crustal contamination are not discernible.

It is notable that the positive Nb-Ta anomalies of the Misiones and Asunción Na-alkaline rocks (closely associated in space with the potassic analogs of the ASU showing contrary Nb-Ta negative anomalies) indicate that the IE enrichment of the lithospheric source mantle, as proposed for the genesis of the Alto Paranaíba kamafugites (Late Cretaceous; "APIP" of Gibson et al. 1995), was produced by low-temperature, small-volume asthenospheric melts. The potassic and sodic rocks from Eastern Paraguay contain primary carbonates (mean $\delta^{13}C = 7.1‰ \pm 0.8‰$, PDB-1) and are associated with carbonatites whose age ranges from 139 to 128 Ma (Comin-Chiaramonti et al. 1991, 1995, 1997, 1999, 2005). These rocks have Sr and Nd isotope ratios (i.e., $Sr_i = 0.70723–0.70784$ and $Nd_i = 0.51136–0.51183$) similar to those of the ASU potassic rocks. Therefore, CO_2 may have played some role in the IE enrichment of the lithospheric mantle, since the volatile-rich fluid/melt compositions are dependent on the CO_2/H_2O ratio (e.g., Dautria et al. 1992; Rudnik et al. 1993).

Assuming an average heat flow value of 58 mW m^{-2} for the Paraná basin (Hamza 1982) in Mesozoic-Cenozoic times and a peridotite solidus with $CO_2/(CO_2 + H_2O) = 0.8$ (Wyllie 1987), volatile fluids could be related to partially melted diapirs generated mainly at depths of less than 200 km. Thus, a wide zone of mantle metasomatism may extend itself between the lower part of the lithosphere and its solidus ledge (Wyllie 1987). The existence of primary carbonates of mantle origin in the ASU and Misiones mafic rocks (Comin-Chiaramonti and Gomes 1996) suggests a CO_2-bearing peridotite source with variable H_2O content.

Roles of Different Mantle Components in the Genesis of the Cretaceous to Paleocene Magmatism in Eastern Paraguay. The possible roles of distinct mantle components in the genesis of the Cretaceous to Paleocene magmatism and the correlations between Sr and Nd isotopes are summarized in figure 9. In general, the potassic rocks follow the trend common to the Early Cretaceous tholeiites and the sodic rocks (both Cretaceous and Paleocene). It is interesting to observe (fig. 10) that the isotopic compositions trend toward the HIMU field rather than the DMM one, particularly in the $^{207}Pb/^{204}Pb$ versus $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ diagrams, suggesting that the HIMU component played an important role in the whole Cretaceous to Paleocene magmatism of Eastern Paraguay. However, the Pb isotopic compositions of some potassic alkaline rocks (those with the highest $^{207}Pb/^{204}Pb$) trend toward the field of the basement rocks (fig. 10). Therefore, the role of crustal components cannot be totally ruled out. The isotopic heterogeneity shown by the potassic magmatism, representing extreme EM I compositions, could reflect old metasomatic events caused by small-volume melts with different U, Th, and Pb ratios. Alternatively, the observed trends can be modeled by mixing process between the K-ASU magmas (as defined by Comin-Chiaramonti et al. 1997) with the lowest initial $^{206}Pb/^{204}Pb$ ratios and St. Helena HIMU magma types.

The calculated patterns show that (1) 10%–30% of the St. Helena magma (HIMU end-member) is consistent with the isotopic heterogeneity observed in the potassic magmatism and (2) the HIMU component appears dominant in the generation of the sodic magmatism. Notably, the proposed isotopic mixing model between K-ASU and HIMU-like magmas also appears to be consistent with reproduction of some critical IE ratios of the sodic magmatism, e.g., Ba/Nb, La/Nb, and Ti/Zr (fig. 11*B*).

Geodynamic Implications and Concluding Remarks

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

Moreover, considering that the lithosphere has a typical time constant of about 60 Ma (see Gallagher and Brown 1997) for dissipating heat and consequently attenuating topography, it is quite improbable that the heat of a plume that reached the base of the lithosphere more than 130 Ma ago could still persist. As matter of fact, no geodesic anomaly or surface expression of the TdC thermal anomaly is recognized in this region (for a discussion, see Molina and Ussami 1999; Ernesto et al. 2002). Schimmel et al. (2003) argued that in South America, all areas with Late Cretaceous postrift alkaline intrusions are characterized by low velocities of seismic waves at lithospheric depths. If this is valid, the Late Cretaceous alkaline intrusions may be extended up to the Apoyaya complex (northwestern Bolivia; Schultz et al. 2004) through Goiás and Mato Grosso states (Brazil; Gibson et al. 1995; Sousa et al. 2005) and southeastern Bolivia (Comin-Chiaramonti et al. 2005), a lineament corresponding to the 125° azimuth of Bardet (1977) but in contrast with the geophysical evidence. Some alternative hypotheses are necessary to explain the 139–60 Ma magmatism at the longitudes of Eastern Paraguay.

Fashionable View (Magma Geochemistry and Tectonic Settings). Considering the whole magmatism from the Eastern Paraguay and following the popular view on the geochemical-geodynamic markers (e.g., Pearce 1983; Beccaluva et al. 1991) and on the mantle plume concepts (Morgan 1971, 1972; Gibson et al. 1999; Lustrino et al. 2005), it would follow that (1) the Paraguayan tholeiitic and potassic magmatism would be related to subduction processes (arc tholeiites and shoshonites, respectively; see fig. 8), whereas the sodic magmatism would be related to extensional regimes (MORB or WPBs), and (2) the close similarity of the geochemical patterns and isotopic characteristics of the sodic magmatism with the TdC and Trindade (TR) magmatism would also suggest some links to TdC and TR plumes (mantle channels of Gibson et al. 1999). Alternatively, the Asunción sodic magmatism (60 Ma) being located 180 km NNW from the Misiones analog (119 Ma), in terms of the classic mantle plume–hot spot model, the two occurrences would be related to a SSE drift of the Paraguayan block over the tail of a new, unknown, mantle plume. Unfortunately, this drift would correspond to a change in the South America movement at about 80 Ma, whereas a N-S displacement is instead apparent at that time (Le Pichon and Hayes 1971).

Factual View (Geological and Geophysical Evidence). Geological and geophysical data indicate that the Mesozoic-Cenozoic block-faulting tectonics in Eastern Paraguay is extensional and responsible for NW-trending grabens, fault systems, and fault-controlled basins (Velázquez et al. 1998; Comin-Chiaramonti et al. 1999). Moreover, the region is actually characterized by a high-velocity upper-mantle lid (S-wave velocity of 4.7 km at a depth of least 200 km; Snoke and James 1997). This extensional tectonics, reflecting old basement faults, controlled magma emplacement in Eastern Paraguay and even in the whole area of the eastern Paraná basin (fig. 1). In particular, the Misiones Province, located in the Santa Rosa graben, is an example of late Early Cretaceous intraplate alkaline magmatism, at the central westernmost side of the Paraná basin. Geological, geophysical, and geochemical data suggest a very fast magma ascent along deep faulting zones.

The so-called geochemical signature of the Early Cretaceous potassic magmatism in the whole Paraná basin is clearly related to extensional tectonics, suggesting that it represents a primary source characteristic. This mantle signature may be related to metasomatic processes that variably affected the source mantle in Meso- and Neoproterozoic times (Comin-Chiaramonti et al. 1997, 1999). Model ages relate Early and Late Cretaceous alkaline rocks that are generally characterized by a Ta-Nb positive anomaly, independently of their sodic or potassic character. This indicates that the Meso- and Neoproterozoic metasomatic events were chemically distinct. In this picture, the alkaline magmatism is linked to the lithosphere partial melting driven by deep transtensional regimes caused by different velocity vectors of various South American subblocks (fig. 1), as exemplified, for instance, by deep lithospheric faults in the Asunción rift (Riccomini et al. 2001).

Finally, it should be stressed that the continental rift systems, mainly N-S trending, developed on the Paleozoic crust at the Salta longitude (late Early Cretaceous–Paleogene; Argentina Central Rift of Lucassen et al. 2002, 2005) mark the western limit of the Chaco-Pantanal system. The latter represents an intercontinental basin probably due to the Paleozoic basement reactivation in a sub-Andean flexural bulge (Ussami et al. 1999), delimited to the east by the ~N-S Paraguay river lineament that corresponds to the western border of the Atlantic domain, where the main structural lineaments have NW-SE trends (see figs. 1–3). We propose that the magma genesis and emplacement in southeastern Paraguay, and even in northwestern Argentina and Bolivia, are on the whole related to reactivation of preexisting lithospheric faults, which promoted local decompression melting of the upper mantle that was previously veined during decompression episodes associated with various extensional rifting phases.

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