Alkaline magmatism in the Paraná Basin: A comparative study. I. Geology, petrography and mineralogy

Magmatismo alcalino na Bacia do Paraná: Um estudo comparativo. I. Geologia, petrografia e mineralogia

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ABSTRACT
Over two hundred occurrences of alkaline rocks are known in different areas of Brazil, Paraguay, Bolivia and Uruguay territories. They are grouped into 16 alkaline provinces that present variable extent, composition and age and are mainly concentrated along the borders of Paraná, Bauru and Santos sedimentary basins. The geological setting for all the occurrences is discussed, with the prevailing emplacement represented by. crustal discontinuities, such as arches, rifts, lineaments, and faults. Most of these structural features correspond to old fractures that were reactivated in the Mesozoic during the Wealdenian episode. For a better characterization and correlation of the numerous occurrences, the alkaline rocks are arranged into diverse associations and compared their principal geological, petrographic and mineralogical aspects.
Keywords: Alkaline magmatism, Brazilian Platform, Paraná Basin, Alkaline province

RESUMO
Mais de duzentas ocorrências de rochas alcalinas são conhecidas em diferentes áreas do Brasil, Paraguai, Bolívia e Uruguai. Elas são agrupadas em 16 províncias que apresentam tamanho variável, composição e idade e estão concentradas principalmente ao longo das bordas das bacias do Paraná, Bauru e Santos. O condicionamento geológico de todas as ocorrências é discutido, com a colocação predominante representada por descontinuidades crustais, tais como arcos, riftes, lineamentos e falhas. Muitas dessas feições estruturais correspondem a antigas fraturas que foram reativadas no Mesozoico durante o episódio Wealdeniano. Para melhor caracterização e correlação das numerosas ocorrências, as rochas alcalinas são reunidas em diversas associações e comparados seus principais aspectos geológicos, petrográficos e mineralógicos.
Palavras-chave: Magmatismo alcalino, Plataforma Brasileira, Bacia do Paraná, Província alcalina

1 INTRODUCTION

The intracratonic Paraná Basin, which occupies approximately 1.6 × 10^6 km^2 of South America (NORTHFLEET *et al.*, 1969; PETRI; FÚLFARO, 1983), spreads mainly over Brazilian and Argentinian terrains and, to a lesser extent, Paraguayan and Uruguayan areas. The basin is situated in regions of the Brazilian Platform affected by the Brazilian Orogenic Cycle, which spanned from 1000 to 450 Ma (ALMEIDA; HASUI, 1984). According to ALMEIDA (1967), the platform encompasses Archean to Proterozoic cratonic areas surrounded by Neoproterozoic orogenic belts overlain by Phanerozoic sedimentary basins. BRITO NEVES *et al.* (1999), in turn, describe the platform basement as preserving litho-structural and tectonic records of three major orogenic collages: a middle Paleoproterozoic or Transamazonian one, a late Mesoproterozoic or early Neoproterozoic one, and a late Neoproterozoic to Cambrian one (the Brasiliano–Pan-African Orogeny). From the Late Neoproterozoic to the Early Cretaceous, the central-southeastern region of the platform was part of the Gondwana supercontinent. CORDANI *et al.* (1984) and MILANI (1997) highlighted the role of tectonic reactivations along shear zones and other discontinuities in basement rocks and cratonic boundaries, which are believed to have influenced both the origin and structural development of the Phanerozoic basins. The spatial and temporal distribution of magmatic activities is thought to have been controlled by tectonic reactivation events within the platform as well.

The curved shape of the Paraná Basin, that trends northeast with an elongated, nearly straight upward segment resembling the letter "J," is due to reactivation of older tectonic structures in the basement, which caused greater local subsidence along the NNE, NE, and NW directions (PICCIRILLO; MELFI, 1988). The most important tectonic elements are represented by surrounding positive, NW-trending elongated structures usually present as arches, except in the basin's continental margin. NW-SE magnetic lineaments also cross the main axis of the basin. The NNE and NE structures, which lie parallel to lineaments in the crystalline basement, may be related to mobile belts formed during the Brazilian Orogenic Cycle, as pointed out by the aforementioned authors. Isopach data shows that the axis of highest deposition in the basin is oriented to NE, likely controlled by the major subsidence of the crystalline basement (NORTHFLEET *et al.,* 1969; ALMEIDA, 1981).

ALMEIDA (1981) identified four evolutionary stages of the Paraná Basin, spanning from the Devonian to the Early Cretaceous. The first two stages involved deposition of marine and continental (lacustrine and fluvial) sediments in a subsiding synform basin, each corresponding to a complete tectonic-sedimentary cycle. The third stage was marked by general uplift and the onset of desert conditions, with characteristic aeolian sedimentation. The fourth stage is characterized by substantial volcanic extrusion (the Serra Geral Group), predominantly flood tholeiitic basalts with minor acidic rock types, along with significant alkaline magmatic activity that lasted up to the Paleogene. This stage is also evidenced by a major Mesozoic tectonic event, the Wealdenian reactivation (ALMEIDA, 1981), which caused the Paraná Basin to assume an antiformal geometry.

Upon revising the Mesozoic to Cenozoic alkaline magmatism that affected the southern South American Platform, ALMEIDA (1983) concluded that it could be segmented into three main stages, all related to the opening of the South Atlantic Ocean: (1) a Late Jurassic to Early Cretaceous one correlated with the rift stage in Atlantic marginal basins; (2) an Aptian to Maastrichtian or even early Paleogene one corresponding to the ocean stage (ASMUS and GUAZELLI, 1981); and (3) a Paleogene one coeval to the installation of continental taphrogenic basins in southeastern Brazil (ALMEIDA, 1976). Based on geochronological data reported by VELÁZQUEZ *et al*. (1996b) and GOMES *et al*. (1996a), RICCOMINI *et al.* (2005) confirmed these stages and suggested a fourth, older one of Middle Triassic age. Furthermore, the latter authors highlighted the division of the Early Cretaceous stage into four pulses of alkaline magmatic activity.

The westernmost fringes of the Paraná Basin are geographically marked by the Paraguay river, whose approximately N-S-oriented course separates sedimentary rocks of the Paraná Basin to the east from rocks of the Chaco Basin and the Pantanal wetland to the west (FÚLFARO, 1996). The boundary consists of an anticlinal structure established in the Early Paleozoic, the Asunción Arch (LIVIERES; QUADE, 1987). The Chaco sediments form a vast aggrading alluvial plain, primarily of continental origin, composed mainly of Paleogene to Quaternary clays and sands. The eastern limits of the Paraná Basin are not clearly defined, as their sediments are associated with and overlain by rocks from different formations. However, successive periods of erosion, including the present one, have reduced the basin's original sedimentation area (RICCOMINI *et al*., 2005).

The present study reviews the occurrence and distribution of alkaline rocks in the Paraná Basin and, to a lesser extent, in its Bauru and Santos counterparts, to better define and characterize its various alkaline provinces. A subsequent report will examine age and geochemical composition aspects of these magmatic events.

2 GEOGRAPHIC DISTRIBUTION OF THE ALKALINE MAGMATISM

More than 200 bodies of alkaline rocks of varied sizes and ages are known to occur in the western, southern, northern, and central-eastern parts of the Paraná Basin, particularly near its borders (Figure 1). Numerous efforts have been made to improve their characterization and correlation by grouping occurrences based on parameters such as radiometric age, petrographic association, tectonic setting, and genetic aspects. The literature on this topic is extensive, including numerous contributions published in both Brazilian and international journals, such as those by HERZ (1977), ULBRICH and GOMES (1981), ALMEIDA (1983), RODRIGUES and LIMA (1984), WOOLLEY (1987), GOMES *et al.* (1990, 1996a, b, 2013, 2018), MORBIDELLI *et al.* (1995), VELÁZQUEZ *et al.* (1996a), COMIN-CHIARAMONTI *et al.* (1996, 2005a, b; 2007a, b), RICCOMINI *et al.* (2005), BROD *et al.* (2005), and SPEZIALE *et a*l. (2020a, b). Regarding tectonic aspects specifically, two studies are of particular interest: an earlier one by ALMEIDA (1983) and a more recent one by RICCOMINI *et al.* (2005).

As the rocks usually form clusters of similar characteristics (e.g., age, tectonic, petrography), ALMEIDA (1983) introduced the concept of an *alkaline province* to define concentrations of rock bodies of such composition. In the Paraná Basin, alkaline bodies occur either clustered, isolated, arranged parallel to eroded borders, or lying obliquely to its margins. Each assemblage consists of relatable alkaline rocks formed within a definite age interval. Furthermore, their rocks are closely associated with local or regional features, such as arches, rifts, lineaments, and fault zones. ALMEIDA (1983) identified 12 such provinces below parallel 15º, distributed over a large portion of the Brazilian Platform. The western occurrences include those of Eastern Paraguay, as well as rocks from the Velasco and Candelaria provinces in southeastern Bolivia. In the southernmost areas, occurrences include Mariscala (latter Valle Chico) in Uruguay, and Piratini in Brazil. Ponta do Morro is a unique alkaline occurrence situated in the northern portion of the Paraná Basin, related to the Rondonópolis Anteclise. The largest concentration of alkaline bodies is found in central-eastern areas of the Paraná Basin, of which are examples the Ponta Grossa Arch, Ipanema, Serra do Mar, Poços de Caldas, Alto Paranaíba, and Rio Verde-Iporá. Except for Velasco and Candelaria, which are situated in the Amazon craton, and the Serra do Mar province, which lies onshore in continental areas parallel to the western border of the Santos basin, all provinces occupy marginal areas of the intracratonic Paraná Basin.

Specifically investigating Paraguayan alkaline occurrences, VELÁZQUEZ *et al.* (1996a) reported geological evidence and age data that allow for the subdivision of ALMEIDA's (1983) Eastern Paraguay province into six units of varied ages. These units, which occur dispersed across the Paraguayan territory, are named Alto Paraguay, Rio Apa, Amambay, Central, Asunción, and Misiones provinces.

An extensive revision of the tectonic control of alkaline magmatism in areas proximal to the Paraná, Santos and Pelotas basins and in eastern Bolivia was presented by RICCOMINI *et al*. (2005) based on recent geochronological ages and geological, structural, and geophysical data. The paper emphasizes the importance of new structural lineaments as controlling and hosting alkaline rocks and suggests incorporation of the Bauru Basin within the limits of the Paraná basin as a hub for alkaline bodies along its borders. Alkaline occurrences are assembled into 15 provinces of varied ages, the designations given by ALMEIDA (1983) to the Poços de Caldas, Ponta do Morro and Mariscala provinces being changed to Cabo Frio Magmatic Lineament, Rondonópolis Anteclise and Valle Chico provinces, respectively. The Santa Catarina province is supressed, and Anitápolis and Lages occurrences are associated to the Ponta Grossa Arch and Serra do Mar provinces, respectively. The alkaline rocks of the Minas-Goiás province have undergone denomination changes over the years, as noted by BROD *et al.* (2005). More recently, GASPAR *et al.* (2003) concluded, based on isotopic data, that the alkaline occurrences in western Minas

Gerais and Iporá-Rio Verde belong to two distinct provinces, Alto Paranaíba and Goiás, respectively. Thus, the total number of provinces has increased to 16, as indicated below:

- *Alto Paraguay* (in Brazil-Paraguay);
- *Rio Apa*, *Amambay, Central, Asunción,* and *Misiones* (in Paraguay);
- *Velasco* and *Candelaria* (in Bolivia);
- *Valle Chico* (in Uruguay) and *Piratini*;
- *Rondonópolis Anteclise;*
- *Ponta Grossa Arch, Serra do Mar*, *Cabo Frio Magmatic Lineament, Alto Paranaíba,* and *Goiás.*

The entire distribution of Brazilian alkaline occurrences bearing silicate and carbonatitic rocks is shown in Figures 2 and 3, respectively. In Paraguay, alkaline rocks scatter across six distinct regions (Figure 4), with carbonatites represented by outcrops B (12), C (14, 16), and E (45, 59, and 65).

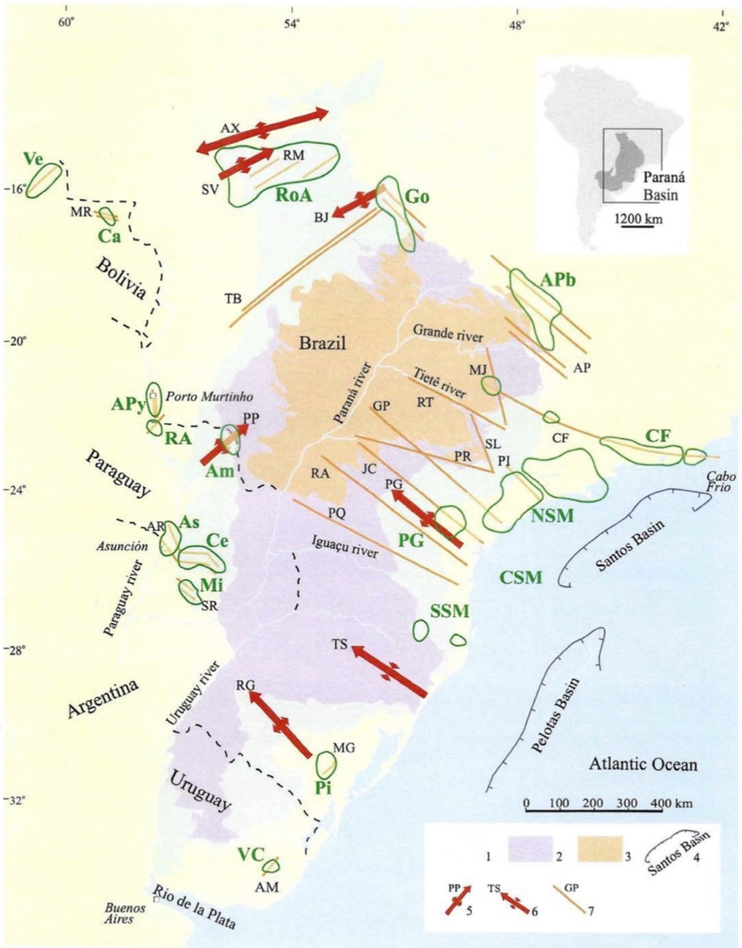

Figure 1. Tectonic features and the regional distribution of alkaline provinces in the area covered by the Paraná Basin (after RICCOMINI *et al*., 2005, modified). **Legends**: 1, Late Ordovician to Early Cretaceous Paraná Basin; 2, Early Cretaceous tholeiitic lava flows; 3, Late Cretaceous Bauru Basin; 4, Offshore marginal basins; 5, Axes of main arches (AX, Alto Xingu; SV, São Vicente; BJ, Bom Jardim de Goiás; PG, Ponta Grossa; RG, Rio Grande; PP, Ponta Porã); 6, TS, Torres Syncline; 7, Major fracture zones, in part deep lithospheric faults (Rifts: MR, Mercedes; RM, Rio das Mortes; MG, Moirão; SR, Santa Rosa; AR, Asunción. Lineaments: TB, Transbrasiliano; AP, Alto Paranaíba; MJ, Moji Guaçu; CF, Cabo Frio; RT; Rio Tietê; SL, São Carlos-Leme; PR, Paranapanema; PI, Piedade; GP, Guapiara; JC, São Jerônimo-Curiúva; RA, Rio Alonzo; PQ, Rio Piqueri; AM, Santa Lucia-Aiguá-Merin. **Alkaline province abbreviations**: Am (Amambay), APy (Alto Paraguay), APb (Alto Paranaíba), As (Asunción), Ca (Candelaria), Ce (Central), CF (Cabo Frio), Go (Goiás), Mi (Misiones), PG (Ponta Grossa), Pi (Piratini), RoA (Rondonópolis Anteclise), RA (Rio Apa), SM (Serra do Mar: N, Northern; C, central; S southern), VC (Valle Chico) and Ve (Velasco).

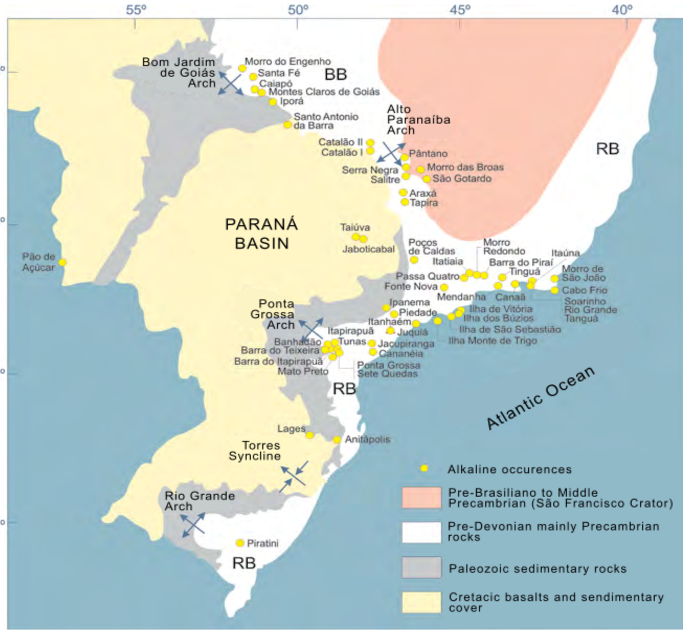

Figure 2. Distribution of the main alkaline and alkaline-carbonatitic centers in the Brazilian territory (after ULBRICH and GOMES, 1981, modified). BB and RB refer to the Brazilian and Ribeira belts, respectively.

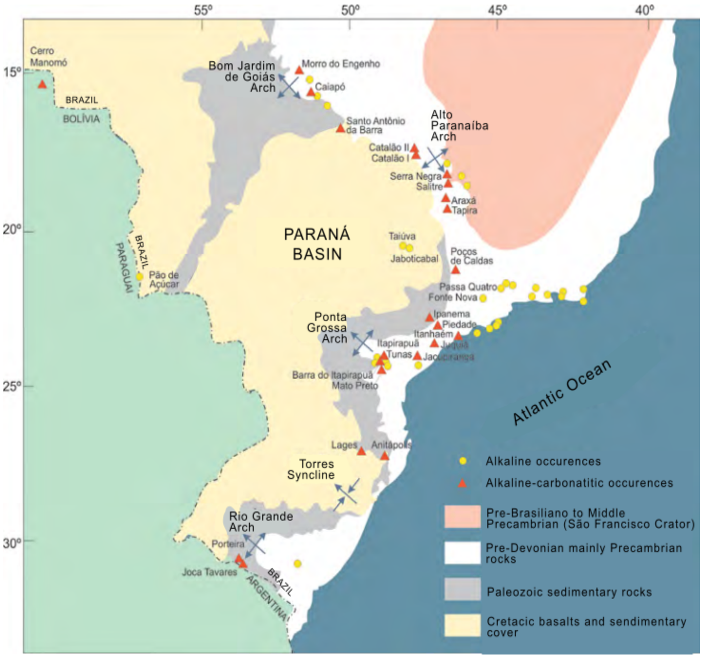

Figure 3. Major occurrences of alkaline-carbonatitic rocks in southern Brazil (after GOMES, 2023). The carbonatite complex of Cerro Manomó in Bolivia is also indicated.

In western areas of the Paraná Basin at the Brazil–Paraguay border, alkaline magmatism is represented by several complexes that form the Alto Paraguay province (Table 1) along both margins of the Paraguay River. In northern Paraguay, alkaline rocks occur near the mouth of the Apa River (the Rio Apa province), while in northeast Paraguay they are associated with the Amambay province, which consists of a few intrusions scattered across a vast region, with carbonatite complexes as its main geological features. Magmatism is also concentrated in two distinct regions of Paraguay, represented by the Central and Asunción provinces, the latter including several bodies that crop out near the capital city, Asunción. Although of minor significance, alkaline magmatism is also present at the southernmost parts of the country (the Misiones province), near the villages of San Juan Bautista and San Ignacio. In Bolivia, occurrences are primarily associated with the prominent Velasco province, an extensive alkaline complex composed of multiple inter-fingering plutons and a carbonatitic body (Cerro Manomó). The Candelaria province covers a small area in the southern portion of the country, including only a few erratic blocks of intrusive rocks.

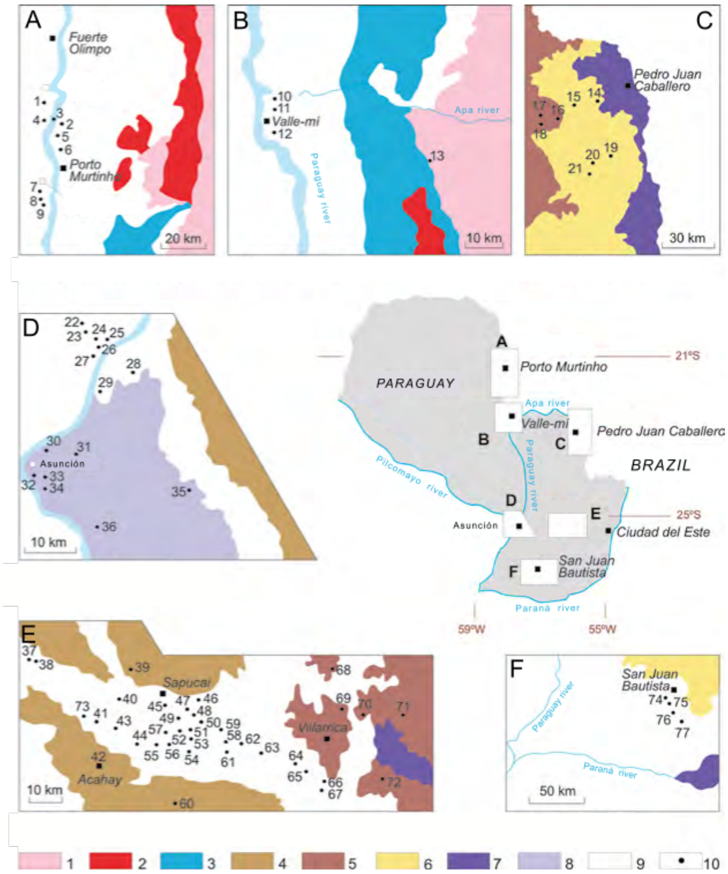

Figure 4. Distribution of alkaline and alkaline-carbonatitic rocks of distinct provinces of Eastern Paraguay: A (Alto Paraguay), B (Rio Apa), C (Amambay), D (Asunción), E (Central), and F (Misiones). Modified after VELÁZQUEZ *et al*. (1996a). **Legends**: 1, Lower Pre-Cambrian, Rio Apa Complex; 2, Upper Pre-Cambrian, Alumiador Intrusive Suite; 3, Cambrian sediments, Itapucumí Group; 4, Silurian sediments, Caacupé Group; 5, Carboniferous sediments, Cerro Corá Group; 6, Triassic sediments, Misiones Formation; 7, Jurassic-Cretaceous tholeiitic magmatism, Alto Paraná Formation (=Serra GeralGroup); 8, Tertiary sediments, Patiño Formation; 9, Quaternary sediments; 10, **Alkaline occurrences**: 1, Cerro Boggiani; 2, Pão de Açúcar; 3, Ilha Fecho dos Morros; 4, Cerrito; 5, Morro São Pedro; 6, Cerro Pedreira; 7, Cerro Siete Cabezas; 8, Satélite I; 9, Satélite II; 10, San Lázaro; 11, Cerro Santa Elena; 12, Cerro Valle mí; 13, Cerro Buena Vista; 14, Cerro Chiriguelo; 15, Arroyo Gasory; 16, Cerro Sarambí; 17, Cerro Apuá; 18, Cerro Peró; 19, Cerro Tayay; 20, Arroyo Blanco; 21, Cerro Guazú; 22, Cerrito; 23, Benjamin Aceval; 24, Estancia La Lomita; 25, Cerro Verde; 26, Villa Hayes; 27, Cerro Confuso; 28, Limpio; 29, Remanso Castillo; 30, San Jorge (NT); 31, Jardin Botánico; 32, Cerro Tacumbú; 33, Barcequillo; 34, Cerro Lambaré; 35, Cerro Patiño; 36, Cerro Ñemby; 37, Cerro Arrúa-í; 38, Cerro Piedra; 39, Cerro Santo Tomás; 40, Cerro Porteño; 41, Cerro Ybytypé; 42, Cerro Acahay; 43, Cerro Yarigua-á; 44, Cerro Gimenez; 45, Sapucai; 46, Tte, Martinez; 47, Cerro Fidel; 48, Cerro Yaguarú; 49, Catalán; 50, Cerro Valle-í; 51, Potrero Naranjaty; 52, Arroyo Paso Villán; 53, Franco Ñú; 54, Iriarte; 55, Cerro Medina; 56, Potrero Arce; 57, Potrero Ybaté; 58, Cerro Chobi; 59, Cerro Cañada; 60, Cerro San José; 61, Martinez Cué; 62, Cerrito (Cel, L, Vera); 63, Cerrito (Costa Jhú); 64, Cerro Itapé; 65, Cerro E Santa Elena; 66, Cerro Km 23; 67, Cerro San Benito; 68, Aguapety Portón; 69, Mbocayaty; 70, Cerro Capiitindy; 71, Cantera MOPC; 72, Ybytyruzú; 73, Estancia Las Rosas; 74, Cerro Guayacán; 75, Cerro Caá Jhovy; 76, Estancia Ramirez; 77, Estancia Guavirá-y.

Table 1. Main characteristics of the alkaline provinces in the western Paraná Basin.

Alto Paraguay	Rio Apa	Amambay
Mode of occurrence		
ring complexes, stocks, dikes, volcanic field	dikes	ring complexes, stocks, lava flows, plugs, dikes
Body size		
small dikes, variable stocks (a few km² wide), volcanic field (about 30 km²)	1-2 cm thick	ring complexes (up to 8.5 km in diameter), stocks, dikes
Country rock		
Pleistocenic sediments	Cambro carbonate platform	Paleozoic sediments, Precambrian basement
Tectonic control		
Rio Apa arch, N-S-trending faults	Rio Apa arch, NW-trending faults	Ponta Porã arch
Age		
Middle Triassic	Early Cretaceous	Early Cretaceous

Central	Asunción	Misiones
Mode of occurrence		
stocks, plugs, dikes, dike swarms, lava flows, lava domes, tuffs, volcanic field	plugs, lava domes, dikes	plugs, dikes
Body size		
variable stocks (up to 17 km²), volcanic field (about 98 km²), small dikes	plugs (up to 300 m in diameter), dikes and lava flows (up to 10 m thick)	plugs (0.3 to 0.8 km² wide)
Country rock		
Quaternary sediments, Paleozoic sediments	Pleistocenic sediments	Triassic sediments
Tectonic control		
Asunción-Sapucai-Villarrica rift	Asunción-Sapucai Villarrica rift	Santa Rosa arch
Age		
Early Cretaceous	Paleogene	Late Early Cretaceous

Velasco	Candelaria
Mode of occurrence	
complex ring stocks, dikes, lava flows	stocks, dikes, lavas
Body size	
variable stocks (1 to 8 km in diameter), dikes (1-3 m thick)	small blocks
Country rock	
Precambrian basement	Quaternary sediments
Tectonic control	
NE-trending fault system	E-W to WNW-ESE-trending faults
Age	
Early Cretaceous	Late Cretaceous

In southern parts of the Paraná Basin (Table 2), alkaline magmatism is represented by an intrusive complex, the Valle Chico province in southeastern Uruguay, and by the Piratini province in Brazil, not far from northern areas and showing numerous volcanic structures within the Sul-Rio-grandense shield. In the northern Paraná Basin, alkaline magmatism is associated with the Rondonópolis Anteclise province, being mainly represented by the Ponta do Morro alkaline massif.

Table 2. Main characteristics of alkaline provinces in southern (Valle Chico and Piratini) and northern (Rondonópolis Anteclise) Paraná Basin.

Valle Chico	Piratini	Rondonópolis Anteclise
Mode of occurrence		
stocks, plugs, dikes, dike swarm, lava flows, lava domes, tuffs	plugs, dikes, pipes	stock, dikes, pipes, lava flows
Body size		
variable stocks (up to a few km^2 wide), small dikes	50 to 100 m in diameter	stock (approximately 7 km^2), small intrusions
Country rock		
Precambrian basement	Phanerozoic cover, Precambrian basement	Precambrian basement
Tectonic control		
WNW-ESE-trending graben, NW-SE-trending structures	NNW-SSE to NW-SE oriented fractures, NE-Moirão graben	NE-SW-trending tectonic feature
Age		
Early Cretaceous	Late Cretaceous	Late Cretaceous

The central-eastern region of the basin contains the largest number of known alkaline intrusions encompassed into distinct provinces (Table 3), such as the 1) Ponta Grossa Arch, highly variable in composition and promptly distinguished by their carbonatitic intrusions, the most important one being Jacupiranga; 2) the Serra do Mar, a group of massifs of varied size lying internally and paralleling to the coastline of São Paulo and Rio de Janeiro; 3) the Cabo Frio Lineament, represented by several bodies placed along a structural feature extending over many kilometers from the interior of Minas Gerais to the coast near the city of Cabo Frio; 4) the Alto Paranaíba, including mostly of the west Minas Gerais alkaline intrusions, and 5) the Goiás, comprising many occurrences of distinct geologic shape found in the Goiás state, as the Catalão for instance.

The concentration of alkaline occurrences is higher in central-eastern Paraguay, while in Brazil they fall primarily within two very distinctive groups across several hundred kilometers. The first group lies parallel to the shorelines of São Paulo and Rio de Janeiro, while the second one relates inner intrusions in Minas Gerais to those near coastal areas of Rio de Janeiro (e.g., Cabo Frio). Other important concentration areas in Brazil are marked by the Ponta Grossa Arch and the Alto Paranaíba and Goiás lineaments. A total of 218 alkaline occurrences associated with the Brazilian Platform are known to occur in four countries, of which 138 in Brazil, 77 in Paraguay, two in Bolivia, and one in Uruguay, as outlined in the volume by GOMES and COMIN-CHIARAMONTI (2017). Figures 2 to 4 display the location of occurrences quoted in parts I and II of the present study.

3 TECTONIC SETTING

Alkaline provinces are controlled by crustal discontinuities primarily represented by extensional or wrench fault zones along the present-day margins of sedimentary basins. The concept that alkaline magmatism in the South American Platform is basically related to regional tectonics was first suggested by ALMEIDA (1971, 1972). Landsat imagery and geophysical evidence (aeromagnetic surveys and Bouguer gravity maps) led COMIN-CHIARAMONTI *et al.* (1997, 1999) to conclude that tectonics in Eastern Paraguay is predominantly extensional, with major NW-trending structures playing a key role in the emplacement of alkaline bodies. For all magmatic events in the Brazilian Platform, the latter authors assumed that an old structural framework of the basement—comprising NE-, NS-, and NWW-trending lineaments and fault zones, active since Precambrian times and subject to intense reactivation—along with positive, parallel, and elongated deep fractures (arches) mainly NW-trending and transverse to the major axis of the Paraná Basin, generally surrounding it, was conclusive for the emplacement of such rocks.

Table 3. Main characteristics of alkaline provinces in the central-eastern Paraná Basin.

Ponta Grossa Arch	Serra do Mar	Cabo Frio Lineament
Mode of occurrence		
complexes, stocks, dike swarms, dikes, plugs, pipes, breccia	massifs, stocks, dikes, dike swarms, domes, breccia	massifs, stocks, dikes, plugs, lava flows, sills, breccia
Body size		
variable complexes (up to 65 km^2) and stocks (up to 22 km^2), small dikes	massifs (up to 136 km^2), variable stocks, small dikes	massifs (over 800 km^2), variable stocks, small dikes
Country rock		
Permo-Carboniferous sediments, Precambrian basement	Cenozoic cover, Precambrian basement	Late Cretaceous sediments, Precambrian
Tectonic control		
Ponta Grossa arch	SE Brazilian Continental rift structural feature	NWW-ESE-trending
Age		
Early Cretaceous	Late Cretaceous	Late Cretaceous-Tertiary

Alto Paranaíba	Goiás
Mode of occurrence	
complexes, stocks, dikes, lavas, tuffs, breccia	volcanic field, complexes, stocks, dikes, plugs, sills, lavas, diatremes, pyroclastic deposits
Body size	
complexes (up to 65 km^2), variable stocks (2 up to 6 km in diameter), small dikes	volcanic field (371 km^2), complexes (up to 50 km^2), small dikes
Country rock	
Precambrian basement	Paleozoic-Cretaceous sediments, Precambrian basement
Tectonic control	
Alto Paranaíba arch	E-W to WNW-ESE-trending faults of the Mercedes rift
Age	
Late Cretaceous	Late Cretaceous

Figure 1 clearly shows that in the Paraná Basin, alkaline rocks cluster along structural features such as arches (e.g., Alto Paranaíba, Ponta Grossa), rifts (e.g., Asunción, Serra do Mar), and lineaments (e.g., Cabo Frio, Piedade). The tectonic setting of each alkaline province in the basin is discussed in the following sections.

4 WESTERN PARANÁ BASIN

4.1 ALTO PARAGUAY, APy (BRAZIL-PARAGUAY BORDER)

The province is represented by at least seven major ring complexes, stocks, dikes, and a volcanic field, all situated along a narrow linear N-S-trending belt parallel to Paraguay River course that extends up to approximately 40 km. Extensional earthquakes, with hypocenters shallower than 70 km, characterize this region (BERROCAL and FERNANDES, 1996). Alkaline occurrences are lying on both margins of the river at the boundary between Brazil (Mato Grosso do Sul state) and Paraguay to the south and north of Porto Murtinho, the most important city in the region. They are cropping out in the Pleistocene alluvial sediments of the Pantanal Formation (OLIVEIRA; LEONARDOS. 1943) that probably cover the Precambrian basement.

Among the interpretations of the tectonic control of this alkaline event in literature, the influence of the Rio Apa arch was initially suggested by LIVIERES and QUADE (1987), while VELÁZQUEZ *et al.* (1996a) related the magmatic activity to a cratonic margin setting. Owing to their restricted areal distribution, with bodies aligned along the Paraguay River, and the presence of structural lineaments, VELÁZQUEZ *et al.* (1998) attributed the tectonic control to N-S-trending faults. Different interpretations are discussed in literature, e.g., USSAMI *et al.* (1999), RICCOMINI *et al.* (2005), and COMIN-CHIARAMONTI *et al.* (2007a). In their account of the stress components associated with the Cabo-La Ventana Orogeny, which are thought to have propagated internally into the Brazilian Platform as N-S-trending structures, RICCOMINI *et al.* (2005) suggested a genetic relationship between the convergence recorded in southwestern Gondwana and the Permian-Triassic alkaline magmatism in the Alto Paraguay province. In a more recent study, RAMOS *et al.* (2010) interpreted the N-S alignment of the Paraguay River as marking the boundary between the Pampa cratonic block to the west and the Rio Apa block to the east.

4.2 RIO APA, RA (PARAGUAY)

Magmatism is poorly represented in this province, consisting solely of a few small, 1–2 m thick dikes filling NE-SW-trending faults (VELÁZQUEZ *et al.*, 1998) in San Lázaro, near the locality of Puerto Valle-mí, at the banks of the Paraguay River. Alkaline bodies cut through a Cambro-Ordovician limestone platform. The authors assert that the scarce magmatic activity was tectonically controlled by the Rio Apa arch.

4.3 AMAMBAY, Am (PARAGUAY)

The Amambay province encompasses several alkaline bodies found at the border of Brazil and northeastern Paraguay, occurring as minor intrusions, plugs, lava flows, dikes, and two ring-shaped carbonatite complexes, Cerro Chiriguelo and Cerro Sarambí, whose estimated diameters are 7.5 km and 8.5 km, respectively (GOMES *et al.,* 2011a). The intrusions are emplaced into domed Silurian and Permo-Carboniferous sediments and Precambrian metamorphic rocks (HAGGERTY; MARIANO, 1983). The province is situated within the domains of an N35E-trending arch, Ponta Porã (THOMAS & ASSOCIATES, 1976), a structural belt lying along a major N55-60E gravity lineament in eastern Paraguay and the northern Chaco Basin, to the west of the Paraguay River (COMIN-CHIARAMONTI *et al.,* 1999). It crosses the Amambay depression, a tectonic feature aligned N40-45W that varies in width from about 40 to 70 km and extends for over 300 km. The Ponta Porã arch lies between two notable depressions probably associated with sedimentary basins, as evident in Bouguer anomaly maps, with two gravity lows, one to the NW (Bella Vista) and the other to the SE (Mbacarayú) of Pedro Juan Caballero city. The latter authors also emphasize the limited field presence of the Amambay belt due to the overlying Paraná tholeiitic lavas and Late Cretaceous Acaray sandstones. All known occurrences in this alkaline province are located within or at the borders of the Ponta Porã arch, where this structural feature intersects the Amambay depression. The tectonic control of the Amambay province by the Ponta Porã arch (Cerro Chiriguelo and Cerro Sarambí complexes) and, to a lower degree, by the less expressive Capitán Bado fracture (Cerro Guazú and Cerro Tayay intrusions), was first pointed out by LIVIERES and QUADE (1987) and, according to VELÁZQUEZ *et al.* (1998), corroborated by magnetic anomalies.

4.4 CENTRAL, Ce (PARAGUAY)

The Central province shows the highest concentration of alkaline intrusions in Eastern Paraguay, occurring mainly as stocks, dikes, lava flows, plugs, and extrusive sheets of pyroclastic flows. It also includes a volcanic field that extends for 98 km^2 and a remarkable dike swarm, both having the village of Sapucai as a geographical reference. The alkaline occurrences, which are emplaced in

Quaternary and Paleozoic sediments, are related to the evolution of the central and eastern areas of the Asunción rift (DEGRAFF, 1985). The rift, which formed in the Early Cretaceous, extends for more than 100 km across the Chaco basin. This approximately 200 km long and 25 to 45 km wide tectonic depression is a striking feature, evidenced in both magnetometric and gravimetric maps. Nearly symmetrical and defined by major faults along each margin, its graben consists of three segments with varying orientations: a western NW-SE segment about 90 km long, a central E-W segment approximately 70 km long, and an eastern NW-SE segment roughly 30 km long (RICCOMINI *et al.,* 2005). Of great importance in the central-eastern part of the rift is the presence of the Sapucai dike swarm, composed of at least 200 bodies ranging from 0.5 to 20 m in thickness, primarily trending NW-SE as single or ramified bodies. These have been investigated in detail by GOMES *et al.* (1989), COMIN-CHIARAMONTI *et al.* (1992, 2013), and VELÁZQUEZ *et al.* (2011). The distribution of dike swarm elements, faults, and joints allowed VELÁZQUEZ *et al.* (1998) to suggest that the Asunción rift was generated under a right-lateral wrenching tectonics associated with an E-W-trending binary.

4.5 ASUNCIÓN, As (PARAGUAY)

The alkaline occurrences in central Asunción rift consist of plugs, lava domes, and dikes associated with NW-SE-striking magnetic lineaments and a gravimetric low near Paraguay's capital city, Asunción. This gravimetric low corresponds to a graben filled with Paleogene fanglomeratic sediments and volcanic rocks (RICCOMINI *et al.*, 2002). A systematic study of faults and fracture patterns associated with these alkaline outcrops allowed RICCOMINI *et al.* (2001) to conclude that the rocks were emplaced along NW-SE-striking lithospheric faults extending to depths greater than 60 km.

4.6 MISIONES, Mi (PARAGUAY)

Alkaline magmatism is scarce in this province, primarily concentrated between the villages of San Juan Bautista and San Ignacio in the southernmost part of Paraguay. The occurrences consist of three small plugs and one dike, all emplaced in Triassic sediments. Tectonically, these rocks are associated with NW-SE-trending lineaments extending up to 150 km. These parallel lineaments lie south of the Asunción rift (VELÁZQUEZ *et al.,* 2002). DEGRAFF and ORUÉ (1984) referred to this crustal fracturing feature as the Santa Rosa rift. Field evidence presented by VELÁZQUEZ *et al*. (2006) indicate that the linear aeromagnetic anomalies scattered throughout the area correspond to faults and fractures locally intruded by alkaline bodies.

4.7 VELASCO, Ve (BOLIVIA)

Situated within the Amazon craton in southeastern Bolivia, the Velasco province lies 1,500 km from the Atlantic coast. Covering an area of 500 km², the province consists of 14 overlapping ring-shaped and elliptical plutons, with diameters ranging from 1 to 8 km. Intruded into Precambrian formations (FLETCHER; BEDDOE-STEPHENS, 1987), the alkaline plutons are primarily aligned along a narrow, 80 km long NE-trending belt that controlled their emplacement. The association also includes stocks, volcanic products (agglomerates, tuffs), various alkaline dikes, and a silicified carbonatite complex (Cerro Manomó) at the northeastern end of the fault system. FLETCHER and LITHERLAND (1981) interpreted this magmatic event as having formed along a deep crustal fracture zone associated with a presumed triple junction during the rifting phase of the South America–Africa separation.

4.8 CANDELARIA, Ca (BOLIVIA)

The Candelaria province is of limited significance, being represented by a few small fragments of intrusive rock types and dikes. Lava occurrences are also found, mostly underneath alluvial sediments of the Pantanal basin. E-W to WNW-ESE-trending faults of the Early Tertiary Mercedes rift extending over 100 km is believed to have controlled this magmatic event (LITHERLAND *et al.,* 1986).

5 SOUTHERN PARANÁ BASIN

5.1 VALLE-CHICO, VC (URUGUAY)

Alkaline magmatism in southern Uruguay is primarily represented by the Valle Chico province, previously referred to in the literature as Mariscala (ALMEIDA, 1983). The unit consists of intrusive rocks, with subordinate dikes and volcanic rocks emplaced into Precambrian to Mesozoic terrains, covering approximately 250 km². The alkaline rocks are tectonically controlled by the WNW-ESE-trending Santa Lucía graben (BOSSI, 1996), while dikes and veins within the complex predominantly follow NW-SE trends (PIRELLI, 1999).

5.2 PIRATINI, Pi

Located in central areas of the Rio Grande arch, the Piratini province encompasses 34 outcrops of volcanic rocks that intrude both the Phanerozoic cover and the crystalline basement of the Sul-Riograndense shield in Santana da Boa Vista (BARBIERI *et al.,* 1987; PHILIPP *et al.,* 2005). The intrusions, occurring as small plugs, dikes, and pipes, are associated with the tectonic depression of the Moirão graben, a NE-oriented structure. A few kimberlite plugs apparently belong to this province, which may also include two carbonatitic intrusions, Joca Tavares and Porteira, first described by MONTEIRO *et al.* (2016) and TONIOLO *et al.* (2013), respectively. The distribution of phonolitic bodies is controlled by NE-SW-trending faults parallel to the graben, as well as by NNW-SSE to NW-SE-oriented fractures.

6 NORTHERN PARANÁ BASIN

6.1 RONDONÓPOLIS ANTECLISE, RoA

The Ponta do Morro complex, the most prominent geological feature in the region of Rondonópolis, is characterized by a crescent-shaped elevation extending over 7 km² that contrasts with the lowlands of the Pantanal formation (SOUSA *et al*., 2005). This province is associated with pipes, lava flows, and dikes of the Poxoréu Igneous Province (GIBSON *et al.,* 1997) which were emplaced along the extensional NE-SW tectonic structure known as the Rio das Mortes rift.

7 CENTRAL-EASTERN PARANÁ BASIN

7.1 PONTA GROSSA ARCH, PG

The Ponta Grossa arch, a prominent NW-SE-trending tectonic feature, was the setting for intense and repeated alkaline magmatism during the Mesozoic (RICCOMINI *et al.,* 2005). There, many occurrences of igneous manifestations (stocks, dikes, dike swarms, plugs) and magma types intrude into Permo-Carboniferous sediments of the Paraná Basin and Precambrian formations (GOMES *et al.,* 2011b). A group of four parallel N40-60W-trending lineaments, namely Guapiara, São Jerônimo-Curiúva, Rio Alonso and Rio Piqueri, was identified by ALMEIDA (1983) in the arch structure. In particular, alkaline rocks are situated on or at a close distance from southern sections of the Guapiara and São Jerônimo-Curiúva lineaments. An NW-SE-trending feature, the Piedade lineament, which encompasses intrusions, e.g., Ipanema, Piedade, and Itanhaém, was described by RICCOMINI *et al.* (2005) to the northeast of the arch's axis. In general, alkaline centers are oriented to NW-SE, aligned and parallel to the arch's axis and the Guapiara lineament (ALGARTE, 1972).

7.2 SERRA DO MAR, SM

As proposed by RICCOMINI *et al.* (2005), three zones can be identified in the Serra do Mar province: a northern one including the islands on the coast of São Paulo and the Ponte Nova massif in the Mantiqueira mountain range, a central one encompassing numerous small intrusions within the geographical domain of the Ponta Grossa arch, and a southern one marked by the structure known as the Lages dome. These zones correspond to areas of major Cenozoic uplift along onshore coastal areas of southeastern Brazil. Their alkaline occurrences consist mainly of massifs, stocks, and dikes emplaced into recent sediments and Precambrian units of the basement. These manifestations are tectonically related to the Southeastern Brazilian continental rifting, a feature developed in the Ribeira belt following the reactivation of ENE to E-W transcurrent systems during the breakup of Gondwana (RICCOMINI *et al.,* 2005). The spatial distribution of the alkaline magmatism follows a linear rifting system parallel to the Santos fault, with the island of São Sebastião, which extends over an area of 136 km², constituting the largest alkaline manifestation (ENRICH *et al.,* 2005).

7.3 CABO FRIO MAGMATIC LINEAMENT, CF

As defined by ALMEIDA (1981), the Cabo Frio lineament represents a 60 km wide WNW-ESE-trending feature extending for more than 1,150 km from Jaboticabal in the state of São Paulo eastward to the borders of the continental and the oceanic crusts (Almirante Saldanha bank). The lineament consists of 26 alkaline occurrences cropping out as massifs, stocks, plugs, sills, effusive centers and an expressive number of dikes (RICCOMINI *et al.,* 2005), most of which emplaced into Late Cretaceous sediments and rocks of the Precambrian basement. The largest alkaline massifs in Brazil, Poços de Caldas (>800 km^2), Itatiaia (220 km^2) and Passa Quatro (165 km^2) are all assigned to this province.

7.4 ALTO PARANAÍBA, APb

The Alto Paranaíba arch (Alto Paranaíba uplift of HASUI *et al.,* 1975), a positive tectonic structure separating Paraná and São Francisco basins, was the setting for intense alkaline magmatism in the Late Cretaceous (the Alto Paranaiba province of ALMEIDA, 1983). N50W-oriented aeromagnometric anomalies are interpreted as indicative of at least 400 km long fractures (BOSUM, 1973) filled with dikes and alkaline intrusions. Many intrusions in western Minas Gerais and part of Goiás, which are associated with this system of faults, occur in distinct igneous forms: plutonic complexes, stocks, dikes, pipes, lava flows, tuffs, and pyroclastic deposits (volcanic ash, lapilli, and blocks). The plutonic complexes, almost circular in shape and of varied sizes (up to 65 km² in area), intrude Precambrian metamorphic rocks, bearing carbonatite bodies as important economic resources for niobium and phosphate.

7.5 GOIÁS, Go

Formerly named Rio Verde-Iporá by ALMEIDA (1983), the Goiás province refers to more than 20 alkaline intrusions occurring as volcanic fields, up to 50 km², stocks, dikes, sills, plugs, diatremes, lavas, and pyroclastic deposits along an approximately 250 km long, 70 km wide belt. The N30W orientation of this belt corresponds to the mean direction of the main faulting zones throughout which the alkaline magma ascended (ALMEIDA, 1983; RICCOMINI *et al.,* 2005).

8 PETROGRAPHY

Alkaline magmatism is characterized by a remarkable petrographic diversity, which is responsible for a numerous and varied association of rock types, as shown in Tables 4 to 6. In general, intrusive forms prevail over fine-grained equivalents, which are particularly well represented in the Cabo Frio Lineament (e.g., Poços de Caldas and Tinguá massifs) as well as in the Alto Paranaíba and Goiás provinces (e.g., Mata da Corda formation). ULBRICH and GOMES (1981) were the first authors to assemble these numerous occurrences in order to better characterize and correlate alkaline magmatic products, defining petrographic associations that account for the wide range of alkaline types on the Brazilian Platform. Their contribution was followed by that of MORBIDELLI *et al.* (1995), who distinguished between carbonatite-bearing and carbonatite-free assemblages. Additional studies published shortly thereafter have focused on associations restricted to the Ponta Grossa arch (GOMES *et al.,* 2011b) and Eastern Paraguay (GOMES *et al.,* 2011a, 2013). The theme was revisited by GOMES and COMIN-CHIARAMONT (2017), who adopted a slightly modified version of the alkaline distribution from ULBRICH and GOMES (1981).

8.1 TYPE I. SATURATED TO SILICA-UNDERSATURATED SYENITIC ASSOCIATIONS AND VARIANTS

Two variants, a *strongly peralkaline* and an *alkali granitic to alkali syenitic* one, prevail over other associations among the alkaline manifestations affecting the Paraná Basin. The prevalence is particularly evident along the borders of the Paraná and Santos basins. Syenites, nepheline syenites, and quartz syenites (pulaskites, nordmarkites), frequently associated with phonolites and trachytes, are the most abundant rock types. Areas presenting clusters of syenitic rocks include most of the outcrops in northern (Ponta do Morro), western (Alto Paraguay, Velasco and Candelaria), southern (Valle Chico), and central-eastern (Serra do Mar and Cabo Frio Lineament) Paraná Basin. This distribution of alkaline types suggests that foid- to quartz-bearing syenitic associations tend to occupy peripheric zones of the basin.

Based on its mineralogy and chemical composition, a strongly peralkaline variant of rocks referred to as *agpaitic* is present in Poços de Caldas and Cerro Boggiani occurrences in the Cabo Frio Lineament and Alto Paraguay provinces, respectively. Although in smaller amounts, these rocks have also been reported in other provinces as distinct igneous bodies (stocks, sills, plugs, and lava flows) by GOMES *et al.* (2021). Nepheline syenites and their aphanitic counterparts (phonolites and tinguaites) are the most frequent types. Alkali granitic to alkali syenitic types have the Itatiaia massif in the Serra do Mar province as their only well-known example, with syenites forming a border zone around granitic core.

8.2 TYPE II. MAFIC-ULTRAMAFIC ALKALI GABBRO ASSOCIATIONS

Yet a few single intrusions are present; mafic-ultramafic alkali gabbro occurrences in the Paraná Basin correspond mainly to two groups of associated manifestations, cropping out in both cases as circular complexes, minor stocks, plugs, lava domes and dikes. The first group encompasses rocks of alkali gabbroic to syenitic filiation and their fine-grained equivalents, all belonging to the Central province in Eastern Paraguay (COMIN-CHIARAMONTI *et al.,* 1996a, b). Alkaline occurrences are found in large numbers (e.g., Cerro Aguapety Portón, Cerro Acahay, Cerro E Santa Helena, Cerro Km 23, Cerro San Benito, Cerro San José, Mbocayaty and many others) following two distinct lines of evolution: basanite to phonolite (B-P) and alkali basalt to trachyphonolite/trachyte (AB-T). The second group of occurrences is composed of olivine-bearing rocks (dunites, peridotites, and olivine clinopyroxenites) in association with clinopyroxenites and types ranging in affinity from gabbroic to syenitic, present in numerous intrusions in the Goiás province (e.g., Morro do Engenho, Santa Fé, Montes Claros, Córrego dos Bois, Morro do Macaco, Fazenda Buriti, and Arenópolis, cf. BROD *et al.,* 2005). Aphanitic rocks forming small dikes are described as trachytes, shonkinites, and lamprophyres (monchiquites). Single manifestations showing similarities with rocks of the two groups of associated occurrences are represented by the Banhadão, Pariquera-Açu and Tunas complexes in the Ponta Grossa Arch province and by the Ponte Nova massif in the Serra do Mar province. In the latter, occurrences are also found in São Sebastião and Monte de Trigo islands along the coast of São Paulo.

8.3 TYPE III. MAFIC-ULTRAMAFIC, ALKALI-SATURATED TO PERALKALINE ASSOCIATIONS

A notably complex petrographic association carrying a *carbonatite lineage* as the most expressive variation is particularly associated with complexes of the Ponta Grossa Arch and Alto Paranaiba provinces. Of the first are the complexes of Jacupiranga, Juquiá, Ipanema, Piedade, Mato Preto, and Anitápolis, while Araxá, Cataláo I and II, Salitre I and II, Serra Negra, and Tapira are representative of such associations in the latter. The Lages carbonatite complex in the Ponta Grossa Arch province consists, according to RICCOMINI *et al.* (2005), of unusual rock types like olivine nephelinites and olivine melilitites. In Eastern Paraguay, the Amambay province is distinguished by the presence of the circular carbonatite complexes of Cerro Chiriguelo and Cerro Sarambi. The Cerro Manomó, a silicified carbonatite body forming a mesa of approximately 4x6 km rising to 300 m above laterized rocks of the Precambrian basement (FLETCHER and LITHERLAND, 1981), represents the northeastern most outcrop of the Bolivian Velasco province, with no equivalent form described in the literature so far.

The carbonatitic rocks emplaced in the Paraná Basin have been investigated by many researchers over the past years, the most recent studies being a volume by GOMES (2020) and two review papers by SPEZIALE *et al.* (2020a, b). Based on petrographic associations (GOMES *et al.,* 2020), the carbonatite occurrences can be classified as (1) **magmatic**, (2) **hydrothermal,** and those showing (3) **unusual geometric relationships**. The magmatic associations are found to be either (a) linked with the urtite-ijolite-melteigite series without extrusive nephelinites (*Vale do Ribeira*: Anitápolis, Ipanema, Itapirapuã, Jacupiranga, Juquiá and Mato Preto; *Goiás*: Caiapó and Morro do Engenho; *Paraguay*: Cerro Sarambí and Sapucai), (b) in contact with olivinites and pyroxenites (Salitre I and Serra Negra) or glimmerites (Araxá, Catalão I, Catalão II and Salitre II), or (c) associated with intrusive ultramelitolites (Tapira) or extrusive olivine melilitites (Lages). The hydrothermal associations, which originated at temperatures ≤ 375ºC, are present in distinct locations (e.g., *Brazil:* Barra do Itapirapuã; *Paraguay:* Cerro Chiriguelo; *Bolivia:* Cerro Manomó). The associations showing unusual geometric relationships are represented by either carbonatitic rocks forming small dikes in Itanhaém, or ocelli-like aggregates in ijolitic rocks (Cerro Cañada and Cerro E Santa Elena) or occurrences linked to basanite dikes (Valle-mí) in Paraguay.

8.4 TYPE IV. ALKALI BASALT-TRACHYTE-PHONOLITE ASSOCIATION

Although of lesser geological significance, alkali basalt-trachyte-phonolite associations are widespread, primarily occurring as dikes, plugs, and other igneous forms. Notable examples include numerous small intrusions in Vale do Ribeira, associated with the Ponta Grossa Arch province (e.g., Barra do Sete Quedas, Barra do Teixeira, Cerro Azul, Mato Preto, Morro do Chapéu (VASCONCELLOS; GOMES, 1998); in the Sul-Riograndense shield - Piratini province (BARBIERI *et al.,* 1987; PHILIPP *et al.,* 2005); cropping out in the Mantiqueira Mountain Range within the Serra do Mar province (ALVES *et al.,* 1992); in the Volta Redonda (RICCOMINI *et al.,* 1990) and Aparecida do Monte Alto (COUTINHO *et al.,* 1982) regions; in the Cabo Frio Lineament province; and as numerous dikes spread along the southern coast of Brazil (VALENTE, 1997; COUTINHO, 2008).

8.5 TYPE V. STRONGLY SILICA-UNDERSATURATED AND PERALKALINE VOLCANIC ASSOCIATION

Associations of strongly silica-undersaturated and peralkaline volcanic rocks are identified only in southeastern and central-western Brazil, being closely related to the Alto Paranaiba Arch and Goiás provinces (BROD *et al.,* 2005). Although occupying a large total area, they are mainly represented in Mata da Corda and Santo Antônio da Barra in western Minas Gerais and southern Goiás, respectively. A wide variety of rare types is distinguished, including subvolcanic and volcanic mafic to ultramafic, potassic to ultrapotassic, and strongly silica-undersaturated varieties occurring as dikes, plugs, sills, diatremes, volcanic vents, and pyroclastic deposits. These rocks are mainly kamafugites (mafurites, ugandites and katungites) and kimberlites. The most important known occurrences of kamafugitic rocks are Amorinópolis, Àguas Emendadas, and São Antônio da Barra.

8.6 TYPE VI. UNDERSATURATED PERSODIC ROCKS

This association is scarce in the Paraná Basin, with the sodic lavas of Asunción and Misiones, in their respective alkaline provinces, being the only well-documented examples in the literature (BITSCHENE, 1987; COMIN-CHIARAMONTI *et al.,* 1991; VELÁZQUEZ *et al.,* 2006, respectively). These rocks occur as plugs, dikes, and lava domes, characteristically containing spinel-peridotite mantle xenoliths. Lavas interbedded with sediments of the Volta Redonda and Itaboraí basins could be included in these associations.

Table 4. Mineral data on alkaline occurrences from the western region of the Paraná Basin.

Alto Paraguay	Rio Apa	Amambay
Rock types		
S, Ns, Sn, Qs, Rh, Pho, Tpho, Ig, Pyro	Bas, Te, Ca	Ca, Cpy, S, Ns, Sd, Fe, Gl, Sh, Tr, Tpho, Phot, La
Main mineralogy		
Af, Pl, Ne, So, Qz, Cpx, Amp, Phlo, Bi, Ap, Ti, Op	Ol, Cpx, Bi, Pl, Af, Tph, Ap, Ti, Op, Ca	Ca, Do, Af, Pl, Cpx, Amp, Bi. Ne, Gr, Zr
*Replacement mineralogy**		
An, Ana, Ba, Bas, Bri, Bur, Ca, Can, Cor, Gal, Mo, Par, Py, Rem Syn, Th, Tho, Ura, Ze	Amp, Ana, Psd, Py	Ana, Anc, Ba, Bas, Ca, Fl, Gr, Hem, Lo, Par, Ver, Ze,
Agpaitic mineralogy		
Ae, As, Cat, Eu, Lam, Lav, Mos, Nor, Ros, Wö		Ae

Central	Asunción	Misiones
Rock types		
Ag, The, Es, Ge, Ij, Ma, Ns, Sg, S, Bas, Te, Pte, Pho, Phot, Ab, Ta, Tb, Tpho, Tr, Sh	Ne, Ank, Bas, Pho	Ne, Bas, Te, Pho
Main mineralogy		
Ol. Cpx, Bi, Amp, Pl, Af, Ne, Ap, Ti, Op. Zr	Ol, Cpx, Ne, Pl, Af, Op, Bi, Ap	Cpx, Ol, Opx, Ne, Af, Pl, Bi, Op
*Replacement mineralogy**		
Ana, Can, Gr, Hay, Hem, Lc, Psd	Ca, Gl	
Agpaitic mineralogy		

Table 4 - Cont.

Velasco	Candelaria
Rock types	
S, Ns. Sn, Qs, Gr, Ca, Tr, Tpho, Agg, Tu	Ns, S, Tr, Ig
Main mineralogy	
Af, Pl, Ne, Cpx, Bi, Amp, Qz, Co, Hc, Ap, Ti, Op, Zr, Ca, Eu, Bri. Fl	Af, Ne, Cpx, Bi, Ap, Zr, Op
*Replacement mineralogy**	
Ank, Ap, Ba, Bas, Ca, Can, Hay, Go, Hem, Mo, Li, Qz, So, Syn	Fl, Gl
Agpaitic mineralogy	
Eu	

Rock abbreviations: Ab, alkali basalt; Ag, alkali gabbro; Agg, agglomerate; Agr, alkali granite; mAnalc, mela-analcimite; Analc, analcimito; Ank, ankaratrite; As alkali syenite; Bas, basanite; Be, bebedourite; Br, breccia; Ca, carbonatite; Cpy, clinopyroxenite; Di, diorite; Du, dunite; E, essexite; Fe, fenite; Ga, gabbro; Ge, essexitic gabbro; Gl, glimmerite; Gr, granite; Ig, ignimbrite; Ij, ijolite; Kam, kamafugite series; Kat, katungite; Ki, kimberlite; La, lamprophyre (fourchite, missourite. monchiquite); Lat, latite; Leu, leucitito; mLeuc, melaleucitite; Lp, lamproite; Ma, malignite; Maf, mafurite; Mel, melteigite; Mon, monzonite; Ms, microsyenite; Mga, monzogabbro; Mzd, monzodiorite; Ne, nephelinite; mNe, melanefelinito; Nel, nelsonite; Ns, nepheline syenite; Per, peridotite; Pho, phonolite; Phos, phoscorite; Phot, phonotephrite; Pic, picrite; Pyro, pyroclast; Qs, quartz syenite; Rh, rhyolite; S, syenite; Sd, syenodiorite; Sg, syenogabbro; Sgr, syenogranite; Sh, shonkinite; Sil, silexite; Sn, syenite nephelinic; Ta, trachyandesite; Tb, trachybasalt; Te, tephrite; Tepho, tephriphonolite; The, theralite; Tin, tinguaite; Tr, trachyte; Tpho, trachyphonolite, Tu, Tuff; Ug, ugandite; Unc uncompahgrite; We, wehrlite, Wb, websterite. ***Mineral abbreviations***: Ae, aenigmatite; Af, alkali feldspar; Al, alstonite; Alla, allanite; Alu, alunite; Alun, alunogen; Amp, amphibole; An, ancylite-(Ce); Ana, analcime; Anat, anatase; Ang, anglesite; Ank, ankerite; Ano, anorthoclase; Ap, apatite; Arag, aragonite; As, astrophylitte; Au, autunite; Ba, baryte; Bad, baddeleyte; Bar, barytocalcite; Bas, bastnäsite; Be, belovite; Ben, benstonite; Ber, berthierine; Bi, biotite; Bor, bortolonite; Bri, britholite; Bur, burbankite; Ca, calcite; Cah, calciohilairite; Cal, calzirtite; Can, cancrinite; Cat, catapleiite; Car, carbocernaite; Cel, celestine; Cels, celsian; Cer, cerite; Ceru, cerussite; Cha, chalcopyrite; Cham, chamosite; Che, chevkinite; Cher, cheralite; Chlo, chlorbartonite;, Clin, clinohumite; Cl, chlorite, Co, corindon; Cof, coffinite; Coq, coquimbite; Cor, cordylite; Cpx, clinopyroxene; Crio, criolite; Do, dolomite; Elp, elpidite; Eu, eudyalite; Fer, fersmite; Ferg, fergusonite; Fers, fersmanite; Fersm, fersmunite; Ferrok, ferrokentbrooksite; Gib, gibbsite; Got, götzenite; Hai, hainite; Flo, florencite-(Ce); Fl, fluorite; Flucap, fluorcaphite; Fluora, fluorapophyllite; Ga, galena; Gai, gaidonnayite; Gal, galgenbergite; Ge, gearksutite; Geo, georgechaoite; Gl, glass; Go, goethite; Gon, gonnardite; Gor, gorceixite; Goy, goyasite; Gr, garnet; Gre, gregoryite; Gy, gypsum; Hal, halloysite; Halo, halotrichite; Hay, haüyne; Hc, hercynite; Hem, hematite; Hi, hiortdahlite; Hil, hilairite; Hu, huanghoite; Hydro, hydrotalcite; Iso, isokite; Jar, jarosite; Ka, kaolinite; Kal, kalsilite; Kali, kalistrontite; Ken, kentbrooksite; Kim, kimzeyite; Ko, kochite; Ku, kutnohorite; Kup, kupletstike; Lam, lamprohyllite; Lan, lanthanite; Lav, låvenite; Lc, leucite; Li, limonite; Lith, lithiophyllite; Lo, loparite; Lor, lorenzenite; Mag, magnesite; Mal, malachite; Man, manasseite; Me, melanite; Mel, melilite; Melch, melcherite; Men, menezesite; Mgeu, manganoeudialyte; Mo, monazite; Mol, molybdenite; Mont, montimorillonite; Monti, monticellite; Mos, mosandrite-(Ce); Nar, narsarsukite; Ne, nepheline; Nena, nenadkevikita; Neo, neotocite; Nep, neptunite; Nio, niobophyllite; Nor, normandite; Nors, norsethite; Nos, Nosean; Ny, nyerereite; Ol, olivine; Ole, oleminskite; Op, opaque (mainly magnetite and ilmenite); Opx, orthopyroxene; Par, parisite; Paul, pauloabitite; Pe, perrierite; Pec, pectolite; Pl, plagioclase; Psd, pseudoleucite; Phlo, phlogopite; Phy, pyrrhotite; Pol, polezhaevaite-(Ce); Pv, perovskite; Py, pyrochlore; Pyr, pyrite, Pyro, pyrophanite; Qz, quartz; Qui, quintinite; Rem, remondite; Rha, rhabdoanio; Rib, riebeckite; Rin, rinkite; Ro, rodochrosite; Ros, rosenbuchite; Roz, rozenite; Ru, rutile; San, sanidine; Se, serandite; Ser., serpentine; Sho, Sid, siderite; So, sodalite; Sp, spinel; Sph, sphalerite; Str, strontianite; Stro, stronadelphite; Syl, sylvite; Syn. synchisite; Tai, tainiolite; Tfpho, tetra-ferriphlogopite; Th, thorite; The, thenardite; Tho, thorianite; Thom, thomsonite; Thorba, thorbastnäsite; Ti, titanite; To, toikilinite; Tor, torbernite; Tu, tuperssuatsiaite; Ura, uraninite; Val, vallerite; Ver, vermiculite; Vil, villiaumite; Vi, vishnevite; Yt, yttrialite; Xe, xenotime; Wad, wadeite; Wit, witherite; Wö, wöhlerite; Wol, wollastonite; Ze, zeolite (mainly natrolite and mesolite); Zem, Zir, zirconolite; Zr, zircon. *It includes late-stage magmatic, subsolidus alteration, hydrothermal, and deuteric phases.

Table 5. Mineral data on alkaline occurrences from the southern (Valle Chico and Piratini) and northern (Rondonópolis Anteclise) regions of the Paraná Basin.

Valle Chico	Piratini	Rondonópolis Anteclise
Rock types		
S, Qs, Gr, Sgr, Lat, Tr, Rh	Pho, Tepho	S, Qs, Agr, Tr, Ta, Tb, Rh, Ki, Lp
Main mineralogy		
Af, Qz, Pl, Cpx. Bi, Amp, Ap, Ti, Op, Zr	Af, Ne, Nos, So, Cpx, Me, Ap, Ti, Op	Af, Qz, Pl, Cpx, Bi, Amp, Phlo, Gr, Ap, Bi, Op, Pv, Ae, As, Ol
Replacement mineralogy		
Cl, Fl, Anat	Ana, Ca, Can, Hem, Psd, Ze	Amp (Rib), Bi, Ca, Ser
Agpaitic mineralogy		
	Ae	Ae, As

Table 6. Mineral data of alkaline occurrences from the central-eastern region of the Paraná Basin.

Ponta Grossa Arch	Serra do Mar	Cabo Frio Lineament
Rock types		
Du, Per, Cpy, Ag, The, E, Ij, Mel, We, Gl. Di, Phos, Ma, Ca, S, As, Ns, Sd, Sg, Mon, Fe, Ank, Ne, Bas, Te, Phot, Ab, Tb, Pho, Tin, Tr, Sh, Ki, Pho, La, Br	S, As, Ns, Qs, Ga, Gr, Mzd, Pho, Bas, Ank, Analc, Ab, Ta, Tb, Tr, Ms, Te, La, Br	Ns, As, Sn, Qs, Pho, Ms, Tr, Ma, Cpy, Pe, Ij, Ga, Ca, Sh, Phot, Te, Mon, Mzd, ga, Ig, Pic, La, Br, Tu
Main mineralogy		
Ol, Cpx, Pl, Ne, Af, San, Ano, Bi, Phlo, Amp, Me, Mel, Ca, Do, Ap, Ti, Op, Pv, Zr, Mol, Val	Af, Cpx, Bi, Amp, Ne, Pl, Eu, Qz, Co, Hc, Ol, Phlo, Me, Ap, Ti, Op, Hy, Wo	Ae, Af, Bi, Cpx, Amp, Qz, Pl, Ne, So, Gr, Ap, Ti, Op, Zr
Replacement mineralogy		
Al, An, Anat, Ang, Ank, Arag, Ba, Bad, Bas, Bur, Cal, Can, Car, Ce, Cels, Ceru, Cha, Cli, Eu, Fer, Fl, Ga, Ge, Hay, Hem, Ka, Kal. Ku, Mag, Mal, elch, Men, Mo, Mont, Monti, Nos, Par, Paul, Pec, Psd, Pyro, Ser, Sid, So, Sph, Str, Syl, Syn, Tfpho, To, Ver, Wo, Ze, Zir	Ana, Alla, Bad, Bast, Bri, Ca, Cha, Che, Ferg, Fl, Gl, Gr, Kali, Kup, Lav, Mo, Pe, Pec, Py, Pyr, Psd, Ru, So, Syn, Th, Yt, Ze, Zir, Zr	Alu, Alun, Ana, Anc, Ank, Ba, Bas, Be, Ber, Bur, Ca, Can, Ce, Cer, Cham, Cher, Chlo, Coq, Crio, Fersm, Fl, Flo, Flucap, Fluora, Gib, Gon, Gy, Hal, Halo, Hay, Jar, Ka, Ku, Lan, Lc, Lith, Lo, Mo, Neo, Nos, Pol, Psd, Py, Pyro, Roz, Stro, Tai, Th, The, Tho, Thom, Thorba, Ura, Vil, Vis, Xe, Ze
Agpaitic mineralogy		
Eu, Pec	Ae, As, Cat, Eu. Hi, Ken, Ko, Låv, Mge, Mos, Nio, Rin. Ros, Wö	Ae, As, Bor, Cah, Cat, Cof, Elp, Eu, Fers, Ferrok, Gai, Geo, Hi, Hil, Göt, Hai, Ken, Ko, Kup, Lam, Lor, Mgeu, Mos. Nar, Nep, Nio, Nor, Pec, Rin, Ro, Se, Tup, Wad, Wö

Table 6. Cont.

Alto Paranaíba	Goiás
Rock types	
Du, Cpy, Per, Phos, Ns, Sm Nel, Gl, Be, Ca, Fe, Sil, Ka, Ki, Tin, Tr, Sil, Unc	Du, Cpy, Per, We, Wb, Ag, The, E, Ij, Mel, Sg, Ns, S, Pho, Tr, Ms, Bas, Te, mNe, Ca, mAnalc, mLeuc, Sh, La, Ki, Lp, Pic, Kam series (Ma, Ug, Kat), Pyro, Br
Main mineralogy	
Ol, Cpx, Gr, Pv, Phlo, Ti, Ca, Do, Cr , Bad	Ol, Cpx, Opx, Ne, Kal, Lc, Mel, Af, Phlo, Bi, Gr, Sp, Ap, Op
Replacement mineralogy	
Al, Amp, Anat, Anc, Au, Ba, Bar, Bas, Ben, Bur, Ca, Cal, Can, Car, Clin, Flo, Go, Gor, Goy, Gre, Hu, Hydro, Iso, Kin, Ku, Man, Mel, Mo, Monti, Nena, Nors, Ny, Ole, Par, Py, Quin, Rha, Ru, Ser, Sho, Str, Tfpho, Tor, Xe, Ze, Zem, Zir, Wad, Wit	Amp, Ana, Ank, Ca, Gl, Lc, Can, Py, Sid
Agpaitic mineralogy	
	Eu

9 MINERALOGY

9.1 TYPE I ASSOCIATION

It is represented by a mineralogical suite with a prevalence of felsic components, particularly feldspars and feldspathoids. Quartz is a frequent phase of silica-oversaturated varieties, being described in pulaskites and nordmarkites of the São Sebastião island and in granites of the Itatiaia massifs, for instance. The syenitic rocks are mostly leucocratic, with clinopyroxene and amphibole as widespread mafic phases. Alkali feldspar is variable in texture, ranging from cryptoperthite to coarse braided and patch perthite. Mesoperthite of distinct degrees of exsolution is abundant. Orthoclase is a common mineral in intrusive syenitic and syenodioritic rocks and cumulates of the ijolite series. Sanidine and anorthoclase, especially as phenocrysts, are more dominant in fine-grained varieties. Plagioclase is either absent or found in small amounts, mainly as albite rims over alkali feldspar grains or as a member of the groundmass. In silica-undersaturated and mafic rocks, it tends to be more calcic and occurs in higher proportion. Nepheline is the most important and primary mineral of the feldspathoid group. Sodalite is subordinate. In most cases, nepheline indicates that it is transformed into sodalite and analcime or altered to secondary phases, such as cancrinite and zeolite. Data available in the literature (MORBIDELLI *et al.,* 1995; GOMES *et al.,* 1996b; COMIN-CHIARAMONTI *et al.,* 2005a) report low values for excess silica, with nepheline compositions falling partially near and partially within the Morozewicz-Buerger convergence field for the plutonic phases (TILLEY, 1954). Sodalite, nosean, and pseudoleucite are also reported as phenocrysts in fine-grained rocks. Mafic minerals have clinopyroxenes and amphiboles as principal phases and minor amounts of biotite. They have been described in all rock types, with amphiboles replacing clinopyroxene and, usually, being lately altered into biotite and chlorite. These minerals change from Mg-rich to Fe-rich varieties, successfully falling within the calcic, sodic-calcic and sodic groups. Clinopyroxenes exhibit a wide compositional variation, plotting mainly in the aegirine-augite field, with Mg-rich varieties associated with less evolved rocks fitting the diopside-salite field and the Fe^{3+}-Na-rich phases (aegirine) related to agpaitic rocks. A continuous variation from diopside to aegirine-augite to aegirine is the main pattern in the crystallization trend diagrams for minerals of various alkaline occurrences (GOMES *et al.,* 2021), reflecting the evolutive stage of the host rocks. Zoning is a common feature of clinopyroxenes, with crystal rims enriched in Fe^{3+}-Na and displaying a dark green color. Amphiboles are mostly indicated by members of the calcic group, which shows as general minerals hastingsite, hornblende, edenite, and kaersutite. The sodic-calcic group occurs subordinately, having as more common phases barroisite, katophorite, wichite, and richerite, according to LEAKE's (1978) nomenclature. The sodic group is relatively scarce and mainly related to peralkaline rocks, as are the agpaitic ones. Compositionally, the last group consists of glaucophane-riebeckite and eckermanite-arfvedsonite (MORBIDELLI *et al.,* 1995). The amphibole compositions strongly reflect the nature of the host rocks. As the alkali's activity increases, a trend from calcic to sodic-calcic varieties is observed. Phlogopite and biotite are essential constituents of almost all mafic rocks, leucocratic lithotypes, and cumulates. A deficiency of Al in the tetrahedral site is the characteristic feature of these minerals (MORBIDELLI *et al.,* 1995). They commonly occur in different forms and represent more than one phase of crystallization. Chemically, they fall along the phlogopite-annite field. The micas are closely associated with opaque minerals (magnetite and ilmenite) resulting from their alteration. Titanite, apatite, and opaques are the most frequent accessory minerals. Other phases recognized include titaniferous garnet (melanite), corundum, zircon, and a few exotic and rare secondary minerals listed in the tables.

The most remarkable feature of the syenitic association is its agpaitic mineralogy, which is primarily present in the Poços de Caldas massif (GOMES *et al.,* 2021, 2023) and the Cerro Boggiani complex (COMIN-CHIARAMONTI *et al.,* 2016). These alkaline rocks contain mineral assemblages that denote a richness of typical halogen-bearing Na-Ca-HFSE phases, with eudialyte, rinkite, and wöhlerite-group minerals being the most frequent ones. In fact, the assemblages are chemically more complex, with accessory minerals including U-Th oxides/silicates, Nb oxides, REE-Sr-Ba-bearing carbonates, fluorocarbonates, phosphates, silicates, and Zr-Na-rich silicates. As noted by GOMES *et al.* (2021), these forms derive from a late magmatic to hydrothermal/deuteric stage of crystallization linked to highly evolved silica-undersaturated rocks.

9.2 TYPE II ASSOCIATION

It contains fewer mineral specimens compared to its syenitic counterpart. In intrusive and fine-grained rocks cropping out in Paraguay, olivine, clinopyroxene, nepheline, and plagioclase are the main phases, whereas alkali feldspar is more pronounced in syenitic varieties (COMIN-CHIARAMONTI *et al.,* 1996a). Olivine and clinopyroxene show marked chemical variation, with their compositions falling within the chrysotile-hyalosiderite and diopside-hedenbergite fields, respectively. In most cases, these minerals occur as cumulus phases. Biotite is common, while amphiboles of the calcic and sodic-calcic groups may be present in more evolved rocks (syenites, syenodiorites). Accessory minerals include apatite, titanite, opaque minerals, zircon, and occasionally garnet. Alteration products include cancrinite, analcime, leucite/pseudoleucite, haüyne, and carbonates. Olivines and clinopyroxenes of the Goiás suite (BROD *et al.,* 2005) exhibit similar characteristics, yet analytical data for feldspar-bearing rocks are limited. Biotite is present, while phlogopite occurs as a pseudomorph of olivine crystals. Additional occurrences of the mafic-ultramafic gabbroic association do not exhibit significant differences, except for the greater abundance of ultramafic cumulates, as observed in the Pariquera-Açu and Ponte Nova massifs, and for the presence of Zr- and Ba-rich minerals in gabbroic lithologies from the Ponte Nova complex (AZZONE *et al.,* 2009).

9.3 TYPE III ASSOCIATION

It has as its principal mark the carbonatites, whose presence is mainly concentrated in two areas of the Brazilian territory: the Alto Paranaíba and the Ponta Grossa Arch provinces. However, these rocks are also recognized in other important locations such as the complexes of Cerro Chiriguelo and Cerro Sarambí in the Paraguayan region of Amambay, and Cerro Manomó in the Bolivian province of Velasco. Primary carbonatitic material forming rounded aggregates (*ocelli*) is described in Eastern Paraguay, associated with ijolitic rocks (Cerro Cañada and Cerro E Santa Helena) and basanite dikes (Valle-mí), and in a small lava flow near the village of Sapucai. The association is characterized by a wide petrographic diversity, including numerous and chemically variable rock types, as well as forms resulting from metasomatic processes (fenites, phoscorites). The mafic-ultramafic varieties bear highly magnesian olivine, with Fo decreasing progressively toward the most differentiated rock types. In the Salitre complex, carbonatites and phoscorites present the highest Fo content (BARBOSA *et al.,* 2012). Clinopyroxenes of mafic-ultramafic lithologies are predominantly in the diopside field, ranging toward augite in gabbroic rocks and aegirine-augite in syenites. Amphiboles are closely associated with clinopyroxenes, replacing them, and mainly belonging to the calcic group. Phlogopite, from primary magmatic crystals to late-stage metasomatic phases, follows a distinct evolutionary trend with magmatic differentiation (BROD *et al.,* 2001). In the least differentiated silicate rocks (dunites, wehrlites), high-Mg phlogopite evolves to annite, while metasomatic micas in carbonatites are characterized by an inversion to tetra-phlogopite. Occasionally, it shows unimineral clustering (glimmerites), as reported in some complexes (Catalão, Ipanema, and Anitápolis, for example). Calcic plagioclase is frequently present in the gabbroic suite, while alkaline feldspar occurs in syenitic-syenodioritic and equivalent aphanitic rocks, either as phenocrysts or as a component of the groundmass. Melilite is an important mineral in the ijolitic rocks of Jacupiranga, reaching modal contents of up to 10% (BECCALUVA *et al.,* 2017), being also described in olivine melilites of Lages by TRAVERSA *et al.* (1994). Regarding accessory minerals, apatite, titanite, garnet, perovskite, baddeleyite, zircon, and opaques (magnetite, ilmenite, and various sulfides) are identified. Late-stage minerals, mainly derived from olivine, are typically represented by clinohumite in the Jacupiranga, Catalão I, and Salitre carbonatites, and by monticellite in the Jacupiranga and Lages complexes, as well as in ultramafic rocks of the Alto Paranaíba province (Catalão I, Indaiá I, Lemes, and Limeira I kimberlites; Canas, kamafugite). The aforementioned associations are also characterized by the presence of high amounts of carbonate and other secondary minerals, related not only to a deuteric stage of crystallization but also to metasomatic mineralizing carbonatitic fluids, which give rise to an assemblage consisting of accessory REE-Sr-Ba-bearing carbonates-fluoro-carbonates, phosphates, silicates, and oxides, usually replacing previous phases such as components of the groundmass and cavity fillings.

9.4 TYPE IV ASSOCIATION

Although of limited areal expression, it is characterized by numerous intrusions scattered across the Brazilian Platform, occurring as dikes, dike swarms, plugs, sills, and lava domes. Its rocks vary greatly in composition, ranging from mafic-ultramafic to more evolved types. In the Serra do Mar region, for instance, foidites, basanites/tephrites, and phonolites are the most common lithotypes, whereas alkali basalts to trachytes are subordinate (BROTZU *et al.,* 2005). Lamprophyric dikes, with monchiquites as the prevalent variety, are abundant along the southern Brazilian coast, where they occur in association with other rock types (GARDA; SCHORSCHER, 1996; VALENTE, 1997; COUTINHO, 2008). Phonolites and associated rocks (tephri-phonolites, nephelinites, trachyphonolites, peralkaline phonolites) are widespread, occurring as dikes in the Piratini and Vale do Ribeira regions. Sodic volcanic rocks (ankaramites) have been reported in lava flows that lie interbedded with sediments of the Volta Redonda (RICCOMINI *et al.,* 1983) and Itaboraí (KLEIN; VALENÇA, 1984) basins in the state of Rio de Janeiro. Additional occurrences of sodic rocks are recorded in Jaboticabal, possibly as a tinguaite sill (GOMES; VALARELLI, 1970) emplaced into sediments of the Bauru Basin, and in Aparecida do Monte Alto, Piranji, and Taiúva in São Paulo. Drill samples collected from a probable sill were described as analcimites by COUTINHO *et al.* (1982).

9.5 TYPE V ASSOCIATION

It is exclusive to central Brazil. A volcanism of large extension affected the area during the Mesozoic, leading to the emplacement of rocks of unusual composition belonging to the kamafugite series and numerous kimberlite pipes, some of which are of economic importance. The kamafugitic lavas (katungites, mafurites, leucite mafurites, and ugandites) are mainly concentrated in the central and southern portions of the Goiás province, but they also extend to the eastern Alto Paranaiba province, forming one of the largest exposures of kamafugitic rocks in the world (BROD *et al.,* 2005). These rocks (lavas and pyroclastic deposits) are highly variable in composition, with some varieties (leucitites, analcimites, olivine analcimites) being redefined as members of the kamafugite series based on new mineralogical evidence. Associated late-stage dikes consist of lamprophyres (monchiquites, fourchites), phonolites, and trachytes. The mineralogy of the feldspar-free rocks exhibits olivine, clinopyroxene, mica, and spinel minerals as the most important mafic phases. Olivine, occurring as phenocrysts or occasionally in the groundmass, is heterogeneous in composition, falling in the hyalosiderite-chrysotile fields. Clinopyroxene, in varied forms, corresponds to the diopside-hedenbergite solid solution. Mica may be classified as phlogopite, sometimes with significant participation of tetra-phlogopite (BROD *et al.,* 2005). Spinel-group minerals form a frequent accessory phase. The felsic group is primarily represented by nepheline, kalsilite, and leucite. Analcime is a common alteration product of kalsilite and leucite.

9.6 TYPE VI ASSOCIATION

It is related to two occurrences of sodic lavas in Eastern Paraguay. The volcanism in the region of Asunción is the most important one, encompassing several small bodies that occur mainly as plugs and lava domes (BITSCHENE, 1987; COMIN-CHIARAMONTI *et al.,* 1991). The Misiones rocks are represented by three plugs and one dike, all cropping out in San Juan Bautista area (VELÁZQUEZ *et al.,* 2006). Nephelinites and ankaratrites bearing mantellic nodules are the dominant rock types, with subordinate peralkaline phonolites. Olivine and clinopyroxene, as phenocrysts or in the groundmass, are the most abundant mafic phases, plotting mostly in the forsterite-chrysotile and diopside-salite fields, respectively. Additional minerals include nepheline, plagioclase, alkali feldspar, biotite, spinel, opaques, and glass.

10 CONCLUDING REMARKS

Numerous alkaline and alkaline-carbonatitic intrusions of highly variable sizes, modes of occurrence, compositions, and ages are known to occur in the Brazilian Platform, close to the borders of the Paraná, Pelotas, and Santos sedimentary basins (GOMES and COMIN-CHIARAMONTI, 2017). The boundaries of the Paraná Basin, an interior cratonic syneclise, are especially characterized by syn- and post-tectonic activities, which resulted in the formation of arches, structural lineaments, rifts, and faulty zones, parallel or transverse to its vicinities. These tectonic features played an important role in the tectonic control and distribution, both temporal and spatial, of associated tholeiitic and alkaline magmatism manifestations (ALMEIDA, 1983; RICCOMINI *et al.,* 2005). Following ALMEIDA's (1983) original concept, these alkaline occurrences are grouped into distinct provinces based on geological evidence, petrographic associations, and ages. Also, to better characterize and correlate among different occurrences, alkaline types are arranged based on their petrographic associations and mineralogical aspects

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