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PETROGRAPHY, TEXTURAL VARIATIONS, AND MAGMATIC EVOLUTION OF SUBALKALINE MAFIC DYKES FROM THE PONTA GROSSA ARCH, BRAZIL

PETROGRAFIA, VARIAÇÕES TEXTURAIS E EVOLUÇÃO MAGMÁTICA DE DIQUES MÁFICOS SUBALCALINOS DO ARCO DE PONTA GROSSA, BRASIL

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ABSTRACT - The Ponta Grossa Arch, located in the northern Paraná Basin, represents an important Mesozoic tectonic structure whose associated magmatism is expressed by mafic dykes trending predominantly NW–SE, highlighting the influence of regional structural control on magma emplacement. This study presents a detailed petrographic analysis of mafic dykes grouped according to the three main structural lineaments of the arch: Guapiara (north), São Jerônimo–Curiúva and Rio Alonzo (central), and Piquiri (south). Four main lithotypes were identified: basalt, diabase, gabbro, and mafic pegmatite. The dykes predominantly exhibit subophitic and intergranular textures, with mineral assemblages composed mainly of plagioclase, augite, pigeonite, opaque minerals, and apatite. Petrographic and textural variations among the dykes indicate distinct emplacement conditions and crystallization histories within each structural sector. The Guapiara Lineament is characterized by shallow emplacement conditions and relatively rapid cooling, locally preserving volcanic glass and hyalophitic textures. In contrast, the São Jerônimo–Curiúva and Rio Alonzo sector records greater magmatic complexity, marked by multiple intrusive pulses, evolved residual melts, and late-stage differentiation processes, including the occurrence of mafic pegmatites. The Piquiri sector presents comparatively more homogeneous petrographic characteristics, suggesting relatively deeper and more uniform crystallization conditions. These petrographic differences are interpreted as the result of variations in cooling rates, emplacement depth, and post-Cretaceous tectonic evolution, which controlled both magma evolution and the present-day differential crustal exposure within the Ponta Grossa Arch.
Keywords: Ponta Grossa Arch. Serra Geral Group. Dyke swarm. Petrographic analysis. Paraná Basin.

RESUMO - O Arco de Ponta Grossa, localizado na porção norte da Bacia do Paraná, representa uma importante estrutura tectônica mesozoica cujo magmatismo associado é expresso por diques máficos com direção predominante NW–SE, destacando a influência do controle estrutural regional na colocação dos magmas. Este estudo apresenta uma análise petrográfica detalhada de diques máficos agrupados de acordo com os três principais alinhamentos estruturais do arco: Guapiara (norte), São Jerônimo–Curiúva e Rio Alonzo (central) e Piquiri (sul). Foram identificados quatro principais litotipos: basalto, diabásio, gabro e pegmatito máfico. Os diques exibem predominantes texturas subofítica e intergranular, com assembleias minerais compostas principalmente por plagioclásio, augita, pigeonita, minerais opacos e apatita. As variações petrográficas e texturais entre os diques indicam distintas condições de colocação e histórias de cristalização em cada setor estrutural. O Alinhamento Guapiara é caracterizado por condições de colocação rasa e resfriamento relativamente rápido, preservando localmente vidro vulcânico e texturas hialofíticas. Em contraste, o setor São Jerônimo–Curiúva e Rio Alonzo registra maior complexidade magmática, marcada por múltiplos pulsos intrusivos, melts residuais evoluídos e processos tardios de diferenciação, incluindo a ocorrência de pegmatitos máficos. O setor Piquiri apresenta características petrográficas comparativamente mais homogêneas, sugerindo condições de cristalização relativamente mais profundas e uniformes. Essas diferenças petrográficas são interpretadas como resultado de variações nas taxas de resfriamento, profundidade de colocação e evolução tectônica pós-cretácea, que controlaram tanto a evolução dos magmas quanto a exposição crustal diferencial atual no Arco de Ponta Grossa.
Palavras-chave: Arco de Ponta Grossa. Província Magmática do Paraná. Enxame de diques. Análise petrográfica. Bacia do Paraná.

INTRODUCTION

The Ponta Grossa Arch (PGA) dyke swarm represents one of the most significant geotectonic manifestations associated with Lower Cretaceous magmatism in Brazil (Almeida, 1986; Almeida et al., 2012). Inserted within the Paraná Magmatic Province (PMP), or the Paraná–Etendeka Magmatic Province (PEMP) when considering the continuity of basaltic flows into the African continent, this swarm is intrinsically related to the structural evolution of the arch during the Late Mesozoic.

Several studies interpret the PGA as a regional crustal uplift structure that exerted decisive tectonic control on the emplacement of Early Cretaceous dykes, as well as on their spatial organization and distribution (Almeida et al., 1977; Almeida, 1986; Pinese, 1989).

Despite the significant number of studies dedicated to the magmatism of these dykes, particularly those of Pinese (1989), Piccirillo et al. (1988, 1990), and Marques (2001), important gaps remain in the integrated understanding of emplacement processes and crystallisation conditions, especially regarding the significance of the observed microtextural variations.

Over the last two decades, highway construction and mining activities have exposed new outcrops, allowing access to previously unavailable areas. Particularly noteworthy are the dykes intercepted along the BR-153 highway and those exposed in mining fronts registered by the Brazilian National Mining Agency, which have enabled more systematic sampling of these bodies.

Accordingly, the present study aimed to characterize the micropetrographic features of the subalkaline dykes of the PGA, with emphasis on the description of textures, structures, and mineral relationships observed in petrographic thin sections. Based on this approach, the study sought to identify textural variations along different segments of the arch and to evaluate their significance in the context of magmatic crystallisation processes.

The different sectors of the PGA were delimited according to the main regional structural lineaments: Guapiara, São Jerônimo–Curiúva and Rio Alonzo, and Piquiri (Ferreira, 1982).

Variations in microtextures, as well as differences in the primary mineral assemblages, appear to be related to exhumation processes acting within the PGA along these structural lineaments. This interpretation is mainly supported by the predominance, particularly in the central sector of the arch, of microtextures compatible with slower cooling regimes and crystallisation at relatively greater crustal depths.

METHODS

A total of 36 samples from subalkaline basaltic dykes, predominantly trending NW–SE, were selected from different localities within the Ponta Grossa Arch (PGA). The samples were grouped according to the main structural lineaments: Guapiara, northern sector, São Jerônimo–Curiúva and Rio Alonzo, central sector, and Piquiri, southern sector.

Most samples were collected from outcrops exposed along highway road cuts in the states of Paraná and São Paulo, ensuring adequate spatial representativeness of the investigated area.

Erosional processes associated with the South American Planation Surface (Franco-Magalhães et al., 2010a and b; Grohmann and Riccomini, 2012) have affected the region, frequently removing or modifying portions of the intrusive bodies, particularly with respect to the preservation of their lateral contacts. In this context, sampling was conducted carefully, prioritizing outcrops with better structural and petrographic preservation.

The central portions of the dykes were systematically prioritized, as grain size is more developed and primary features are better preserved in these domains. This criterion aimed to minimize the effects of secondary alteration, generally more intense along dyke margins, thereby ensuring greater reliability in the petrographic characterization of the samples.

During petrographic analyses, parameters such as texture, grain size, and intergranular relationships were evaluated, as these may constitute direct records of the thermal conditions acting during the emplacement and cooling of the mafic bodies.

Petrographic analyses were carried out at the Microscopy Research Laboratory, Department of Geology, Federal University of Paraná. Thin sections were examined under a polarizing optical microscope, and photomicrographs were acquired using a coupled digital imaging system, Canon EOS Rebel T7, which also enabled crystal measurements and the acquisition of basic descriptive statistics. The anorthite content of plagioclase crystals was determined using the Michel-Lévy method.

Petrographic descriptions and rock classify-cation followed the recommendations of Le Maitre et al. (2002) and Gill (2010), according to the nomenclature criteria proposed by the International Union of Geological Sciences (IUGS).

Rock nomenclature was based exclusively on descriptive criteria derived from the observed mineralogy and textures, avoiding interpretations conditioned by provenance or geotectonic setting (Gill, 2010).

INTRUSIVE EVENTS OF THE PARANÁ MAGMATIC PROVINCE

The Paraná Magmatic Province (PMP) (Figure 1) extends across southern, southeastern, and central Brazil. The PMP also reaches portions of Argentina, Paraguay, and Uruguay (Bellieni et al., 1983, 1984a and b).

Within the stratigraphy of the Paraná Basin, this province comprises the volcanic flows of the Serra Geral Group (SGG), as well as associated intrusive bodies represented mainly by dykes and sills.

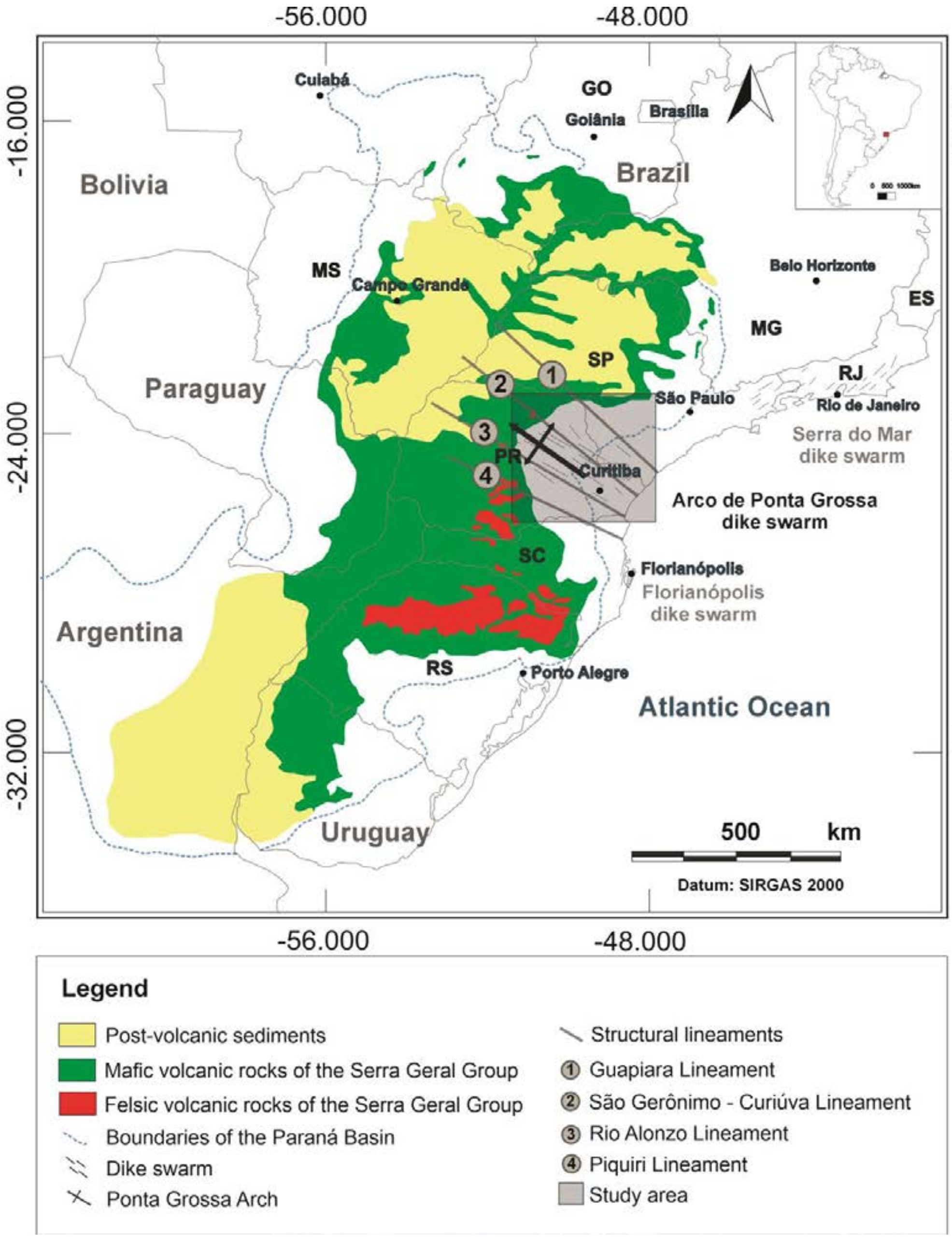

Figure 1 - Simplified geological map of the Paraná Basin showing the subalkaline dyke swarms, with emphasis on the Ponta Grossa Arch (PGA) and its structural lineaments according to Ferreira et al. (1981) and Ferreira (1982). The map also shows the distribution of post-volcanic sedimentary units, mafic and felsic volcanic rocks of the Serra Geral Group, as well as the limits of the Paraná Basin according to Nardy et al. (2008), Janasi et al. (2011), and Polo and Janasi (2014).

The lava flows cover approximately 75% of the basin surface, totaling an estimated area of about 917,000 km² (Frank et al., 2009). Compositionally, they consist predominantly of tholeiitic basalts and basaltic andesites, approximately 90%, together with subordinate andesites, 7%, and felsic rocks, 3%, according to Nardy et al. (2008).

The Lower Cretaceous lava flows are related to the Wealdenian Reactivation, which profoundly affected the Paraná Basin and resulted mainly from epirogenetic tectonic processes (Almeida, 1967).

During this period, the region was subjected to an extensional tectonic regime (Rostirolla et al., 2000), expressed by extensive fault systems predominantly trending NW–SE (Zalán et al., 1990). This tectonic framework favored not only the emplacement of lava flows, but also the intense intrusion of sills and dyke swarms.

According to Marques and Ernesto (2004), the highest concentrations of these intrusions occur in the eastern and northeastern portions of the PMP, particularly in the states of São Paulo and Paraná, where the Ponta Grossa Arch dyke swarm stands out. In addition to the PGA, other important dyke swarms are recognized, as described below.

The Florianópolis Dyke Swarm is composed of tholeiitic basalts, basaltic andesites, andesites, trachyandesites, and dacites / trachydacites. Approximately 90% of these bodies are classified as high-Ti, $TiO_2 > 2$ wt%, whereas the remaining 10% are low-Ti, $TiO_2 < 2$ wt% (Marques et al., 1993; Peate et al., 1999). U–Pb dating of two baddeleyite fractions yielded an age of approximately 134 Ma (Florisbal et al., 2011).

The Serra do Mar Dyke Swarm is distributed along the coastal region of the states of São Paulo, Rio de Janeiro, and part of Espírito Santo (Heilbron et al., 2004). Those dykes are composed mainly of basaltic andesite and trachybasalt, together with intermediate rocks (Dutra, 2006).

Geochemical studies indicate the predominance of high-TiO_2 units, although two subordinates low-TiO_2 geochemical signatures have also been recognised (Corval et al., 2008; Monteiro and Valente, 2003). K–Ar and Ar–Ar dating indicate ages close to 134 Ma (Tomba, 2012).

Ponta Grossa Arch (PGA)

The Ponta Grossa Arch (PGA) is interpreted as an important crustal flexure extending across almost the entire State of Paraná, also encompassing small portions of the states of Santa Catarina and São Paulo, totalling approximately 134,000 km² (Almeida et al., 1977; Pinese, 1989).

According to Zalán et al. (1990), tectonic reactivations occurring between the Devonian and Permian produced local faulting in the PGA region, while the Paraná Basin evolved as an intracratonic syneclise controlled by pre-existing fault systems. Isopach data indicate that, as early as the Devonian, during deposition of the Furnas Formation, the central sector of the PGA already constituted a relatively uplifted area (Almeida, 1983).

Between the Permian and Jurassic, the region underwent recurrent episodes of crustal uplift interpreted as the result of thermal processes, possibly related to intraplate lithospheric reactivation. These events promoted the reorganization of the structural framework along the eastern margin of the Paraná Basin, controlling differential subsidence and restricting sedimentary deposition, while also favoring the development of a broad domal structure (Zalán et al., 1990).

The present structural configuration of the PGA was consolidated between the Late Cretaceous and the Eocene, when uplift of the Serra do Mar triggered successive reactivations of inherited crustal discontinuities, intensifying brittle deformation and tectonic compartmenttalization along the eastern border of the basin, with consequent regional uplift of the arch (Franco-Magalhães et al., 2010a, b).

The structural framework of the PGA was defined from the integrated interpretation of aeromagnetic data carried out by Ferreira et al. (1981), Ferreira (1982), Fúlfaro (1982), and Oliveira and Montes (1984) (Figure 2). According to these authors, the northern boundary of the arch is marked by the Guapiara Structural Lineament, which extends from southeastern São Paulo State towards the Paraná Basin and is characterized by magnetic anomalies associated with dyke emplacement and fracture zones displaying a general N50°W orientation.

The central portion of the PGA is delimited by the São Jerônimo–Curiúva and Rio Alonzo structural lineaments, characterized by a high density of dykes predominantly oriented between N45°W and N55°W. To the south, the Piquiri Structural Lineament defines the southern boundary of the system, being characterized by fault systems with downthrown blocks, lower dyke density, and predominant orientations between N60°W and N65°W.

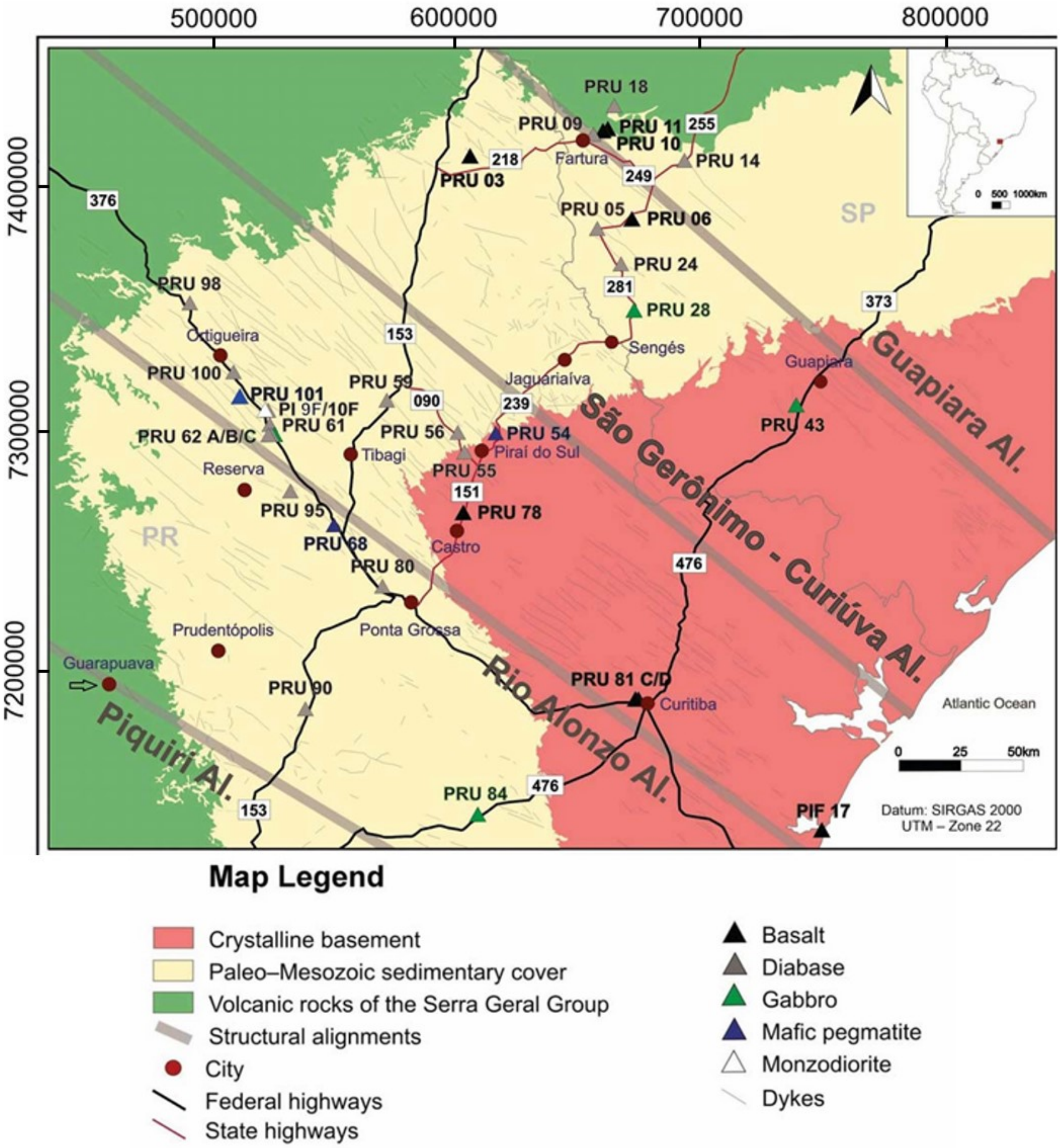

Figure 2 - Location map of the samples collected within the Ponta Grossa Arch, showing the structural lineaments defined by Ferreira et al. (1981), Ferreira (1982), Fúlfaro (1982), and Oliveira and Montes (1984), together with the simplified geological map modified from Horn et al. (2022).

The PGA Dyke Swarm

The PGA dyke swarm is composed predominantly of mafic dykes displaying variable thicknesses, locally reaching hundreds of metres, and extending for up to hundreds of kilometres (Raposo, 1995).

These bodies intrude both Precambrian basement rocks and the sedimentary units of the Paraná Basin (Figures 3 and 4), and less frequently the volcanic flows of the Serra Geral Group (Almeida et al., 2012). These intrusions constitute an essential component of the Mesozoic magmatic event, whose peak activity occurred during the Lower Cretaceous.

The swarm is composed predominantly of mafic rocks with tholeiitic affinity, although subordinate felsic and alkaline dykes also occur (Pinese, 1989; Piccirillo et al., 1990).

Structural evidence indicates that dyke emplacement was associated with an extensional tectonic regime, which promoted the reactivation of pre-existing regional faults, generating crustal discontinuities and zones of weakness that acted as preferential conduits for the ascent and intrusion

Figure 3 - Diabase dyke exposed in a mining front, displaying columnar jointing. Samples PI-10F and PI-09F are indicated in figure 2.

Figure 4 - Diabase dyke exposed along the BR-373 highway. Sample PRU-80 is indicated in figure 2.

of dykes predominantly trending NW–SE (Renne et al., 1992; Strugale et al., 2007; Coutinho, 2008). As a consequence, crustal extension has been estimated at approximately 3 km, according to Almeida et al. (2012).

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According to Pinese (1989) and Piccirillo et al. (1988, 1990), basalt, diabase, or dolerite, basaltic andesite, andesite, trachyandesite, and trachyte dykes have been identified, representing between 80% and 85% of the total dykes within the arch. Among these, basalts and basaltic andesites are the most abundant, whereas approximately 15% to 20% correspond to alkaline dykes. The mineralogy is dominated by plagioclase, clinopyroxenes, augite and pigeonite, subordinate olivine, and Fe–Ti oxides.

$^{40}Ar/^{39}Ar$ dating of plagioclase performed by Renne et al. (1992) indicates ages between 131.4 ± 0.4 Ma and 129.2 ± 0.4 Ma for the NW-trending dykes, with a peak at 130.5 Ma, reflecting the principal phase of magmatic activity in the region.

Subordinate NE-trending dykes, in contrast, yield ages between 125 and 120 Ma.

More recently, Almeida et al. (2018) employed the ID-TIMS U–Pb method on baddeleyite and zircon to date subalkaline rocks, together with the $^{40}Ar/^{39}Ar$ step-heating method on phlogopite for alkaline rocks. In that study, two tholeiitic bodies, basalt and basaltic andesite, were analyzed, yielding ages ranging from 133.4 ± 0.1 Ma to 133.9 ± 0.2 Ma.

Despite the limited age dispersion, variations in palaeomagnetic directions indicate multiple intrusive episodes. Palaeomagnetic studies carried out by Raposo (1995) identified nine main episodes of magmatic intrusion within the PGA, distributed among five normal polarity phases, three reversed polarity phases, and one transitional magnetic field phase.

The normal polarity phases comprise episodes N1, restricted to Fartura, figure 2, N2, regional, N3, simultaneous activity in Curitiba and Fartura, N4, secondary regional phase, and N5, the most extensive, involving all studied areas.

The reversed phases include episodes R1, regional in Fartura and Guapiara, figure 2, R2, local in Curitiba, figure 2, and R3, restricted to Fartura. Finally, episode T1, corresponding to a transitional magnetic field and recorded only in Fartura and Guapiara, indicates a local geomagnetic excursion or reversal.

PETROGRAPHIC RESULTS

General micropetrographic characteristics of the mafic dykes

The 36 analysed thin sections, corresponding to 36 mafic dykes distributed across three structural lineaments, Guapiara, São Jerônimo–Curiúva and Rio Alonzo, and Piquiri, include lithotypes classified as basalt, diabase, gabbro, and locally mafic pegmatite (Table 1).

The intrusive bodies are predominantly emplaced within the sedimentary sequences of the Paraná Basin, except for dykes intruded into the crystalline basement and the volcanic succession of the Serra Geral Group, as shown in figure 2.

Table 1 - Distribution of samples, structural lineaments, and lithotypes.

Structural lineament	No. of sampled dykes	Lithotypes identified in the sampled dykes	Geological context
Guapiara	11	5 diabases, 4 basalts, 2 gabbros	Paraná Basin, crystalline basement, and Serra Geral Group.
São Jerônimo–Curiúva and Rio Alonzo	23	14 diabases,4 basalts, 3 pegmatites, 1 gabbro, 1 monzodiorite	Predominantly Paraná Basin, with exceptions in the crystalline basement.
Piquiri	2	1 diabase, 1 gabbro	Paraná Basin.

Note: Dykes with samples PRU-81C, PRU-81D, and PIF-17 (Figure 2) occur in the crystalline basement.

In general, the dykes are fine- to medium-grained, with a predominance of inequigranular textures. Slightly porphyritic textures occur locally, ranging from very low proportions of phenocrysts, approximately 1%, to more expressive cases reaching approximately 5% in specific samples.

Vitrophyric and hypohyaline textures are locally observed, particularly in dykes emplaced within the crystalline basement. Crystal morphology is predominantly hypidiomorphic, with irregular grain contacts.

Mineral assemblage

Plagioclase is the most abundant mineral in all analyzed dykes, with modal proportions ranging from approximately 35 to 42%. Crystals are predominantly subhedral, displaying tabular to lath-shaped habit, with dimensions generally smaller than 1 mm, although locally reaching 2–3 mm in diabase and up to 3–5 mm in gabbros and mafic pegmatites.

Albite, or polysynthetic, twinning is dominant throughout all structural lineaments and is locally accompanied by Carlsbad twinning, which may predominate in coarser-grained rocks. Cross-twinning is observed in some samples.

Undulose extinction is recurrent, and compositional zoning occurs locally, particularly in gabbros. Estimated anorthite contents range predominantly from An_{40} to An_{55}, with values of An_{45}–An_{50} commonly observed in dykes from the Guapiara Lineament and values close to An_{55} in dykes from the Piquiri Lineament. Incipient saussuritization occurs mainly along crystal margins.

In slightly porphyritic or glomeroporphyritic rocks, features such as sieve texture are observed in larger crystals (Figure 5).

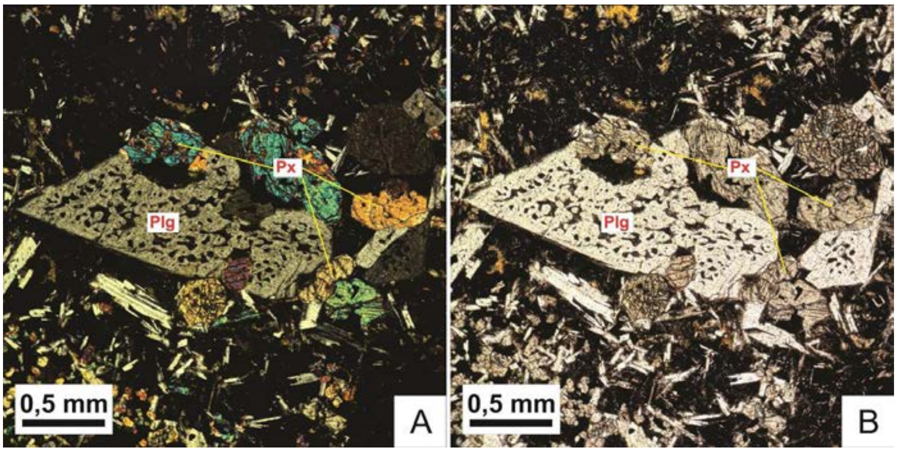

Figure 5 - Photomicrograph of a plagioclase (Plg) phenocryst in glomeroporphyritic basalt displaying sieve dissolution texture and augite crystals (Px). Crossed polars A) and plane-polarized light B). Sample PRU-18.

Pyroxenes constitute the second most abundant mineral group, represented predominantly by augite, with average contents of approximately 26–27% of the modal volume. Augite crystals are generally subhedral to anhedral, displaying predominantly granular habits, although locally prism-shaped or tabular forms may occur. Crystal dimensions are commonly smaller than 1 mm, although subordinate porphyritic crystals reaching 2–3 mm occur in diabase and gabbro samples.

Pigeonite occurs subordinately (Figure 6), with average proportions ranging from approximately 0.8 to 1% of the modal volume.

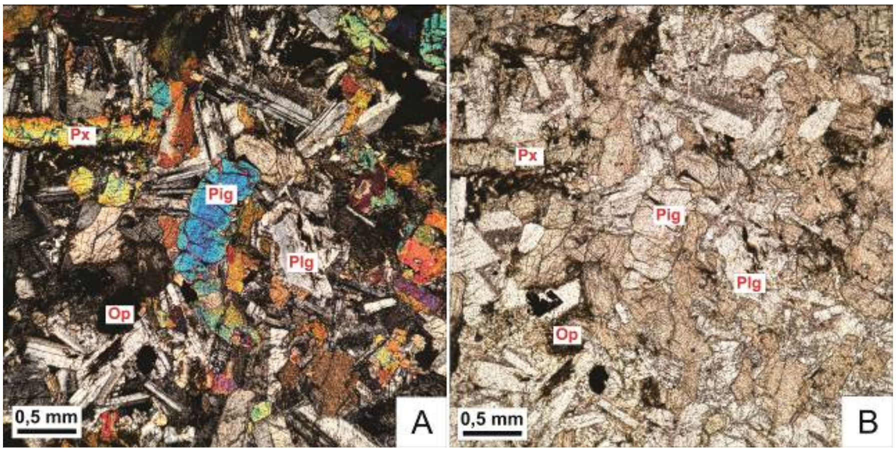

Figure 6 - Photomicrograph of a pigeonite crystal (Pig), at the centre, displaying a prismatic habit and forming an intergranular texture with prismatic and tabular plagioclase crystals (Plg), augite (Px), and opaque minerals (Op). Crossed polars A) and plane-polarized light B). Sample PRU-62A.

Crystals are subhedral, displaying granular to short-prismatic habits, generally smaller than 1 mm, and may locally exhibit twinning. Intergrowths between augite and pigeonite are occasionally observed.

Alteration of pyroxenes is recurrent, particularly along crystal margins, and may locally affect the entire crystal. This process results predominantly in the formation of iron oxides and hydroxides, possibly approaching goethite composition, with local occurrences of celadonite and chlorite. Uralitization processes were not observed, even in the gabbros and mafic pegmatites from the central portion of the PGA.

Opaque minerals, probably represented by magnetite and ilmenite, constitute between 8 and 10% of the modal volume. They display predominantly granular habits, with subhedral to anhedral forms and dimensions generally smaller than 1 mm, frequently occurring as dispersed crystallites within the groundmass. In some dykes, particularly within the central lineaments, larger crystals occur, reaching up to 2–3 mm and occasionally displaying prismatic habits.

Skeletal crystals associated with quenching textures are common (Figure 7), reflecting intense undercooling processes (Gill, 2010). Part of the grains displays partial alteration to iron oxides and hydroxides, possibly approaching goethite composition, with moderate intensity.

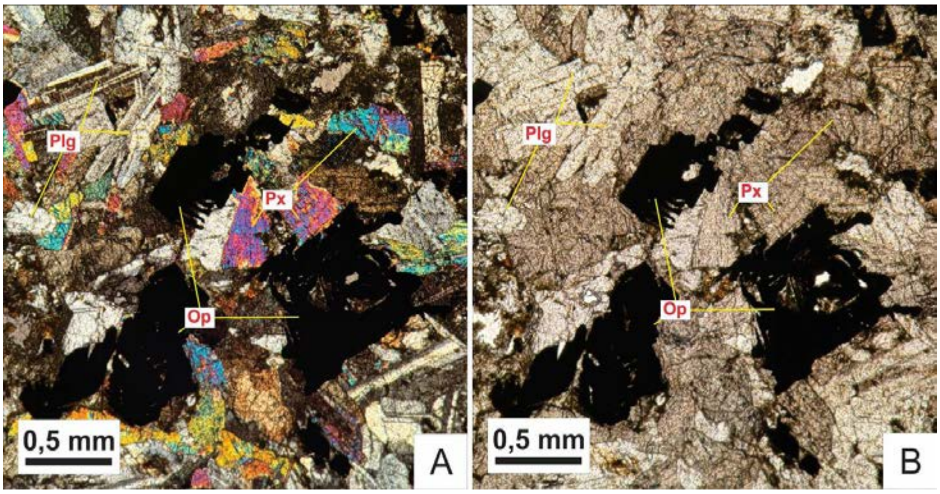

Figure 7 - Photomicrograph showing prismatic opaque minerals (Op) displaying quenching textures attributed to intense undercooling, associated with prismatic and tabular plagioclase crystals (Plg) and pyroxenes (Px; augite and pigeonite at the centre). Crossed polars (A) and plane-polarized light (B). Sample PRU-62A.

Groundmass (mesostasis)

The groundmass is predominantly microgranular throughout all structural lineaments, corresponding to average proportions ranging from approximately 15 to 21% of the modal volume. It is composed mainly of plagioclase, pyroxene, and apatite microlites. In some samples, it occurs as an interstitial phase filling spaces between plagioclase and pyroxene crystals.

Locally, fine intergrowths of quartz microlites with rare interstitial alkali feldspar crystals are observed, associated with late-stage residual crystallization phases (Figure 8). These occurrences display low modal proportions, ranging from approximately 0.3 to 4%, and are characterized by fine intergrowths between quartz and subordinate alkali feldspar in gabbros.

Undevitrified glassy groundmass is poorly developed in most samples, presenting average values lower than approximately 1% of the modal volume. However, in dykes emplaced within the crystalline basement, this phase becomes significantly more abundant, locally reaching approximately 40–56% in specific bodies.

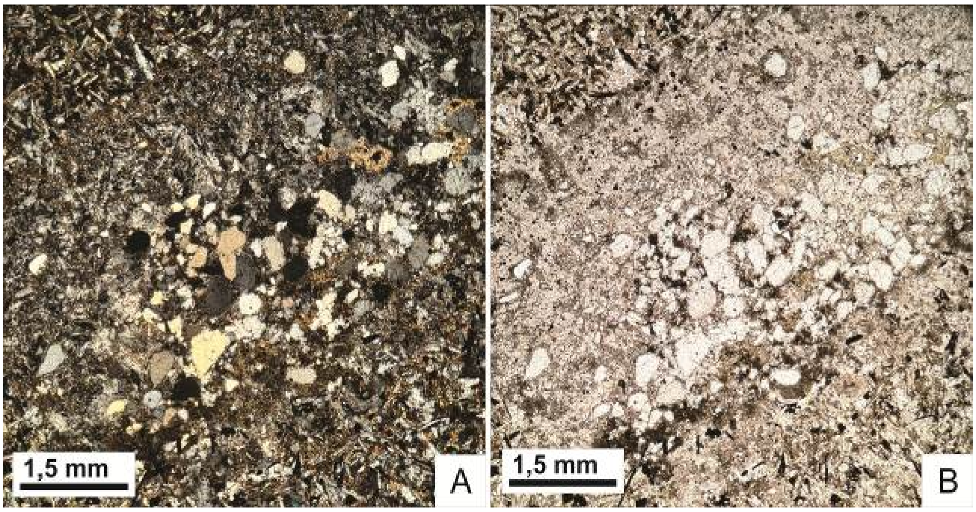

Figure 8 - Photomicrograph showing residual anhedral quartz within the microgranular groundmass (mesostasis) of a gabbro, occupying spaces between plagioclase crystals (Plg), augite (Px), and opaque minerals (Op). Crossed polars A) and plane-polarized light B). Sample PRU-61.

Textures

The analysed samples show a predominance of subophitic textures (Figure 9) and intergranular textures (Figure 6) in dykes from all studied areas.

Ophitic, intersertal, and micrographic-like textures, the latter associated with residual quartz and rare submillimetric alkali feldspar, occur subordinately, being more common in gabbros and mafic pegmatites.

Intersertal texture, together with swallow-tail morphology in plagioclase crystals (Figure 10), is observed mainly in samples with higher proportions of glassy groundmass, especially in basalts.

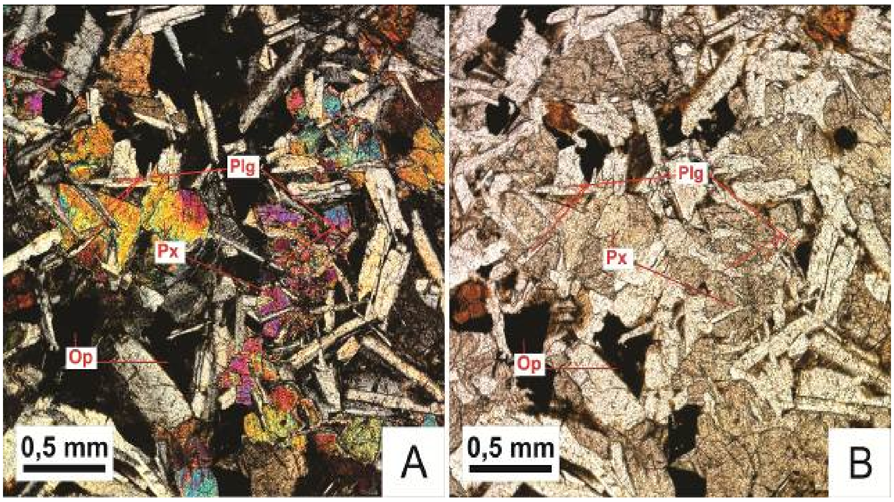

Figure 9 - Photomicrograph of subophitic texture in diabase, showing tabular plagioclase crystals (Plg), prismatic augite (Px), and opaque minerals (Op). Crossed polars (A) and plane-polarized light (B). Sample PRU-98.

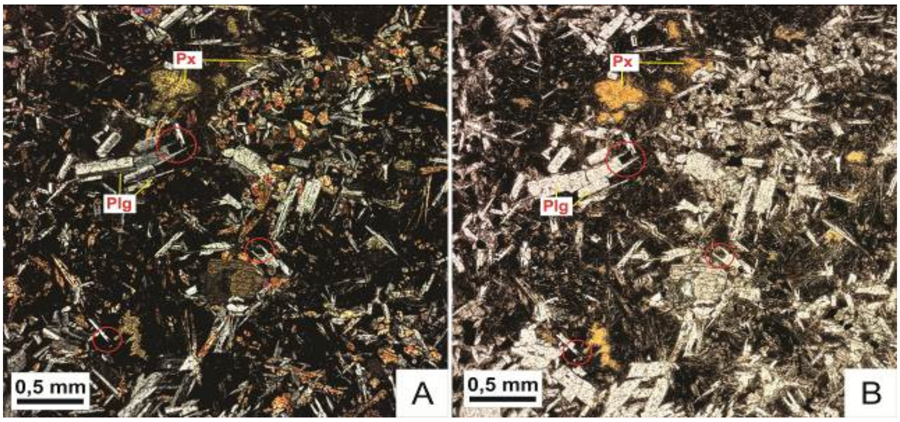

Figure 10 - Photomicrograph showing several plagioclase crystals (Plg) with swallow-tail morphology in a sample with intersertal texture. Altered augite crystals (Px), opaque minerals, and microgranular groundmass are also present. Crossed polars A) and plane-polarized light B). Sample PRU-18.

Porphyritic and glomeroporphyritic textures (Figure 5) occur locally, associated with local grain-size variations and the presence of phenocrysts in basalts, diabases, and gabbros. In these rocks, phenocrysts do not exceed 5% of the sample volume, and plagioclase crystals are commonly zoned.

Pilotaxitic texture (Figure 11) is observed in finer-grained rocks, mainly basalts, whereas trachytic (Figure 12) and poikilitic textures occur locally in gabbros associated with glomeroporphyritic texture.

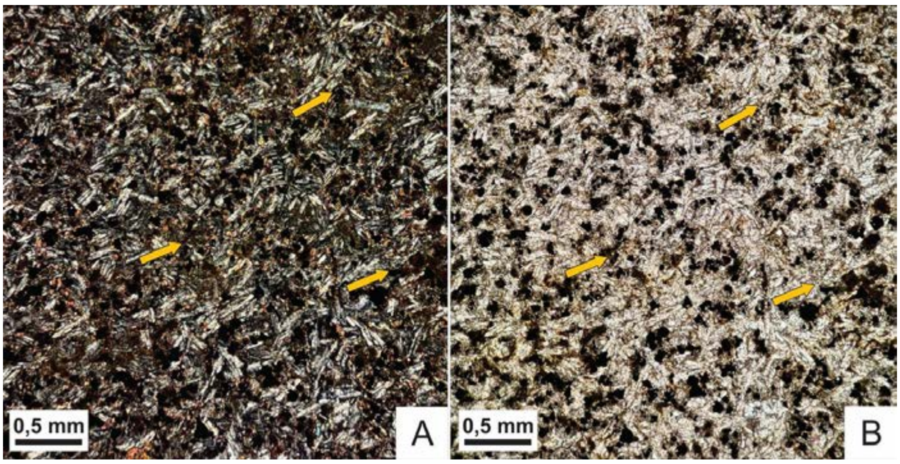

Figure 11 - Photomicrograph showing pilotaxitic texture in basalt, with moderately oriented tabular plagioclase microlites aligned according to the direction indicated by the yellow arrow, interpreted as magmatic flow. Crossed polars A) and plane-polarised light B). Sample PRU-14.

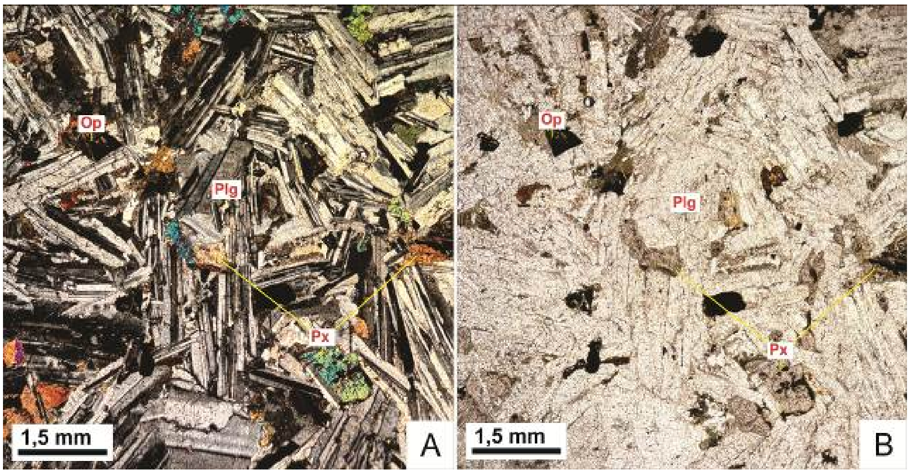

Figure 12 - Photomicrograph showing trachytic texture in gabbro, characterized by the preferred orientation of tabular plagioclase crystals associated with turbulent magmatic flow. Crossed polars A) and plane-polarized light B). Sample PRU-54.

Mafic pegmatites occur within the São Jerônimo–Curiúva and Rio Alonzo lineaments (Figure 13), characterised by the development of poikilitic textures (Figure 14) and trachytic textures.

These features are typical of very coarse-grained rocks and indicate crystallisation under slower cooling conditions, with limited diffusion and heterogeneous crystal growth (Gill, 2010)

Figure 13 - Mafic pegmatite with tabular plagioclase crystals (light colored) and prismatic pyroxene crystals reaching up to 2 cm in length. Sample PRU-101.

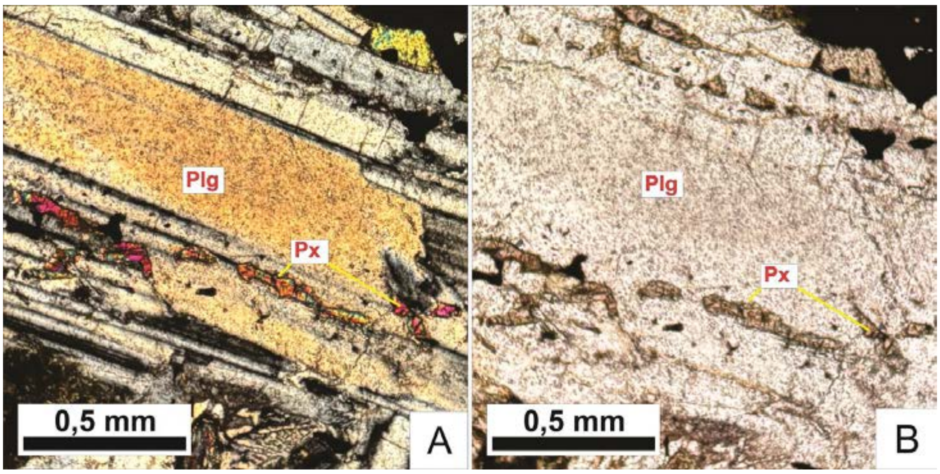

Figure 14 - Photomicrograph of poikilitic texture in gabbro, showing pyroxene inclusions (Px) within a plagioclase phenocryst (Plg). Note the occurrence of micrographic material beneath the plagioclase crystal. Crossed polars (A) and plane-polarized light (B). Sample PRU-54.

Subordinate mineral phases and secondary processes

Apatite occurs as a primary accessory mineral in all samples, with proportions ranging from trace amounts to approximately 0.8% of the modal volume. It displays a predominantly acicular habit and is commonly associated with micro-granular, micrographic, or glassy groundmass. Locally, it may occur as medium-grained euhedral crystals.

The identified secondary minerals include iron oxides and hydroxides, up to approximately 4%, celadonite, approximately 0.6–0.8%, and chlorite, approximately 0.4–1%.

These phases are generally associated with the alteration of pyroxenes, opaque minerals, or volcanic glass in the groundmass.

Quartz occurs as an accessory and residual phase, interpreted as primary in origin and mainly associated with the microgranular groundmass. It may reach up to approximately 4% in diabases and gabbros.Amygdales are rare and occur locally in some samples, filled by carbonate and clay minerals, such as saponite (Figure 15).

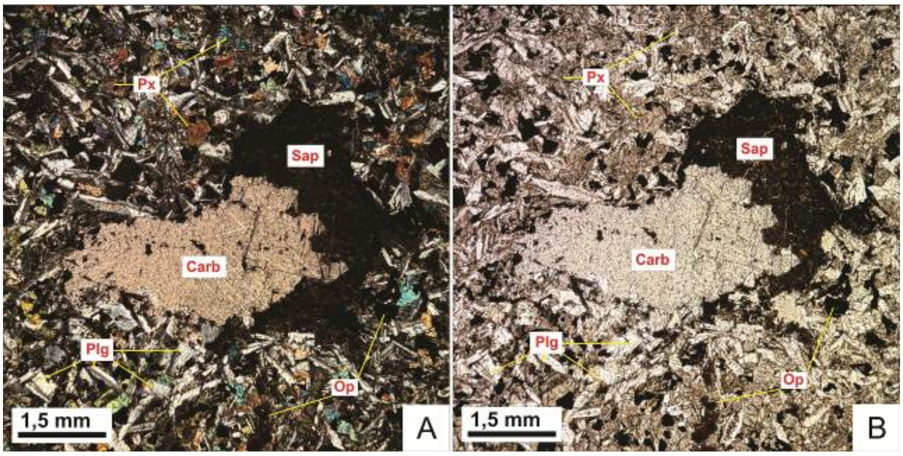

Figure 15 - Photomicrograph of a centimetric amygdale in basalt with intergranular texture. Crossed polars (A) and plane-polarized light (B). Sample PRU-10.

Petrographic variations by structural lineament

Guapiara Lineament

The dykes of the Guapiara Lineament include basalts, diabases, and gabbros, with predominantly fine to medium and inequigranular grain size. Subophitic texture is dominant, accompanied by intergranular texture and, locally, intersertal, glomeroporphyritic, pilotaxitic, and hyalophitic textures, the latter associated with the development of plagioclase crystals displaying swallow-tail morphology (Table 2).

The mineral assemblage is composed of plagioclase An45–An50 (35%), augite (26%), subordinate pigeonite (0.8%), opaque minerals (10%), and accessory apatite (0.8%), with olivine absent.

Table 2 - Textural characteristics of the studied dykes.

Alignment	**Guapiara (Northern Sector)**	**São Jerônimo–Curiúva and Rio Alonzo (Central Sector)**	**Piquiri (Southern Sector)**
Predominant grain size	Fine to medium	Fine to coarse	Medium to coarse
Dominant textures	Subophitic, intergranular	Subophitic, intergranular	Subophitic, intergranular
Secondary textures	Swallow-tail (hyalophitic), glomeroporphyritic, pilotaxitic, sieve	Ophitic, porphyritic, glomeroporphyritic, sieve, pilotaxitic, poikilitic, trachytic, spinifex-like	Ophitic, porphyritic

The groundmass is predominantly microgranular, with subordinate occurrences of residual quartz and glassy material. The mineral assemblage is dominated by plagioclase and augite, with subordinate pigeonite and absence of olivine (Table 3).

São Jerônimo–Curiúva and Rio Alonzo lineaments

This group contains the largest number of analysed dykes (Table 1) and displays the greatest petrographic diversity among the studied lineaments (Table 2). The samples include basalts,

Table 3 - Average modal mineral composition of the dykes by structural lineament (%).

Lineament	Guapiara (Northern Sector)	São Jerônimo–Curiúva and Rio Alonzo (Central Sector)	Piquiri (Southern Sector)
Plagioclase (%)	35%	42%	35%
Plagioclase composition (An%)	An_{45}–An_{50}	An_{40}–An_{55}	~An_{55}
Augite (%)	26%	27%	27%
Pigeonite (%)	0.8%	1%	1%
Opaque minerals (%)	10%	8%	9%
Apatite (%)	0.8%	0.8%	0.5%
Olivine (%)	–	>1%	–
Microgranular groundmass (%)	19%	16%	21%
Residual quartz (%)	1.0%	4%	2%
Iron oxides and hydroxides (%)	4%	4%	3%
Celadonite (%)	0.6%	0.8%	–
Chlorite (%)	0.5%	0.4%	1%

diabases, gabbros, and mafic pegmatites, with frequent occurrence of porphyritic features, locally reaching up to 5% phenocrysts.

The mineral assemblage is inequigranular and composed of plagioclase An40–An55 (42%), augite (27%), subordinate pigeonite (1%), and traces of pseudomorphosed olivine (Table 3). Opaque minerals reach up to 8% of the modal volume, whereas apatite may reach up to 0.8%.

The microgranular groundmass reaches up to 16%, whereas glassy groundmass and residual quartz, with rare alkali feldspar, correspond respectively to up to 0.8% and 4%.

Mafic pegmatites are noteworthy, developed both within the crystalline basement and the sedimentary sequence, and characterized mainly by poikilitic and trachytic textures. Monzodiorite and quartz monzodiorite veins also occur in association with diabase dykes, together with local traces of primary sulphides.

Piquiri Lineament

In the Piquiri Lineament, the analyzed dykes correspond to diabases and gabbros, with grain size ranging from medium to coarse. The rocks display inequigranular textures, with restricted porphyritic features and predominance of sub-ophitic and intergranular textures (Table 2). The mineral assemblage is dominated by plagioclase An55 (35%) and augite (27%), with subordinate pigeonite (1%) and absence of olivine (Table 0). The groundmass is predominantly microgranular, reaching up to 21%, with subordinate occurrences of residual quartz, up to 2%, and absence of glassy material.

DISCUSSION

The subdivision of the samples into three sectors, Guapiara (north), São Jerônimo–Curiúva and Rio Alonzo (central), and Piquiri (south), allowed the recognition of significant petrographic differences, mainly regarding magmatic textures and lithological distribution.

These variations may be associated not only with the cooling rates of the magmatic bodies, but also with the degree of exposure controlled by the tectonic evolution of the PGA and by post-Cretaceous landscape exhumation processes. Thus, the observed contrasts suggest the combined influence of magmatic processes, structural controls, tectonic evolution, and differential erosion.

The lithological variations summarized in table 1 probably reflect the action of multiple magmatic pulses, as well as differences in crustal depth during magma emplacement, even considering later uplift and exhumation processes. This scenario may corroborate the different magnetic polarities identified by Raposo (1995).

Guapiara Lineament

In the Guapiara Lineament, northern sector, fine- to fine-medium-grained rocks predominate (Table 2), typical of basalts and diabases, and are mainly associated with subophitic and intergranular textures.

The presence of glassy groundmass, together with structures related to gas escape, suggests a relatively shallow intrusive environment, in which faster cooling favoured the local preservation of amorphous material. In this context, hyalophitic textures developed in association with plagioclase crystals displaying swallow-tail morphology.

The occurrence of sieve texture may be interpreted as the result of partial dissolution of crystals. According to Hibbard (1994) and Renjith (2014), this process is related to adiabatic decompression during magma ascent from the magma chamber, an interpretation compatible with the shallow emplacement context inferred for the northern sector.

The restricted occurrence of porphyritic and glomeroporphyritic textures suggests localized episodes of early crystallization during magma ascent and/or short periods of residence at shallow crustal levels, compatible with transient magma storage, and not necessarily indicative of complex magmatic systems (Gill, 2010).

Although subophitic texture is dominant, tabular plagioclase microlites with preferred orientation are locally observed, characterizing pilotaxitic texture. This feature suggests relatively rapid crystallization conditions, associated with the presence of mobile residual melt and a high nucleation rate of microlites (Gill, 2010), when compared with the central sector. It should be emphasized that this interpretation does not establish a direct comparison with dykes intruded into the crystalline basement.

São Jerônimo–Curiúva-Rio Alonzo lineaments

The central sector, comprising the São Jerônimo–Curiúva and Rio Alonzo lineaments, stands out for the greatest magmatic complexity observed in this study. The lithological diversity, including basalts, diabases, gabbros, and mafic pegmatites, the wide grain-size variation, from fine to coarse, and the textural diversity, particularly the expressive occurrence of residual quartz associated with rare alkali feldspar crystals in the microgranular groundmass, up to 4%, suggest a relatively more prolonged magmatic evolution than in the other sectors.

In this context, residual liquids of more evolved composition may have been responsible for the formation of monzodiorite and quartz monzodiorite veins in porphyritic diabases, corroborating the interpretations of Machado et al. (2005, 2007), Lino et al. (2018), and Lino and Vlach (2021) for Early Cretaceous intrusive rocks from the state of São Paulo, Brazil, north of the PGA.

The presence of primary sulphides in these veins suggests magmatic segregation processes, as discussed by Gill (2010). The occurrence of primary sulphides in intrusions of the PMP was also described by Machado et al. (2007) in intrusive bodies from southern Minas Gerais, Brazil, north of the PGA.

As in the Guapiara Lineament, porphyritic and glomeroporphyritic textures also occur, although with greater incidence. These features suggest localized episodes of early crystallization during magma ascent, associated with the development of poikilitic and trachytic textures during late crystallization stages.

Three dykes were classified as mafic pegmatites, presenting diagnostic textures such as trachytic and poikilitic textures. In the latter, oriented growth of augite is observed following specific crystallographic surfaces of plagioclase, generally related to the (010) and/or (001) planes. This textural relationship suggests crystallization under conditions of low nucleation rate and relatively slow crystal growth, compatible with late-magmatic stages in systems locally enriched in residual melt (London, 2008, 2018).

Although traditionally associated with deeper crustal environments and isolated magmatic pockets, pegmatites are defined mainly by textural and structural criteria. Among these criteria, wide grain-size variation, mineralogical zoning, occurrence of monomineralic portions, and evidence of rapid growth or quenching stand out (London, 2008, 2018).

In this sense, the mafic pegmatites of the PMP meet these criteria, despite their association with basaltic rocks.

Petrographically and texturally, they display ophitic to subophitic textures, centimetre-scale elongated crystals with spinifex-like aspect, and mineralogy dominated by plagioclase and clinopyroxene, as well as grain-size variations and internal structures compatible with late-magmatic segregation.

It is worth noting that the identification of mafic pegmatites in intrusive rocks associated with the SGG corroborates previous studies by Arioli (2008) and Vasconcellos et al. (2008).

The term spinifex-like is used here in a morphological sense, due to the presence of centimetre-scale elongated pyroxene crystals resembling classical spinifex texture, but without a significant amount of olivine, a mineral generally associated with its petrographic definition (Le Maitre et al., 2002 and Gill, 2010).

The intermediate composition of plagioclase indicates that, in principle, neither the presence of porphyritic texture nor the occurrence of residual quartz exerted a significant influence on the chemistry of this essential mineral.

Additionally, the identification of two distinct pyroxene types, augite and pigeonite, reinforces the tholeiitic character of the basaltic magma, according to the classification of Le Maitre et al. (2002).

Piquiri Lineament

The Piquiri Lineament, southern sector, displays a relatively more homogeneous petrographic character. Medium- to coarse-grained rocks predominate, with predominantly microgranular groundmass, suggesting more uniform crystallization conditions when compared with the sectors located farther north.

Coarser-grained rocks occur locally, such as diabases and gabbros with porphyritic and poikilitic textures, respectively. However, the low frequency of dykes in this sector limits more robust petrographic correlations with the other lineaments.

The scarce occurrence of olivine is compatible with the intermediate composition of plagioclase and with the localised presence of residual quartz, suggesting relatively more evolved magmas close to silica saturation (Gill, 2010 and Le Maitre et al., 2002).

CONCLUSION

The significant lithological, mineralogical, and textural variation of the subalkaline dykes of the PGA indicates a more complex magmatic evolution than that traditionally recognized for intrusive rocks associated with the Serra Geral Group.

The subdivision of the PGA into three sectors allowed the recognition of important regional petrographic differences. The northern sector, Guapiara Lineament, is characterized mainly by fine- to medium-grained basalts and diabases, with hyalophitic and pilotaxitic textures, as well as glassy groundmass, suggesting relatively shallow emplacement conditions and faster cooling.

The central sector, São Jerônimo–Curiúva and Rio Alonzo lineaments, displays the greatest petrographic diversity, including basalts, diabases, gabbros, and mafic pegmatites. The occurrence of ophitic, poikilitic, trachytic, and spinifex-like textures, associated with residual quartz, primary sulphides, and monzodiorite to quartz monzodiorite veins, suggests more developed late-magmatic stages and a greater contribution of evolved residual melts.

These features indicate relatively deeper crystallization conditions and/or a greater level of crustal exposure when compared with the northern sector, possibly related to the tectonic evolution and post-Cretaceous uplift and exhumation processes within the PGA.

The southern sector, Piquiri Lineament, displays a relatively more homogeneous petrographic character, with predominance of diabases and gabbros containing microgranular groundmass. However, the limited number of outcrops restricts more robust comparative interpretations.

The diagnostic textures identified, especially poikilitic, trachytic, pilotaxitic, and spinifex-like textures, reinforce the importance of magmatic differentiation, fractional crystallisation, and late-magmatic segregation processes in the evolution of magmas associated with the PGA.

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APENDIX

Sample geographic coordinates

SAMPLE		Latitude	Longitude
PRU	28	-24,010722	-49,331556
PRU	37	-24,147333	-48,474889
PRU	42	-24,317639	-48,619889
PRU	43	-24,254028	-48,596028
PRU	45	-24,180278	-48,560722
PRU	52	-24,128889	-49,484167
PRU	55	-24,527333	-49,963694
PRU	56	-24,496222	-50,001611
PRU	57	-24,407361	-50,349111
PRU	58	-24,398056	-50,336972
PRU	63	-24,486583	-50,733333
PRU	64	-24,498167	-50,721333
PRU	65	-24,543111	-50,693083
PRU	67	-24,668583	-50,603500
PRU	68	-24,785250	-50,512472
PRU	72	-24,778500	-50,461833
PRU	73	-24,749556	-50,464694
PRU	75	-24,725417	-50,451472
PRU	78	-24,753194	-50,001667
PRU	95	-24,679972	-50,710500
PRU	98	-23,997556	-51,085361
PRU	99	-24,190417	-50,959667
PRU	100	-24,227028	-50,927333
PRU	101	-24,308694	-50,867917
PRU	11co	-23,370806	-49,486028
PRU	24co	-23,759444	-49,272806

SAMPLE		Latitude	Longitude
PRU	36co	-24,140972	-48,460472
PRU	3co	-23,443611	-49,953889
PRU	40co	-24,149167	-48,498278
PRU	5co	-23,703056	-49,451417
PRU	68d	-24,785250	-50,512472
PRU	6co	-23,669472	-49,355611
PRU	77a	-24,606139	-50,441000
PRU	77a	-24,606139	-50,441000
PRU	77b	-24,606139	-50,441000
PRU	77b	-24,606139	-50,441000
PRU	77c	-24,606139	-50,441000
PRU	77c	-24,606139	-50,441000
PRU	81a	-25,422250	-49,389278
PRU	81b	-25,422250	-49,389278
PRU	81c	-25,422250	-49,389278
PRU	81d	-25,422250	-49,389278
PRU	81e	-25,422250	-49,389278
PRU	9co	-23,375583	-49,494250
PRU	23	-23,800750	-49,262222
PRU	12	-23,369028	-49,485528
PRU	46	-24,217111	-48,763972
PRU	50	-23,749417	-49,781361
PRU	51	-24,239417	-49,741556
PRU	91	-25,194500	-50,923861
PRU	93	-25,186111	-50,807611
PRU	4co	-23,611389	-49,858611