



Hybridization of mantle- and crust-derived magmas during the late-collisional stage of the Sergipano Orogenic System, NE Brazil

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ABSTRACT

Understanding the petrogenetic processes of granitoid plutons is fundamental for reconstructing the evolution of orogenic belts. The Borborema Province (NE Brazil) hosts extensive magmatism represented by numerous batholiths and stocks associated with the Brasiliano/Pan-African Orogeny. The late-collisional Lagoa do Roçado Stock (618 ± 8 Ma, SHRIMP U-Pb zircon) intrudes metasedimentary rocks of the Macururé Domain, within the Sergipano Orogenic System, in the southeastern sector of the province. The presence of syn-plutonic mafic dikes and abundant mafic microgranular enclaves (MMEs) makes this intrusion a prime example for investigating the role of magma mixing in the chemical evolution of plutonic systems. The stock is predominantly composed of granodiorites and quartz monzodiorites, which host MMEs ranging in composition from diorite to quartz monzodiorite. These rocks are uniformly metaluminous, magnesian, and show affinities with the high-K calc-alkaline to shoshonitic series. Both host rocks and MMEs are enriched in LILE and display moderately fractionated REE patterns, with similar negative Eu anomalies. The geochemical signature of the host granitoids is consistent with derivation from an amphibolitic lower-crustal source, whereas the MMEs exhibit compositions comparable to melts derived from a metasomatized, phlogopite-bearing lithospheric mantle source. Trace-element modeling demonstrates that hybridization between primitive mafic magmas and evolved felsic magmas provides a robust explanation for the compositions of intermediate enclaves. Field relationships, petrographic evidence, and geochemical modeling collectively support the interpretation that repeated injections of enriched, mantle-derived mafic magmas into a felsic magma chamber and subsequent mixing were the dominant petrogenetic process controlling the evolution of the Lagoa do Roçado Stock.

1. Introduction

Granitoid rocks are the main constituents of the continental crust (Rudnick and Gao, 2003; Han et al., 2025), and understanding the petrogenetic mechanisms responsible for their formation is essential for reconstructing the evolution of orogenic belts. The close association between granitic and mantle-derived mafic rocks results from complex processes such as crustal assimilation, fractional crystallization, magma mixing, or a combination of these mechanisms (Barbarin and Didier, 1991; Clemens and Stevens, 2021). The emplacement of mantle-derived

magmas into the crust or underplating is commonly associated with the generation of felsic magmas and subsequent interactions between them (Huppert and Sparks, 1988; Barbarin, 1999; Annen et al., 2015), leading to rocks with mixed origins, including both crustal and mantle-derived components.

The interaction between compositionally contrasting magmas may produce homogeneous or heterogeneous systems. When, during interaction, chemical exchanges occur between magmas, the process is referred to as mixing. This process is characterized by the mobilization of chemical elements between the molten fractions and may result in

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abrupt chemical variations or even in completely homogenized magma portions. In contrast, when the interaction between two or more magmas occurs solely at a physical level, the process is termed mingling. This process is controlled by the rheology of the magmas involved and depends strongly on their viscosities (Perugini et al., 2015; Morgavi et al., 2022). Experimental petrology studies and numerical modeling (e. g. Perugini et al., 2015; Perugini, 2021; Morgavi et al., 2022) have demonstrated that factors such as system geometry, magma viscosity and density, driving forces, and time strongly control the degree of homogenization during the mixing process, which develops under chaotic conditions. As a result, a variety of mixing and mingling structures are produced and, occasionally, the formation of hybrid magmas occurs (Morgavi et al., 2022). In plutonic environments, these magmatic enclaves represent the primary field evidence for magma chaotic mixing (Perugini, 2021; Morgavi et al., 2022). Additional indicators of magma mixing or mingling include reaction rims on enclaves, syn-plutonic dikes, mineralogical disequilibrium in crystals, hybrid zones at mafic-felsic contacts, and the occurrence of similar xenocrysts in the enclaves and their host rocks (Vernon, 1990; Kumar et al., 2004; Perugini and Poli, 2012).

The Macururé Domain, located in the central sector of the Sergipano Orogenic System (SOS) that forms the southernmost part of the Borborema Province, hosts extensive late Cryogenian-Ediacaran plutonism associated with the main stages of the Brasiliano/Pan-African Orogeny (Oliveira et al., 2010; Pereira et al., 2023). The plutonic rocks in this region are potassic in nature and exhibit geochemical affinities with high-K calc-alkaline, shoshonitic, and ultrapotassic suites (Lisboa et al., 2019; Sousa et al., 2022; Pereira et al., 2024). Many of these intrusions contain abundant mafic microgranular enclaves, recording different degrees of interaction between mafic and felsic magmas.

The Lagoa do Roçado Stock is composed primarily of porphyritic granodiorites and quartz monzodiorites. The presence of synplutonic dikes and numerous mafic microgranular enclaves makes this intrusion a prime example for investigating the role of magma mixing in the geochemical evolution of plutonic bodies. This study integrates field observations, petrographic analyses, geochemical data, and geochronological constraints to elucidate the petrogenetic history of the Lagoa do Roçado Stock and evaluate the contribution of magma mixing to its development.

2. Geological Background

The Borborema Province, NE Brazil, was formed by the convergence and collision of the Amazonian, São Luís-West Africa, and São Francisco-Congo cratons during the buildup of the Western Gondwana supercontinent during the Brasiliano/Pan-African Orogeny (Almeida et al., 1981; Caxito et al., 2020).

The basement of the Borborema Province largely consists of Paleoproterozoic orthogneisses and migmatites (2.4–2.0 Ga), with sparse Archean remnants (3.8–2.5 Ga) (Brito Neves et al., 2000; Van Schmus et al., 2008; Pereira et al., 2020). Tonian orthogneisses and metavolcano-sedimentary sequences occur in the Central and Southern subprovinces, associated with the Cariris Velhos Event (1.0–0.9 Ga) (Neves et al., 2021; Lima et al., 2024). This basement is overlain by late Neoproterozoic metasedimentary sequences and intruded by voluminous Brasiliano/Pan-African magmatism (650–530 Ma) throughout the province (Neves et al., 2015; Oliveira et al., 2015), represented by numerous batholiths, stocks, and dike swarms. The Brasiliano orogenic event involved intense deformation, widespread development of shear zones, and reactivation of pre-existing crustal structures, which partially overprinted or obliterated earlier tectonic features, ultimately shaping the present-day architecture of the Borborema Province (Almeida et al., 1981).

The Borborema Province is compartmentalized into the Northern, Central, and Southern subprovinces, bounded by the shear zone systems of Patos and Pernambuco (Van Schmus et al., 2008). The Southern

Subprovince extends between the northern limit of the São Francisco Craton and the Pernambuco shear zone, encompassing the Pernambuco-Alagoas Domain, the Sergipano, and the Riacho do Pontal orogenic belts (Fig. 1a).

The SOS represents the southernmost part of the Borborema Province and is commonly divided into six tectonostratigraphic domains: Canindé, Poço Redondo, Maracó, Macururé, Vaza-Barris, and Estância (Davison and Santos, 1989). The shear zones of Itaporanga, São Miguel do Aleixo, Belo Monte Jeremoabo, Poço Redondo, and Macururé limit these domains (Fig. 1b). A significant magmatism intrudes the domains north of the São Miguel do Aleixo shear zone, comprising mafic-ultramafic to acidic rocks (Oliveira et al., 2015; Pereira et al., 2023, 2024).

The Macururé Domain consists essentially of metasedimentary rocks of the Macururé Complex, including phyllites, schists, metarhythmites, and quartzites, deposited above the Paleoproterozoic Jirau do Ponciano Dome, just prior to the beginning of the Brasiliano Orogeny (Davison and Santos, 1989; Oliveira et al., 2010; Pereira et al., 2025). These rocks underwent metamorphism under greenschist and amphibolite facies (Silva et al., 1995) and were intruded by several plutonic bodies between 643 and 603 Ma (Pereira et al., 2023). Based on new and compiled geochronological and geochemical data (Pereira et al., 2023), recognized three main groups of plutonic rocks in the Macururé Domain:

(i) Early-collisional plutonism (643–628 Ma) includes elongated and rounded bodies of gabbros and diorites, with minor granites and ultramafic rocks, displaying a tectonic foliation and solid-state deformation. Mafic and intermediate rocks typically have a shoshonitic affinity, while granitoids belong to the high-K calc-alkaline series.

(ii) Syn-collisional plutonism (630–624 Ma) encompasses muscovite-biotite granites, which show a foliation parallel to the metasedimentary country rocks, indicating that the emplacement was contemporary with regional deformation. They are magnesian to ferroan, mostly peraluminous and high-K calc-alkaline. Geochronological constraints for this group are considered the best estimate for the collision between the São Francisco paleoplate and the Pernambuco-Alagoas Domain.

(iii) Late-collisional plutonism (625–603 Ma) includes stocks and batholiths of underformed granodiorites and monzonites, magnesian, metaluminous, showing affinity with the high-K calc-alkaline and shoshonitic series.

Magmatic enclaves are widespread across all plutonic suites but are particularly abundant in late-collisional plutons. Their compositions vary from diopside-biotite cumulates and gabbros to diorites, monzodiorites, monzonites, and minettes, reflecting diverse magmatic sources and genetic processes (Long et al., 2005; Oliveira, 2014; Conceição et al., 2016; Lisboa et al., 2019; Sousa et al., 2022; Fernandes et al., 2024; Pereira et al., 2024).

Many authors have proposed that the lower continental crust represents the most likely source of the late-collisional SOS plutons (e.g., Long et al., 2005; Lisboa et al., 2019; Pereira et al., 2023). Nevertheless, different petrogenetic processes have been proposed for the various plutons associated with this magmatism. Plutons with more evolved compositions, such as the Santa Helena and Coronel João Sá plutons, are interpreted as products of crustal partial melting, with no involvement of mantle-derived components (Long et al., 2005; Pereira et al., 2023). In contrast, the Glória Norte pluton, which exhibits less-evolved facies, has been interpreted as involving the participation of mantle-derived magmas in its genesis (Lisboa et al., 2019). Together, these characteristics suggest that complex and variable petrogenetic processes operated during the late-collisional stage of the SOS.

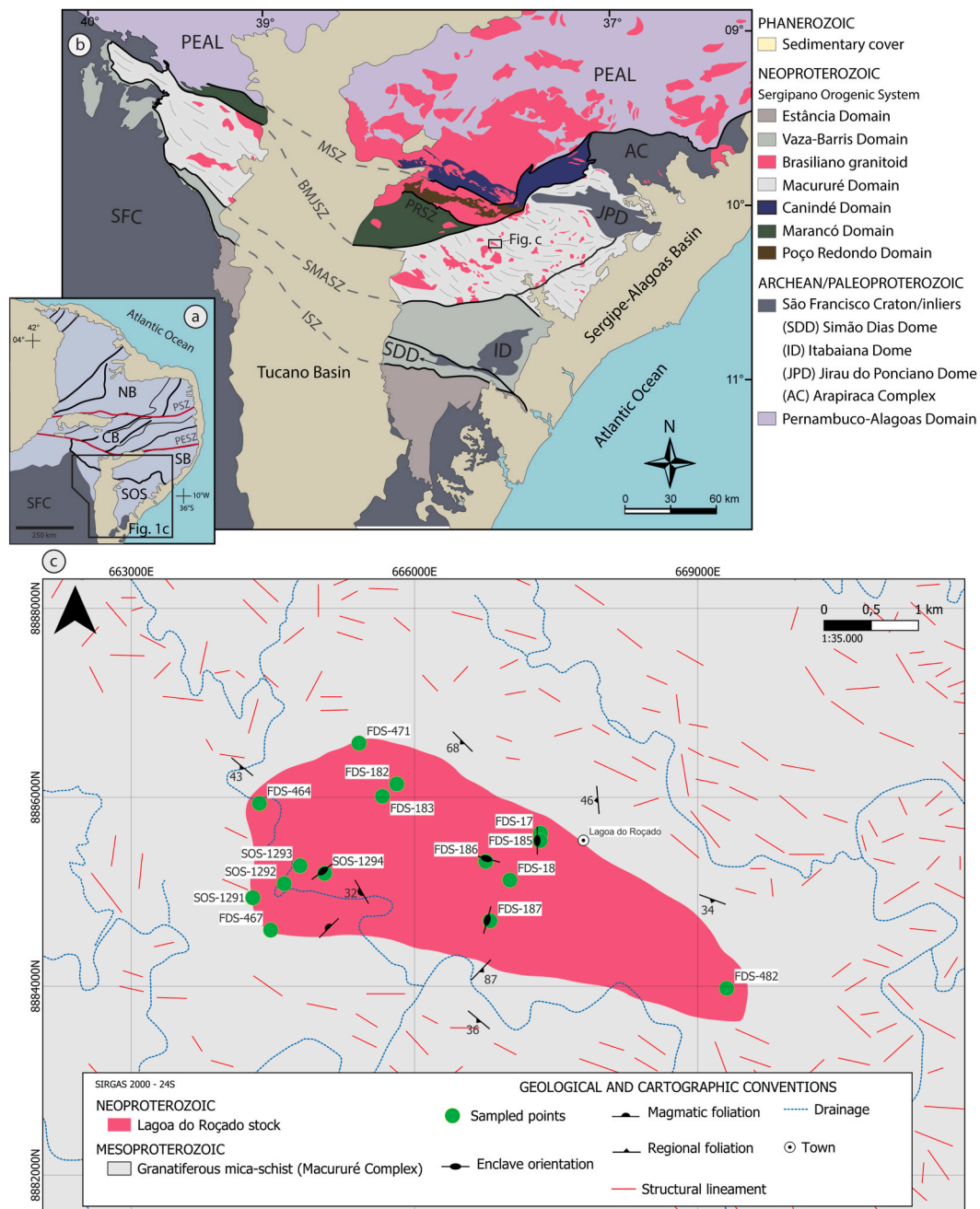


Fig. 1. Geological configuration of the study area. (a) Division of the Borborema Province into the Northern (NB), Central (CB), and Southern subprovinces (Van Schmus et al., 2008), limited by the Patos (PSZ) and Pernambuco (PESZ) shear zones. (b) Compartmentation of the SOS based on Davison and Santos (1989), featuring lithostratigraphic domains bounded by the shear zones of Macururé (MSZ), Poço Redondo (PRSZ), Belo Monte-Jeremoabo (BMJSZ), São Miguel do Aleixo (SMASZ), and Itaporanga (ISZ). (c) Simplified sketch of the Lagoa do Roçado Stock.

3. Materials and Methods

Thirty-one samples were collected from 11 outcrops of the Lagoa do Roçado Stock, including representative host rocks and mafic enclaves. The samples were washed with running water and prepared for petrographic, geochemical, and geochronological analyses.

3.1. Petrography

Petrographic analysis was performed on 28 thin sections, using an OPTON TNP-09T microscope in the Petrography and Metallography Laboratory of the Condomínio Multiusuários das Geociências at the Universidade Federal de Sergipe (CLGeo-UFS). The semiquantitative

modal proportions of the rock-forming minerals were visually estimated in 40 non-overlapping microscope fields of view. Minerals that could not be identified through conventional petrographic methods were examined using a scanning electron microscope Tescan Vega 3 LMU at CLGeo-UFS. The backscattered electron (BSE) detector was used to obtain high-resolution textural images.

3.2. Whole-rock geochemistry

The major element concentrations of the 14 samples were determined using an X-ray fluorescence spectrometer Shimadzu XRF-1800 installed at the CLGeo-UFS. Sample preparation included crushing and quartering, followed by pulverization to a 100-mesh granulometric

fraction. The resulting rock powder was mixed with boric acid (H_3BO_3) in a 3:1 powder-to-acid ratio. The mixture was homogenized, deposited in steel disks, and compacted in a hydraulic press operating at 60 kN for 30 s. Calibration curves for XRF in CLGeo-UFS include 26 certified materials spanning a wide range of compositions. The precision and accuracy of the geochemical results were monitored through replicate analyses of three samples and comparisons with certified reference materials (Supplementary Material S1). Loss of mass on ignition (LOI) was determined from dried samples (at 120 °C) by calcination in a muffle furnace at 1000 °C for 2 h.

The chemical composition of nine samples was analyzed at Acme Laboratories, Canada. The analytical package 4A-4B included major element analysis by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) and trace element analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Detailed information on the analytical protocols is available at https://geochem.nrcan.gc.ca/cdofgs/content/lab/lab000003_e.htm. Additionally, four representative samples were selected for trace element analysis at ALS Laboratories, Canada. The analytical procedure followed the ME-MS81 package (<https://www.alsglobal.com/pt/geochemistry/>), which includes lithium borate fusion prior to acid digestion, followed by ICP-MS analysis.

Geochemical data were processed in Excel spreadsheets, and geochemical diagrams were generated in R using the Geochemical Data Toolkit (GCDkit; Janoušek et al., 2006). Major and trace element data for the studied rocks are shown in Supplementary Material S1.

3.3. Geochemical modeling

The petrogenetic evolution of the Lagoa do Roçado Stock was investigated using Rayleigh fractional crystallization, assimilation-fractional crystallization, and simple binary mixing models (DePaolo, 1981; Rollinson, 1993; Rollinson and Pease, 2021). The mineral/melt partition coefficients (Kd), obtained from Rollinson (1993) and the

Geochemical Earth Reference Model (GERM) database (<https://kdd.earthref.org/KdD/>), are listed in Supplementary Material S2. Assimilated composition in the AFC process corresponds to a garnet-mica schist from the Macururé Complex (Conceição, 2014).

3.4. Zircon U-Pb geochronology

A diopside-biotite granodiorite (FDS-187A) was selected for U-Pb dating using the Sensitive High-Resolution Ion Microprobe (SHRIMP) at the Centro de Pesquisa em Geocronologia of the Universidade de São Paulo (CPGeo-USP). Zircon concentrates were obtained by the conventional methods of crushing, panning, magnetic and gravimetric separation, using bromoform heavy liquid. Inclusion- and fracture-free zircon crystals were handpicked under a binocular stereomicroscope and mounted in 2.5 cm epoxy resin discs alongside the reference zircon TEMORA (Black et al., 2003). The mounts were polished and imaged under cathodoluminescence (CL) to investigate internal zoning and to guide spot selection for U-Pb analysis. Isotopic measurements were performed using a 30 µm spot diameter following the analytical protocols described by Sato et al. (2014). U-Pb data were graphically represented using the IsoplotR software (Vermeesch, 2018).

4. Results

The enclave-bearing host rocks are quartz monzodiorites and granodiorites. These rocks are gray-colored, leucocratic to mesocratic, and isotropic (Fig. 2a). Locally, a well-developed magmatic foliation may be recognized, characterized by the alignment of feldspar and biotite crystals, along with mafic enclaves. They show inequigranular and porphyritic textures, marked by phenocrysts of K-feldspar and plagioclase immersed in a fine-to coarse-grained subhedral groundmass composed of plagioclase, K-feldspar, quartz, biotite, and diopside. Locally, these rocks are crosscut by synplutonic dikes approximately

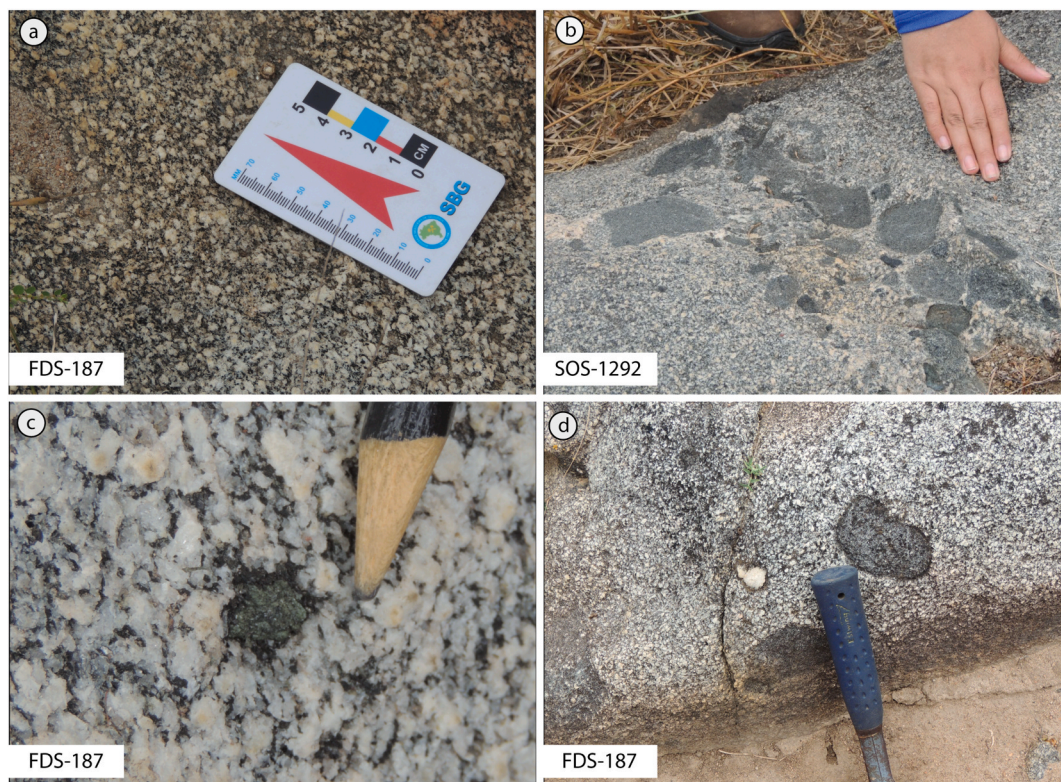


Fig. 2. Field aspects of the Lagoa do Roçado Stock. (a) Isotropic porphyritic granodiorite with phenocrysts of plagioclase and K-feldspar. (b) Syn-plutonic mafic dike composed of rounded and ellipsoid MME, emplaced into the host quartz monzodiorite. (c) Mafic clot of cumulate clinopyroxene, with a biotite-rich margin at the contact with the host rock. (d) MME displaying a dark edge, mainly composed of biotite. Note the xenolith of quartzite with irregular borders.

20 cm wide and a few meters long. In these dikes, MMEs with well-defined circular shapes and sharp contacts with the host rocks are observed (Fig. 2b).

Two main types of enclaves are recognized in the Lagoa do Roçado Stock: (i) centimeter-scale mafic clots composed of cumulate diopside or amphibole, rimmed by a thin biotite border (Fig. 2c), and (ii) mafic microgranular enclaves (MMEs), characterized by ellipsoidal to rounded shapes, occasionally displaying elongated shapes, and sizes ranging from 1 to 100 cm (Fig. 2d). The first may occur dispersed within the host rock or enclosed within the microgranular enclaves. Their low abundance and small size make them poorly representative; therefore, petrographic and geochemical analyses were only conducted on the MMEs.

The MMEs are predominant in the Lagoa do Roçado Stock and are composed of diorite, quartz diorite, and quartz monzodiorite. These enclaves are dark gray to black, leucocratic to melanocratic ($M' = 33\text{--}75$ vol%), and exhibit porphyritic, cumulate, and inequigranular textures with fine- to medium-grained mineral assemblages. Contacts between host rocks and enclaves are generally sharp, suggesting a significant thermal contrast between the two. In these cases, the modal proportion of biotite increases markedly along the margins of the enclave, forming a narrow reaction rim. More transitional contacts occur mainly in enclaves with a low color index. In addition, the Lagoa do Roçado Stock contains xenoliths of quartzite and schists, further supporting its intrusive nature into the metasedimentary succession of the Macururé Complex.

4.1. Petrography

A summary of the modal composition of the investigated rocks is presented in Table 1. The main petrographic features of the host rocks and MMEs are described separately below.

4.1.1. Lagoa do Roçado Stock

The compositions of the Lagoa do Roçado Stock rocks range from quartz monzodiorites to granodiorites (Fig. 3a). They are essentially composed of plagioclase, quartz, biotite, K-feldspar, and diopside. Hornblende, epidote, titanite, apatite, zircon, ilmenite, and magnetite are accessory phases. Muscovite, epidote, and carbonate are the main alteration products, related to late-magmatic stage associated with fluid- or volatile-rich phases.

Plagioclase occurs as euhedral and subhedral phenocrysts (2.1–5.0 mm) (Fig. 3b) and as anhedral crystals in the matrix (1.0–2.0 mm). They commonly show albite and albite-Carlsbad twinning. Oscillatory concentric zoning is also present in phenocrysts, recording changes in physical conditions in the magmatic system. K-feldspar also appears as subhedral phenocrysts (2.0–3.5 mm) and as anhedral crystals in the matrix (0.1–2.0 mm), displaying Carlsbad twinning. Poikilitic phenocrysts commonly include acicular apatite, biotite, diopside, and zircon. Secondary transformation of plagioclase produces epidote, calcite,

quartz, albite, and sericite.

Anhedral quartz (0.01–2.0 mm) is present in the matrix and, occasionally, makes up monomineralic aggregates.

Brown biotite (0.5–3.0 mm) is the dominant mafic phase. It typically occurs as subhedral crystals in the matrix, forming aggregates with other mafic minerals. Some crystals have corroded edges (Fig. 3c) and exhibit reentrant/gradational contacts with diopside and hornblende, frequently encasing these minerals. Other frequent inclusions are K-feldspar, epidote, zircon, ilmenite, magnetite, and acicular apatite. Ilmenite and magnetite fill cleavage planes, associated with the destabilization of primary biotite crystals.

Diopside (0.1–3.5 mm) is an important mafic phase in granodiorites and quartz monzodiorites of the Lagoa do Roçado Stock that make up between 3.1 and 8.0 vol%. It occurs as subhedral and anhedral individual crystals dispersed within the rock or forming aggregates with biotite and, less commonly, hornblende. Some diopside crystals exhibit gradational and reentrant contacts with biotite. They are often inclusion-free, but some poikilitic crystals enclose hornblende, plagioclase, ilmenite, and magnetite. Ilmenite and magnetite commonly occupy cleavage planes, likely reflecting the destabilization of primary diopside during the late magmatic or subsolidus stage.

Hornblende (0.03–4.5 mm) is a rare mafic phase (<2.1 vol%) that displays an intense green color and occurs predominantly as anhedral crystals within the matrix; occasionally, it occurs as subhedral crystals with a tabular habit. Some crystals are found in mafic aggregates together with biotite and diopside and display diffuse or embayed boundaries with these minerals. Other hornblende crystals occur along the margins of relict diopside cores, indicating the destabilization of diopside during magmatic evolution.

Epidote (0.2–1.5 mm) appears yellowish-green and is found in the matrix as both euhedral and anhedral crystals. Titanite (0.3–1.0 mm) is dark brown and occurs as subhedral to anhedral crystals, including plagioclase, ilmenite, and magnetite. Apatite (0.08–0.6 mm) occurs as stubby and acicular crystals (Fig. 3e). Zircon (0.05–0.3 mm) is frequently included in biotite, plagioclase, and diopside. Ilmenite and magnetite (0.05–0.9 mm) occur as euhedral and anhedral crystals in the matrix or filling cleavage planes in biotite, diopside, and titanite, indicating late-stage or subsolidus alteration.

4.1.2. Microgranular mafic enclaves

The most primitive enclave sample has dioritic composition. It exhibits a porphyritic texture defined by diopside and biotite, immersed in a fine-grained, inequigranular, xenomorphic matrix, constituted of plagioclase, biotite, diopside, zircon, apatite, ilmenite, and magnetite. Euhedral to subhedral diopside (0.1–1.2 mm) is a cumulate phase but is also present in the intercumulus matrix. Some contacts with biotite are gradational and reentrant, suggesting that some biotite crystals may have formed from the destabilization of diopside. The accessory phases (ilmenite, magnetite, apatite, and zircon) are usual inclusions. Reddish brown biotite (0.2–2.7 mm) occurs as a cumulate phase and composes

Table 1
Summary of modal composition for host rocks and MMEs of the Lagoa do Roçado Stock.

Mineral (vol%)	Host rocks		Mafic microgranular enclaves		
	Granodiorite	Quartz monzodiorite	Quartz monzodiorite	Quartz diorite	Diorite
Quartz	16.4–21.6	9.0–12.0	3.0–7.0	3.0–4.0	-
K-feldspar	11.7–18.4	6.0–7.0	3.8–11.0	0.0–2.0	-
Plagioclase	33.1–39.8	51.0–58.0	23.0–43.0	21.0–33.0	23.0–66.0
Diopside	3.1–8.0	5.0–6.0	15.0–26.0	20.0–31.0	5.0–35.5
Biotite	16.1–26.0	17.0–22.0	21.0–43.5	40.0–41.0	21.0–34.0
Hornblende	0.1–2.1	0.0–1.0	0.0–2.7	0.0–1.5	0.0–13.0
Epidote	0.1–1.3	0.1–2.0	0.0–1.7	0.0–1.5	0.0–2.0
Titanite	0.1–0.6	0.0–1.0	0.1–0.5	0.0–0.5	0.0–1.0
Apatite	0.1–0.3	0.1–0.3	0.1–0.3	0.0–0.1	0.1–1.0
Zircon	0.1–0.2	0.1–0.3	0.1–0.4	0.0–0.1	0.1–0.4
Opaque minerals	0.1–0.5	0.0–0.4	0.0–0.5	0.1–0.3	0.0–3.0

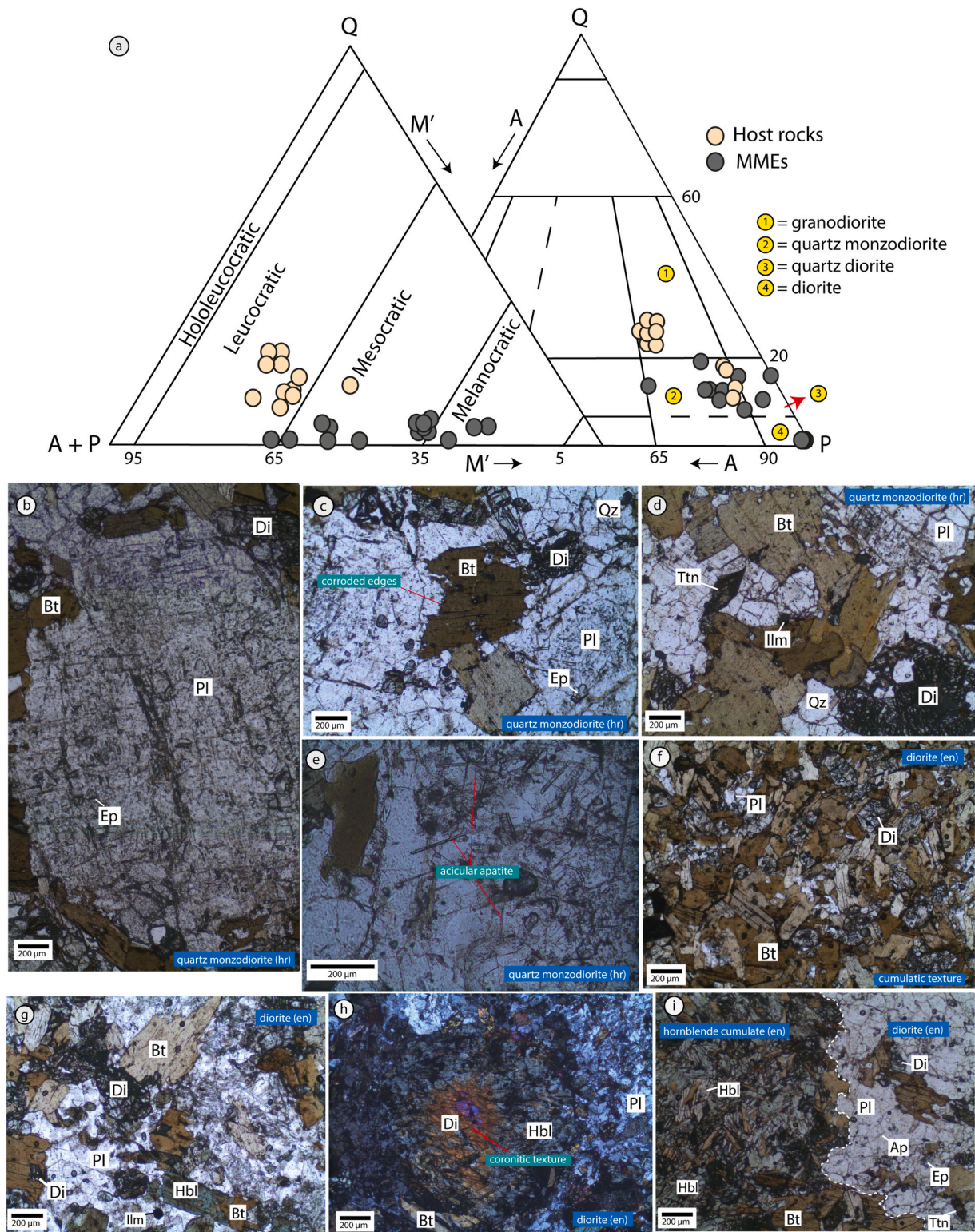


Fig. 3. Petrographic characterization of the Lagoa do Roçado Stock. (a) QAP and A(A+P)M' plots (Le Maitre et al., 2002). (b) Subhedral plagioclase phenocryst rimmed by biotite and diopside, defining a mantle texture. (c) Corroded rims in biotite from a dioritic enclave. (d) Large biotite agglomerates in irregular contacts with plagioclase from a host quartz monzodiorite. (e) Acicular apatite included in plagioclase within a host quartz monzodiorite. (f) Cumulate texture in a dioritic enclave composed of biotite, diopside, and plagioclase. (g) Inequigranular texture in dioritic enclave. Note the gradational contacts between hornblende and biotite crystals (lower right). (h) Diopside crystal strongly replaced by hornblende, defining a coronitic texture in a dioritic enclave. (i) Well-defined contact between a hornblende cumulate and a dioritic enclave. Note the presence of biotite crystals with corroded rims in the dioritic enclave.

the matrix. It includes crystals of diopside, zircon, ilmenite, and magnetite. Plagioclase (0.1–2.3 mm) is the main mineral phase of the matrix, which is weakly transformed to sericite.

Diorites, quartz diorites, and quartz monzodiorites vary in grain size from very fine-grained to medium-grained. They show inequigranular, cumulate, and porphyritic textures, defined by plagioclase, biotite, and diopside immersed in a matrix containing feldspars, quartz, and hornblende. Epidote, titanite, apatite, zircon, ilmenite, and magnetite are the accessory minerals, while sericite and epidote are typical secondary phases.

Plagioclase occurs as subhedral and anhedral phenocrysts up to 3.4 mm and as anhedral crystals in the matrix up to 1.4 mm. The phenocrysts contain inclusions of biotite, titanite, diopside, hornblende, acicular apatite, ilmenite, and magnetite. Some crystals show saussurization, altering to epidote and muscovite.

As in the host granodiorites and quartz monzodiorites, the biotite is the dominant mafic mineral. It occurs as euhedral to subhedral phenocrysts (<3.4 mm), and as subhedral crystals in the matrix (<0.6 mm) (Fig. 3f). Some crystals exhibit gradational and reentrant contacts with

diopside and hornblende (Fig. 3g).

Diopside is identified as euhedral to subhedral phenocrysts (<4.8 mm) or as composing the matrix (<0.4 mm). Some crystals show coronitic textures, enclosed by biotite and hornblende (Fig. 3h). Other crystals are found in mafic aggregates together with biotite and hornblende and display diffuse or embayed boundaries with these minerals.

Compared to the host granodiorites and quartz monzodiorites, hornblende is more abundant in enclaves, reaching 13 vol%. It is a common matrix component (0.6–2.0 mm) in gradational contact with both diopside and biotite (Fig. 3i). It commonly occurs in aggregates with diopside and biotite, showing embayed contacts with these minerals. Some crystals occur as a product of diopside uranization and occupy the outer portions of these crystals.

Quartz typically occurs as anhedral crystals in the matrix.

4.2. Zircon U-Pb age

Zircon grains from the diopside-biotite granodiorite FDS-187A are predominantly euhedral, with prismatic shapes and bipyramidal

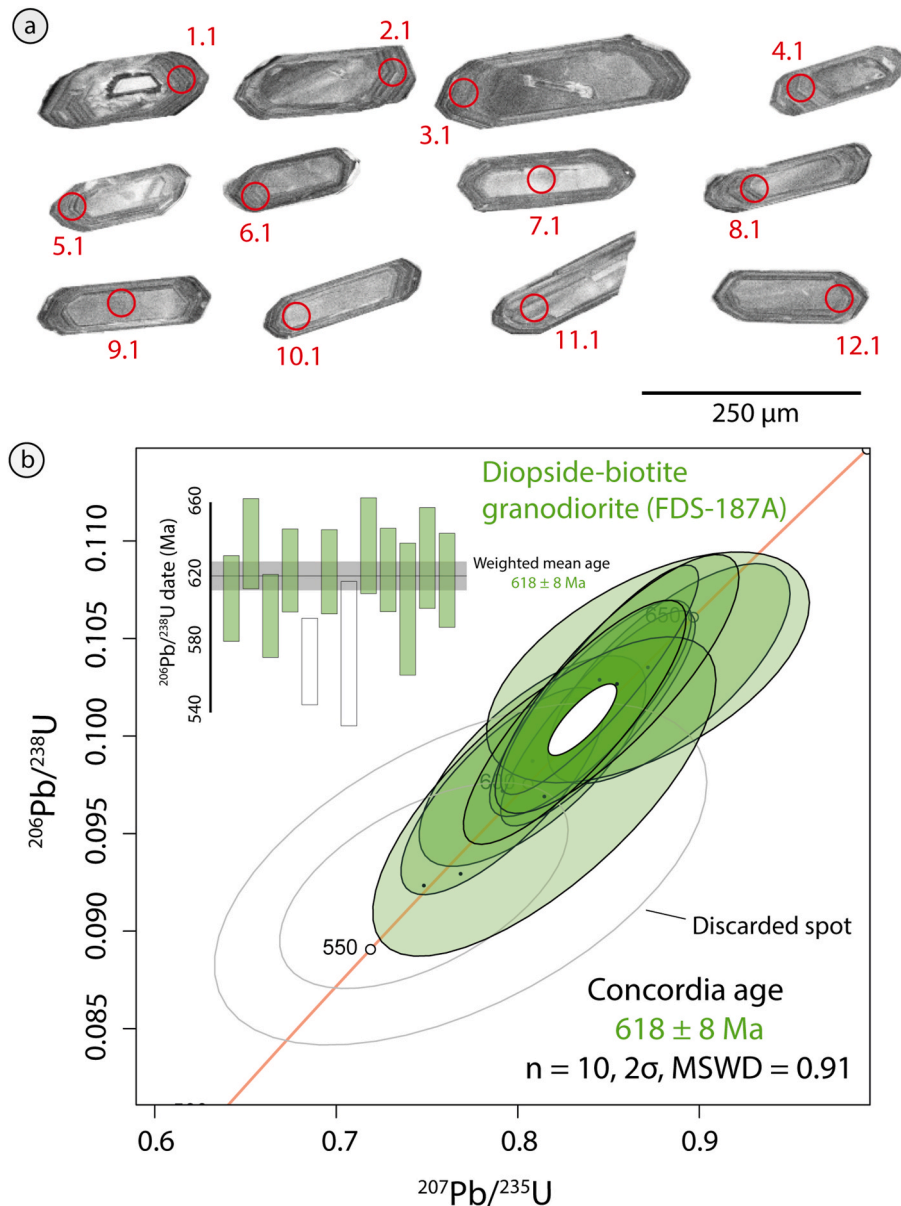


Fig. 4. Zircon U-Pb geochronology. (a) Cathodoluminescence images of dated zircon crystals, with the approximate spot location. (b) Concordia diagram and $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age.

terminations (Fig. 4a). Grain sizes range from 148 to 283 μm , with length/width ratios between 3:1 and 4:1. All zircons display concentric oscillatory zoning and euhedral, compositionally homogeneous cores, and $^{232}\text{Th}/^{238}\text{U}$ ratios vary from 0.29 to 0.51 (Table 2). These characteristics, together with the textural features, are consistent with magmatic zircons (Rubatto, 2017). Two analytical spots (5.1 and 7.1) record elevated proportions of common ^{206}Pb , leading to increased uncertainties in their calculated dates. An age of $612 \pm 8 \text{ Ma}$ ($n = 12$, 2σ , $\text{MSWD} = 0.26$) was obtained when all analyses are considered. Excluding the two analyses with high common Pb contents yields a refined concordia age of $618 \pm 8 \text{ Ma}$ ($n = 10$, 2σ , $\text{MSWD} = 0.91$) and a $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of $618 \pm 8 \text{ Ma}$ ($n = 10$, 2σ , $\text{MSWD} = 1.1$) (Fig. 4b). Based on the textural and geochemical characteristics of the analyzed zircon crystals, this is interpreted as the best estimate for the crystallization age of the Lagoa do Roçado Stock.

4.3. Whole-rock geochemistry

The petrographic observations reveal the presence of secondary phases (muscovite, sericite, carbonate, albite, and epidote) resulting from alteration of the primary assemblage. Their chemical effects have been evaluated before petrogenetic interpretations. LOI values range from 0.5 to 1.85 wt%, indicating that the formation of hydrous phases was reduced. Furthermore, host granitoids and mafic enclaves record values of chemical index of alteration (Nesbitt and Young, 1982) between 40 and 47, respectively, corresponding to the range of fresh basalts and granites.

The host rocks show variable SiO_2 contents ranging from 56.50 to 63.11 wt%, with high alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 6.66\text{--}7.90 \text{ wt\%}$) and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ between 0.86 and 1.65. They have moderate concentrations of Al_2O_3 (14.77–15.34 wt%), MgO (3.53–5.40 wt%), CaO (4.07–5.25 wt%), FeO^* (4.23–6.70 wt%), and TiO_2 (0.78–1.06 wt%). Values of magnesium-number, defined as $\text{Mg\#} = \text{molar MgO}/(\text{MgO} + \text{FeO}^*)$, range from 0.57 to 0.60.

The composition of the enclaves partially overlaps with that of granitoids. They have lower SiO_2 (50.42–57.59 wt%), along with significantly higher FeO^* (6.71–12.00 wt%), MgO (5.11–10.87 wt%), and TiO_2 (0.94–1.60 wt%). $\text{Mg\#}$ values oscillate between 0.55 and 0.70.

The alkalis sum is uniformly high ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 5.68\text{--}8.22 \text{ wt\%}$), rendering $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios between 0.78 and 6.41. Contents of Al_2O_3 (11.43–14.74 wt%) and CaO (3.85–8.12 wt%) are moderate.

In the total alkalis vs. silica diagram (Middlemost, 1994), the host rocks display compositions ranging from monzonite, quartz monzonite, and granodiorite (Fig. 5a). On the other hand, the enclaves plot in the foid monzodiorite, monzodiorite, and monzonite fields. Both rock groups are metaluminous, with alumina saturation index ($\text{A/CNK} = \text{molar Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) ranging from 0.76 to 0.90 in host rocks and from 0.53 to 0.83 in enclaves (Fig. 5b).

According to the Fe-number classification index (Fig. 5c), all studied samples feature magnesian affinities, akin to Cordilleran and Caledonian granitoids (Frost et al., 2001). In a plot of SiO_2 vs. modified alkali-line index ($\text{MALI} = \text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$), the host rocks follow the trends of calc-alkaline and alkali-calcic series, whereas the enclave compositions spread across the calc-alkaline, alkali-calcic, and alkalic series (Fig. 5d).

In the SiO_2 – K_2O diagram (Fig. 5e), most host-rock samples show geochemical affinities with the high-K calc-alkaline magmatic series. The enclaves are somewhat more potassic, plotting in the field of the shoshonite series (Peccerillo and Taylor, 1976).

The geochemical composition of the Lagoa do Roçado Stock rocks is similar to that of granodiorites and monzonites of comparable ages found in the Macururé Domain, especially those belonging to the Glória Norte pluton ($621 \pm 2 \text{ Ma}$; Lisboa et al., 2019; Pereira et al., 2023) and the Coronel João Sá pluton ($625 \pm 2 \text{ Ma}$; Long et al., 2005).

Bivariate diagrams using SiO_2 as a differentiation index are presented in Fig. 6. At first glance, the geochemical composition of the host rocks and enclaves appears to follow a similar evolution. The contents of MgO , FeO^* , TiO_2 , and CaO decrease toward evolved compositions, while Al_2O_3 and Na_2O increase. However, K_2O and P_2O_5 exhibit paired evolution paths in host rocks and enclaves, ruling out a common evolutionary history for these two groups. Despite the overall decreasing trend of these oxides toward more evolved rocks, the enclaves show an abrupt drop within a narrow SiO_2 interval. Furthermore, the values of the ratio between alkalis with increasing SiO_2 show a trend consistent with the high-K liquid line of descent (Bucholz et al., 2014).

Regarding trace elements, host rocks display high Ba (1006–

Table 2
SHRIMP U–Pb zircon isotopic results for the diopside-biotite granodiorite FDS-187A.

Spot ID	U (ppm)	Th (ppm)	$^{232}\text{Th}/^{238}\text{U}$	$^{206}\text{Pb}_c$ (%)	Isotopic ratios							Ages (Ma)		Disc (%)
					$^{207}\text{Pb}/^{235}\text{U}$	1s (%)	$^{206}\text{Pb}/^{238}\text{U}$	1s (%)	Rho	$^{207}\text{Pb}/^{206}\text{Pb}$	1s (%)	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$	
1.1	741	248	0.35	0.30	0.8074	3.1	0.099	2.2	0.70	0.0594	2.2	608 ± 13	580 ± 48	–4.3
2.1	630	221	0.36	0.08	0.8830	3.0	0.103	2.2	0.73	0.0621	2.1	634 ± 14	677 ± 44	6.9
3.1	732	230	0.33	0.16	0.7916	2.8	0.097	2.2	0.78	0.0591	1.8	600 ± 13	571 ± 39	–4.5
4.1	583	211	0.37	–0.11	0.8442	2.5	0.101	2.2	0.86	0.0607	1.3	623 ± 14	628 ± 28	1.3
5.1 ^a	764	374	0.51	0.94	0.7477	4.3	0.092	2.3	0.54	0.0588	3.6	576 ± 14	559 ± 79	–1.8
6.1	640	233	0.38	0.09	0.8399	2.7	0.101	2.2	0.82	0.0601	1.5	626 ± 14	606 ± 33	–2.7
7.1 ^a	444	144	0.33	0.87	0.7683	7.1	0.093	3.8	0.53	0.0600	6.0	574 ± 22	604 ± 130	5.4
8.1	411	189	0.47	0.01	0.8724	4.1	0.104	2.3	0.56	0.0611	3.4	638 ± 15	643 ± 72	1.2
9.1	677	253	0.39	0.00	0.8453	2.6	0.103	2.3	0.88	0.0596	1.2	633 ± 15	590 ± 27	–6.5
10.1	424	186	0.45	0.59	0.8144	4.7	0.097	3.4	0.72	0.0610	3.2	598 ± 21	639 ± 69	7.3
11.1	422	168	0.41	0.09	0.8546	3.2	0.103	2.6	0.82	0.0604	1.8	632 ± 17	618 ± 39	–1.9
12.1	432	122	0.29	0.00	0.8326	3.0	0.101	2.5	0.84	0.0599	1.6	620 ± 16	601 ± 35	–2.8

^a Spots excluded from the concordia age calculation.

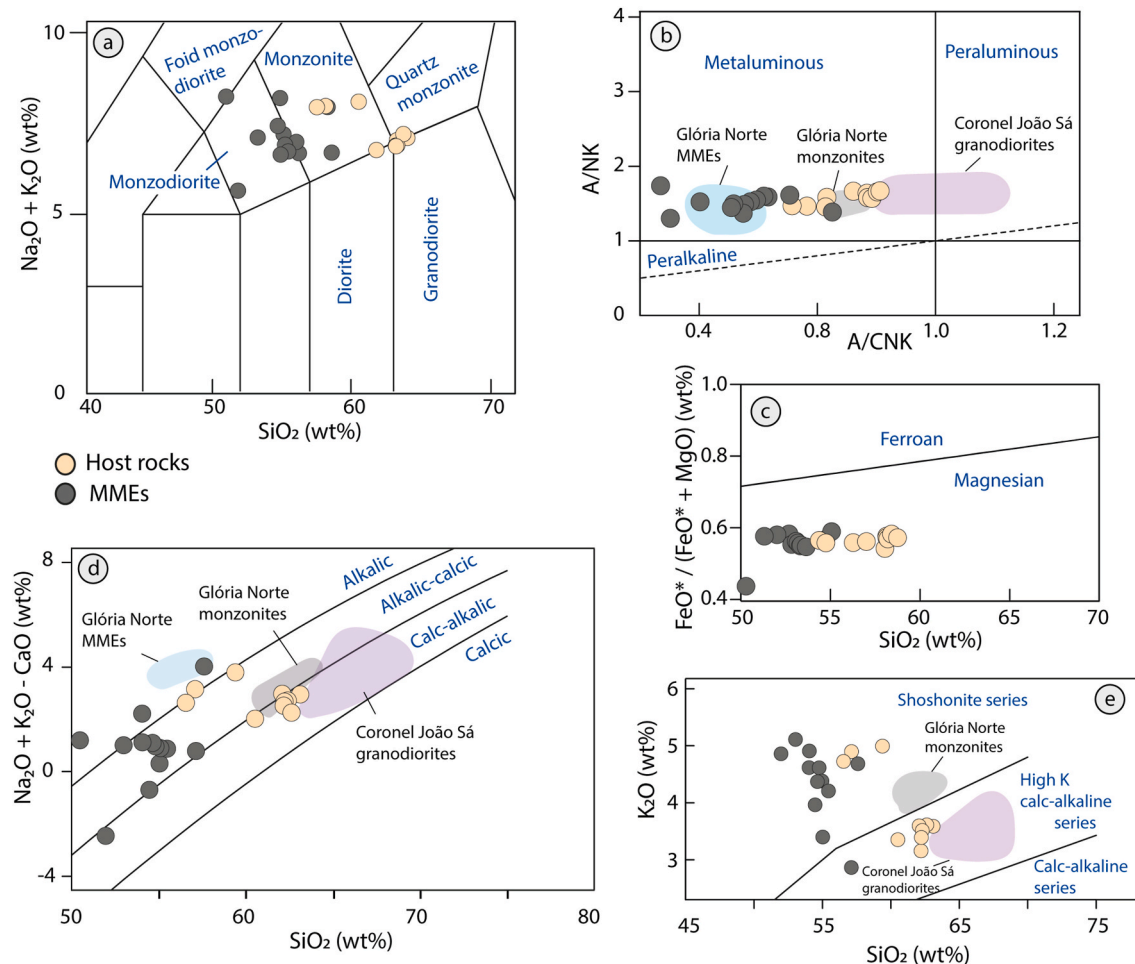


Fig. 5. Major element geochemistry of the Lagoa do Roçado Stock. (a) Total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) vs. SiO_2 (Middlemost, 1994). (b) A/CNK = molar $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. A/NK = molar $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$ (Shand, 1943). SiO_2 vs. (c) $\text{FeO}^*/(\text{FeO}^* + \text{MgO})$ and (d) $\text{MALI} = \text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ with fields by Frost et al. (2001). (e) SiO_2 vs. K_2O (Peccerillo and Taylor, 1976). Fields of Cel. João Sá (Long et al., 2005) and Glória Norte (Lisboa et al., 2019) plutons are also shown.

1276 ppm), Sr (597–729 ppm), and Rb (112–130 ppm) concentrations, along with moderate Zr (183–216 ppm). Part of these values overlap partially with those of the mafic enclaves, which show Ba (741–2160 ppm), Rb (128–134 ppm), and Sr (263–483 ppm). The total rare earth element (REE) concentrations for the host granitoids (185–219 ppm) and mafic enclaves (163–248 ppm) also overlap, but some enclaves are notably richer.

Chondrite-normalized (CN; McDonough and Sun, 1995) REE patterns for host granitoids are enriched in light REE (LREE) relative to heavy REE (HREE; $\text{Ce}/\text{Yb}_{\text{CN}} = 14.7\text{--}19.2$), with weak fractionation among LREE ($\text{Ce}/\text{Sm}_{\text{CN}} = 2.7\text{--}3.2$) and HREE ($\text{Dy}/\text{Yb}_{\text{CN}} = 1.5\text{--}1.7$) (Fig. 7a). The mafic enclaves show lower LREE/HREE fractionation ($\text{Ce}/\text{Yb}_{\text{CN}} = 7.5\text{--}13.7$), as well as lower enrichment among LREE ($\text{Ce}/\text{Sm}_{\text{CN}} = 1.8\text{--}2.2$) and HREE ($\text{Dy}/\text{Yb}_{\text{CN}} = 1.4\text{--}1.6$). Negative Eu anomalies are observed in both host rocks (0.83–0.87) and enclaves (0.52–0.81), but are significantly higher in the latter.

In a multielement diagram normalized to the primitive mantle (McDonough and Sun, 1995), the investigated samples show overall enrichment in large-ion lithophile elements (LILE) and LREE relative to high-field-strength elements (HFSE) and HREE. Both rock groups feature deep troughs at Nb and Ta (Fig. 7b).

5. Discussion

5.1. Mixing: structural and textural evidence

As discussed previously, evidence of magmatic interaction indicates that chaotic mixing can generate strong chemical disequilibrium within magma chambers, leading to pronounced compositional heterogeneity. Disequilibrium in magmatic systems may be recorded by a variety of textures and patterns at different length scales, including the development of geochemical and isotopic inhomogeneities, the formation of chemical zoning and/or resorption textures in mineral phases, as well as the preservation of relics of one of the interacting magmas that did not undergo complete hybridization (e.g., magmatic enclaves and/or banded structures) (Perugini, 2021; Morgavi et al., 2022). Nevertheless, the evidence indicates that chaotic mixing was an important process in generating hybrid magmas and in developing the lithological and textural diversity observed in the Lagoa do Roçado Stock.

Syn-plutonic mafic dikes and MMEs showing varied shapes and sizes reflect the injection of mafic magmas into a felsic magma chamber. The enclaves display ellipsoidal, globular, and stretched shapes, reflecting mechanical dispersion and plastic deformation within a more viscous felsic magma (Vernon, 1984; Barbarin, 2005). The contacts between enclaves and host granitoids vary from sharp, curved, and lobate to gradational. Biotite-rich chilled margins around enclaves and along these contacts record rapid quenching of hotter mafic magma against cooler felsic hosts. Furthermore, compositional gradients between the

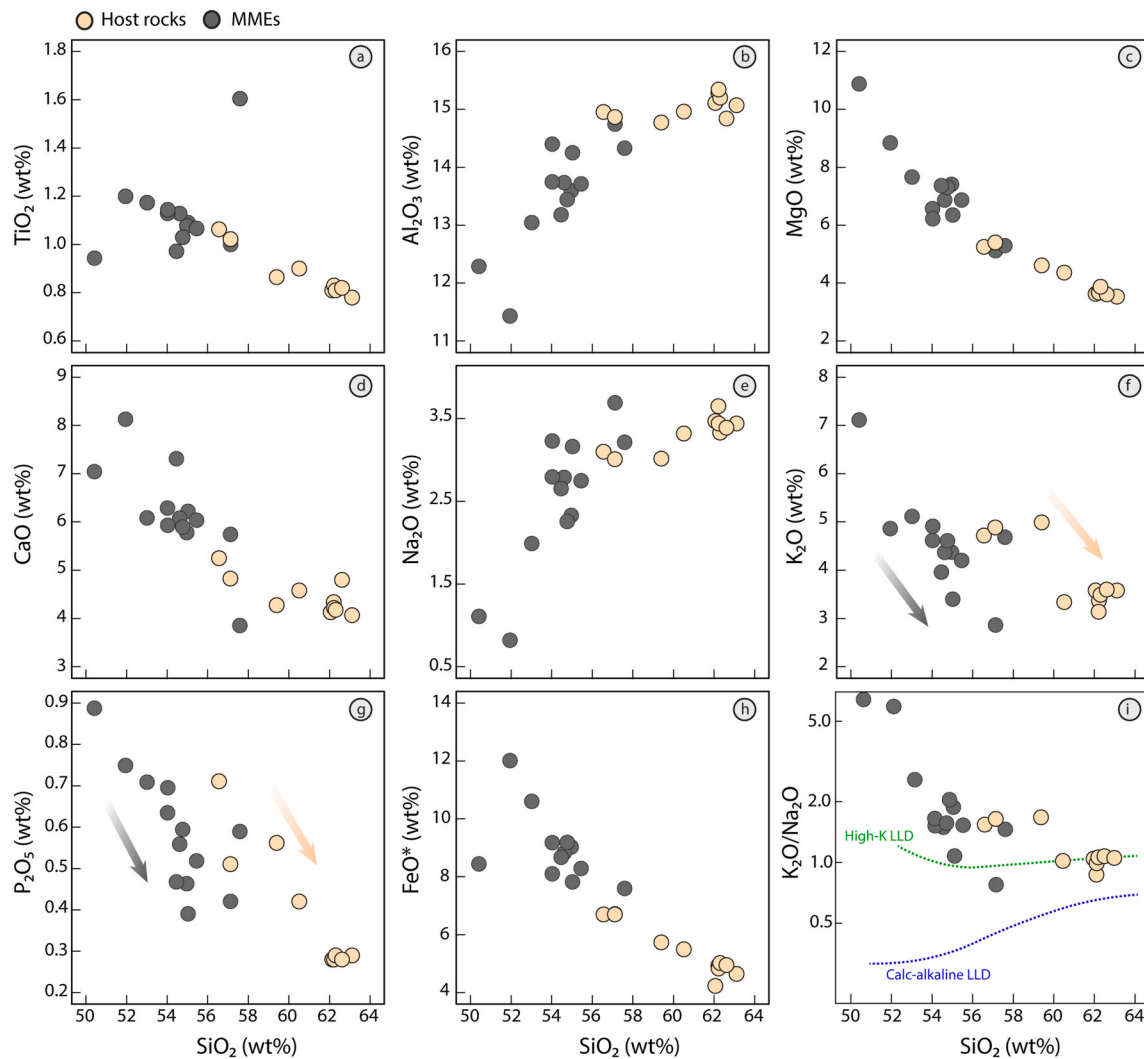


Fig. 6. Variation diagrams for selected oxides against SiO_2 . Liquid line of descent (LLD) comparing the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ enrichment of high-K and calc-alkaline series (Bucholz et al., 2014), showing a match of the investigated samples with potassic LLD.

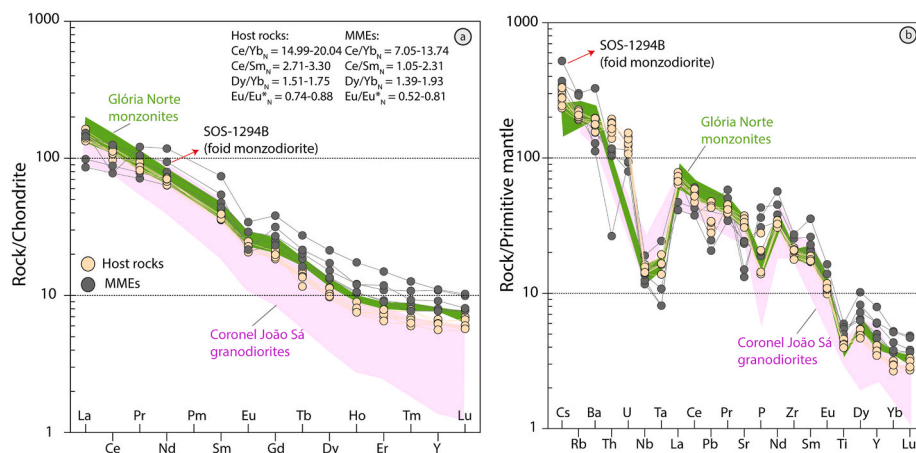


Fig. 7. Chondrite-normalized (a) REE and (b) primitive mantle-normalized trace element patterns of the Lagoa do Roçado Stock. Normalization values are from McDonough and Sun (1995). Trace element data for the Cel. João Sá batholith (Long et al., 2005) and Glória Norte pluton (Lisboa et al., 2019) are also shown for comparison.

MMEs and host granitoids indicate incomplete homogenization of the interacting magmas. In addition, the presence of mafic clots composed

of diopside and hornblende indicates the early segregation of these phases in the parental mafic magma and their subsequent interaction

with the host felsic magma.

Microtextural evidence also supports the role played by chaotic mixing processes. Textural heterogeneities, such as plagioclase phenocrysts in the MMEs, are interpreted as xenocrysts mechanically transferred from the host magma to the mafic magma (Barbarin and Didier, 1992). Resorbed and corroded edges of mafic phases (e.g., diopside, biotite), as well as mantled feldspars, are typical disequilibrium mineral textures observed in enclaves and host granitoids. They are indicative of physicochemical and thermal changes in the magma chamber resulting from the injection of hot, mantle-derived mafic magma into the cooler felsic host magma (Tsuchiyama, 1985; Streck, 2008). Acicular apatite suggests a thermal contrast due to quenching when a hot mafic magma is injected into a cooler felsic magma (Wyllie et al., 1962).

Together, these features support a shared evolution between the MMEs and the host rocks, marked by the interaction of magmas with contrasting compositions. This interaction is recorded at mesoscopic and microscopic scales and reflects the compositional heterogeneity observed in the Lagoa do Roçado Stock rocks.

5.2. Source of host granitoids

Quartz monzonites and granodiorites of the Lagoa do Roçado Stock are intermediate to acidic and feature high alkali contents. They are metaluminous, magnesian, and show affinities with the high-K and shoshonitic series. Significant enrichments in LILE and LREE relative to

HFSE and HREE characterize these rocks. Such features are consistent with those of I-type granitoids derived from igneous protoliths, as described by Chappell and White (2001), indicating a crustal component in the genesis of the Lagoa do Roçado pluton.

Major element data were compared with the compositions of partial melts derived from several source rocks to infer the most likely protoliths responsible for generating the granodiorites and quartz monzonites. The concentrations of CaO and alkalis differ from those observed in partial melts of pelitic rocks and graywacke, but match those of liquids derived from dehydration melts of amphibolites (Fig. 8; Patiño Douce, 1999). A mafic/metabasaltic source is also indicated in the plots of Na₂O and K₂O vs. SiO₂ (Fig. 8; Sisson et al., 2005), where the composition of granitoids overlaps those of medium- to high-K basaltic sources. Amphibolites are important components of the middle/lower crust (Rudnick and Gao, 2003) and fertile lithologies to generate granitoids.

Apatite saturation temperatures calculated relative to the calibration of Harrison and Watson (1984) range from 933 to 995 °C, compatible with initial stages of dehydration melting of amphibolites at 3–15 kbar (Rushmer, 1991; Patiño Douce and Beard, 1995). These findings reinforce that the magma genesis of the Lagoa do Roçado Stock involved the partial melting of an amphibolitic/basaltic protolith.

An intriguing feature of the quartz monzonites and granodiorites is their elevated Mg# values (0.57–0.60). These values are markedly higher than those expected for melts experimentally derived from

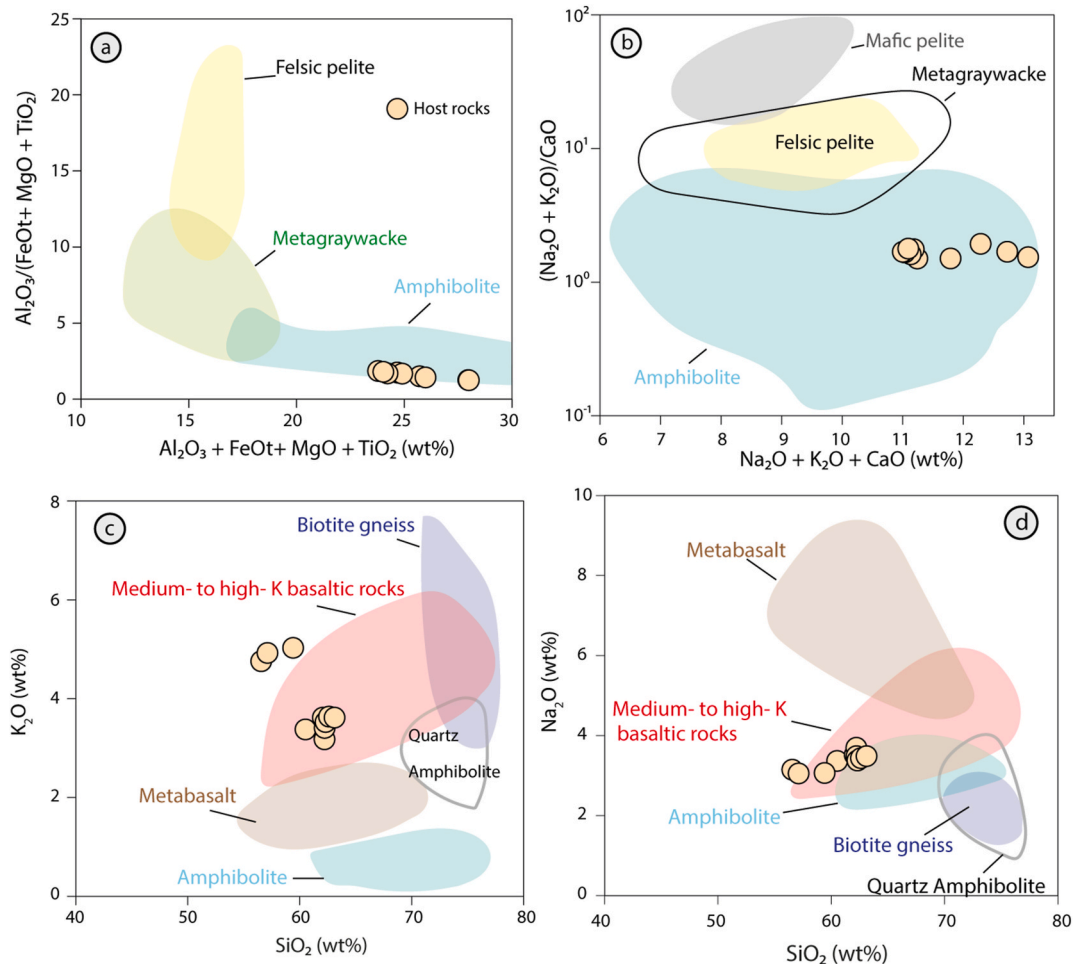


Fig. 8. Petrogenesis of the host rocks from Lagoa do Roçado Stock. (a) $\text{Al}_2\text{O}_3/(\text{FeO}^* + \text{MgO} + \text{TiO}_2)$ vs. $\text{Al}_2\text{O}_3 + \text{FeO}^* + \text{MgO} + \text{TiO}_2$ and (d) $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ vs. $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$ with fields of partial melts from amphibolites, metagraywackes, and felsic pelites (Patiño Douce, 1999). Plots of SiO_2 vs. (c) K_2O and (d) Na_2O with the composition of experimental glasses derived from amphibolites (Beard and Lofgren, 1991), metabasalt (Rapp and Watson, 1995), quartz amphibolite and biotite gneiss (Patiño Douce and Beard, 1995), and medium- to high-K basalt (Sisson et al., 2005) compiled by Chen et al. (2013).

amphibolitic or metabasaltic sources representative of the deep continental crust, which typically yield $Mg\#$ values below 0.40 (Rapp and Watson, 1995). In addition, moderate Ni (43–67 ppm) contents suggest that a mantle-derived source was involved in the Lagoa do Roçado magma. Since magmas generated directly from mantle peridotite are typically basaltic rather than andesitic (Takahashi, 1986), a purely mantle-derived origin can be ruled out. Thus, we envisage that hybridization between crustal magmas and mantle-derived mafic magmas may account for the chemical composition of the investigated rocks.

The major and trace element characteristics of the investigated granitoids partially overlap with those reported for the Glória Norte monzonites (Lisboa et al., 2019) and the Coronel João Sá granodiorites (Long et al., 2005). Lisboa et al. (2019) interpreted the origin of the Glória Norte pluton as mantle-derived magmas (MMEs) that evolved by fractional crystallization to form the monzonites. In contrast, Long et al. (2005) interpreted the Coronel João Sá pluton as a product of mixing between crust-derived magmas. In general, the granodiorites of the Coronel João Sá pluton are more evolved and display higher LREE/H-REE and LILE/HFSE ratios compared to the Lagoa do Roçado pluton.

5.3. Source of the MMEs

The MMEs display compositions of diorite, quartz diorite, and quartz monzodiorite. These rocks are metaluminous, magnesian, and predominantly belong to the shoshonitic series. Compared to the host granitoids, the MMEs show significant variation in silica (50.42–57.59 wt%) and total alkalis (5.68–8.22 wt%), as well as higher concentrations of MgO , CaO , TiO_2 , and FeO^* . It is noteworthy that the composition of the most evolved enclaves overlaps with that of the host granitoids (Fig. 6), suggesting a genetic relationship or advanced hybridization. Trace element composition of the MMEs is marked by strong enrichment in LILE relative to HFSE, negative Sr anomalies, pronounced depletions in Nb, Ti, and Ta, and moderately fractionated chondrite-normalized REE patterns (Fig. 7).

The most primitive sample (SOS-1294B) among the MMEs shows a composition of foid monzodiorite, with CIPW-normative nepheline, and elevated $Mg\#$ (0.70), Cr (755 ppm), K_2O (7.11 wt%), K_2O/Na_2O (6.41), and Ba (2160 ppm). Such geochemical features are consistent with a primary mantle-derived alkali basalt (Wilson, 1989), resulting from low degrees of partial melting of enriched peridotites at approximately 15 kbar (Jaques and Green, 1980).

The other enclaves feature higher SiO_2 contents (>51 wt%), lower $Mg\#$ (<0.61) and Cr concentrations (<359 ppm), which are inconsistent

with primary mantle-derived magmas (Kushiro and Kuno, 1963; Baker et al., 1994). These features suggest the primitive composition was modified by differentiation processes such as fractional crystallization, magma mixing, or crustal contamination (Wilson, 1989; Gill, 2010).

To assess the source characteristics of the enclaves, we compared their chemical compositions with experimental melts derived from various potential mantle sources. As shown in Fig. 9, partial melting of a refractory peridotitic mantle cannot produce melts with the high SiO_2 and K_2O contents and low ratio CaO/Al_2O_3 observed in the MMEs (Herzberg and Zhang, 1996; Gaetani and Grove, 1998; Hirschmann et al., 2003; Tenner et al., 2012). Conversely, the major-element compositions are comparable to experimental melts produced by partial melting of amphibole- and/or phlogopite-bearing peridotitic sources (Conceição and Green, 2004; Condamine and Médard, 2014; Condamine et al., 2016), as well as melts derived from hybrid sources involving mixtures of peridotite and granitoid components (Rapp et al., 2010; Mallik et al., 2015).

The sample SOS-1294B displays Ba enrichment relative to Rb in multielement patterns normalized to the primitive mantle (Fig. 7b), suggesting the presence of a residual phase that preferentially incorporates Rb over Ba. Pargasite and phlogopite, which are the principal metasomatic phases in the mantle (Class and Goldstein, 1997; Foley, 1992; Conceição and Green, 2004), exhibit distinct partition coefficients for these elements. Unlike pargasite, phlogopite preferentially retains Rb and produces a marked increase in Rb/Sr ratios over narrow intervals of Ba/Rb ratios (Fig. 10a; Furman and Graham, 1999), and is therefore interpreted as a residual phase during magma generation. This behavior is also observed in the rocks of the Macururé Mafic Suite (Pereira et al., 2020, 2024), suggesting that the MMEs and these units may have been derived from comparable mantle sources. Additionally, the high Th/Yb and low Ba/La ratios observed in the MMEs of the Lagoa do Roçado Stock are also typical of the mafic rocks associated with the Capela pluton (Fig. 10b). Given the higher solubility of LILE in fluids relative to REE and HFSE, these signatures are more consistent with mantle enrichment by sediment melts rather than by slab-derived fluids (Woodhead et al., 2001), accounting for the presence of residual phlogopite associated with enrichment in K, LILE, and REE.

Therefore, we propose that partial melting of an enriched (metasomatized) mantle source containing phlogopite produced mafic magmas that were subsequently injected into a magma reservoir hosting more evolved felsic melts. The interaction between these contrasting magmas promoted mixing and hybridization, modifying the composition of the primitive melts and generating the geochemical signatures

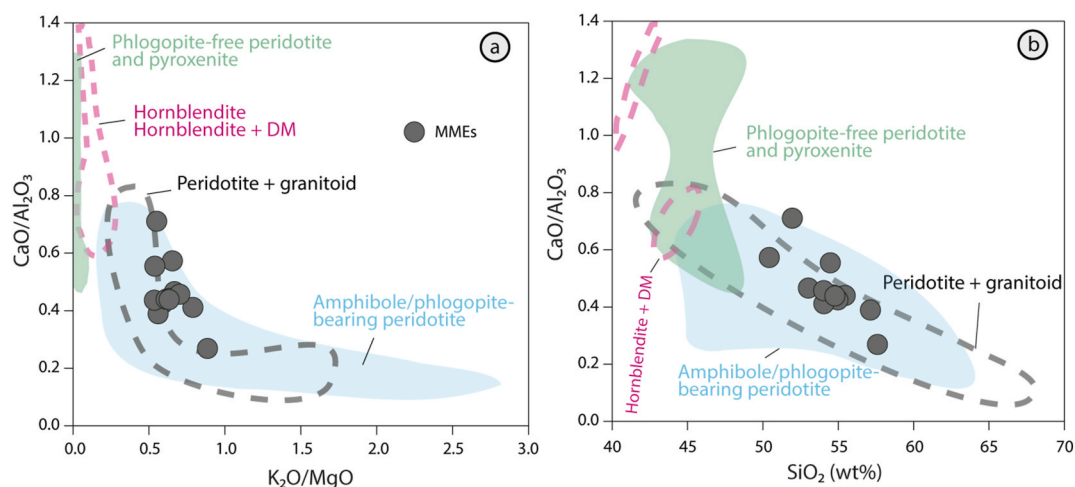


Fig. 9. Petrogenesis of the enclaves from Lagoa do Roçado Stock. (a) K_2O/MgO vs. CaO/Al_2O_3 and (b) SiO_2 vs. CaO/Al_2O_3 with fields of experimental melts derived from metasomatized phlogopite/amphibole-bearing peridotite (Conceição and Green, 2004; Condamine et al., 2016; Condamine and Médard, 2014), hornblende and mixed hornblende with a depleted mantle component (Pilet et al., 2008), hybridized peridotite and granitoid sources (Mallik et al., 2015; Rapp et al., 2010), and phlogopite/amphibole-free peridotite and pyroxenite (Gaetani and Grove, 1998; Herzberg and Zhang, 1996; Hirschmann et al., 2003; Tenner et al., 2012).

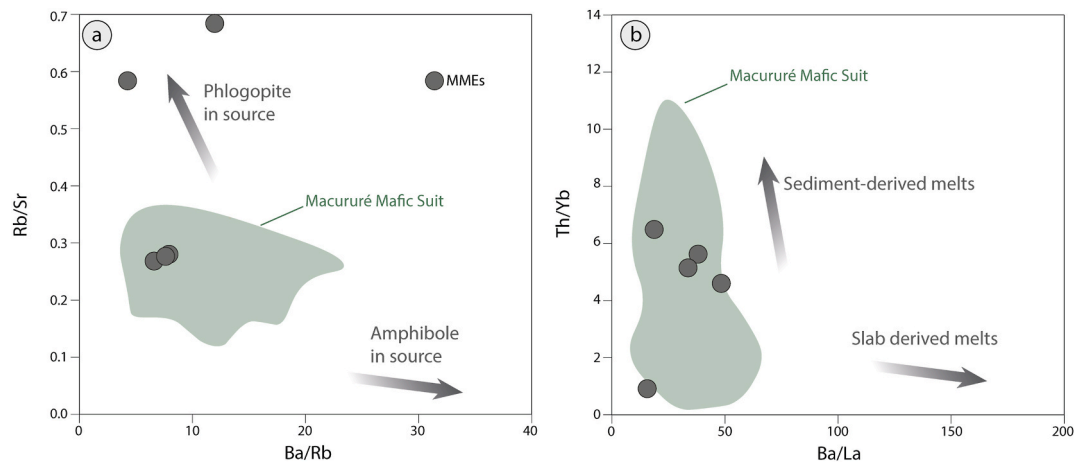


Fig. 10. Source of the MMEs from Lagoa do Roçado Stock. (a) Ba/Rb vs. Rb/Sr ratios indicating the compositions resulting from partial melting of a mantle source containing phlogopite or amphibole (Furman and Graham, 1999). The fields for the Macururé Mafic Suite are from Pereira et al. (2020). (b) Ba/La vs. Th/Yb (Woodhead et al., 2001).

observed in the studied enclaves. The compositions of the more evolved enclaves, in turn, are interpreted as the result of intracrustal differentiation processes. A similar interpretation has been proposed for the origin of mafic plutons in the Macururé Domain (Pereira et al., 2020, 2023, 2024), as well as for the mafic enclaves within the Rio Jacaré batholith in the Poço Redondo Domain (Sousa et al., 2022).

However, it is important to emphasize that these interpretations are limited to the whole-rock geochemical data. As demonstrated by experimental studies (e.g., Perugini et al., 2015; Morgavi et al., 2022), chaotic mixing commonly produce deviations in elemental concentrations of hybrid products relative to the conceptual linear mixing model (e.g., Fourcade and Allegre, 1981; Perugini and Poli, 2012). Therefore, further isotopic geochemical studies are required to better constrain the nature of the mantle source involved in the genesis of the MMEs.

5.4. Differentiation processes

The behavior of major and trace elements may result from distinct processes, such as partial melting, fractional crystallization, and magma mixing (Cox et al., 1979; Frost and Frost, 2008).

Log-log plots of elements with contrasting geochemical behavior are useful tools for identifying the processes that control magma evolution (Cocherie, 1986). Fractional crystallization typically results in a progressive enrichment of incompatible elements and a marked depletion of compatible elements, whereas partial melting tends to yield relatively stable concentrations of compatible elements accompanied by significant variations in incompatible elements. The log-log plots reveal a sharp depletion of Cr and V relative to Sr (Fig. 11a and b), suggesting that fractional crystallization plays a significant role in magma evolution of the enclaves and the host rocks.

In a scenario dominated by fractional crystallization, the decreasing trends of CaO, MgO, FeO*, K₂O, TiO₂, and P₂O₅ with increasing SiO₂ in Harker diagrams can be ascribed to the fractionation of diopside, amphibole, biotite, ilmenite, and apatite. On the other hand, the increase in Al₂O₃ and Na₂O contents with SiO₂ may be interpreted as the late plagioclase crystallization.

To investigate compositional changes in the liquid during crystallization, we examined variations in trace element concentrations using bivariate diagrams that incorporate Rayleigh fractionation vectors for individual mineral phases (Rollinson, 1993). As illustrated in Fig. 11, Ba, Rb, and Sr behave as compatible elements, showing decreasing concentrations as fractionation progresses. The removal of K-feldspar and plagioclase largely controls the distribution of these elements. Vanadium and Ti also exhibit a compatible behavior, although their trends

are predominantly governed by ilmenite fractionation (Fig. 11e).

Unlike the host rocks, Ba (except for the enclave SOS-1294B) and Sr are incompatible in the mafic enclaves, whereas Rb and Cr are compatible. The distribution of these elements seems to be mainly controlled by the fractionation of biotite and diopside. Similar to the host rocks, magnetite and ilmenite fractionation controlled the budget of V and Ti.

These relationships indicate that fractional crystallization operated differently within each rock group. Three main lines of evidence support the interpretation that the enclaves and their host rocks are not genetically related through a simple fractional crystallization process:

- The fractionation of a basaltic magma toward dacitic compositions through the removal of diopside, amphibole, and biotite would yield Mg# values lower than those observed in the host rocks.
- The contrasting behavior of compatible and incompatible elements in the enclaves and host rocks is inconsistent with the trends expected from fractional crystallization.
- The MMEs exhibit more pronounced negative Eu anomalies than the more evolved host rocks. Such stronger anomalies would typically be associated with advanced stages of crystallization involving significant feldspar fractionation.

Accordingly, trace element modeling was carried out to evaluate the effects of the main differentiation processes on the most primitive samples of the Lagoa do Roçado Stock. The dioritic enclave SOS-1294B stands out from the others due to its elevated concentrations of both compatible and incompatible elements. Thus, the second most primitive sample (SOS-187K; SiO₂ = 51.95 wt%, Mg# = 0.57, Cr = 961 ppm) was selected as the starting composition for fractional crystallization and the mafic endmember in the mixing process. The host rocks constitute a chemically coherent group, exhibiting overlapping compositions in several major and trace elements; therefore, sample FDS-182A (SiO₂ = 62.21 wt%, Mg# = 0.57) was selected as the felsic endmember. The composition of a garnet-bearing mica schist from the Macururé Complex (Conceição, 2014) was used as the assimilated composition in the AFC (assimilation and fractional crystallization) model.

As presented in Fig. 12a–c, the trace element composition of enclaves and host rocks cannot be explained by either fractional crystallization or AFC processes. On the other hand, most samples plot along the mixing line between the mafic and felsic endmembers. According to these results, high proportions of the felsic component (>40%) are required to reproduce the composition of intermediate enclaves. On the other hand,

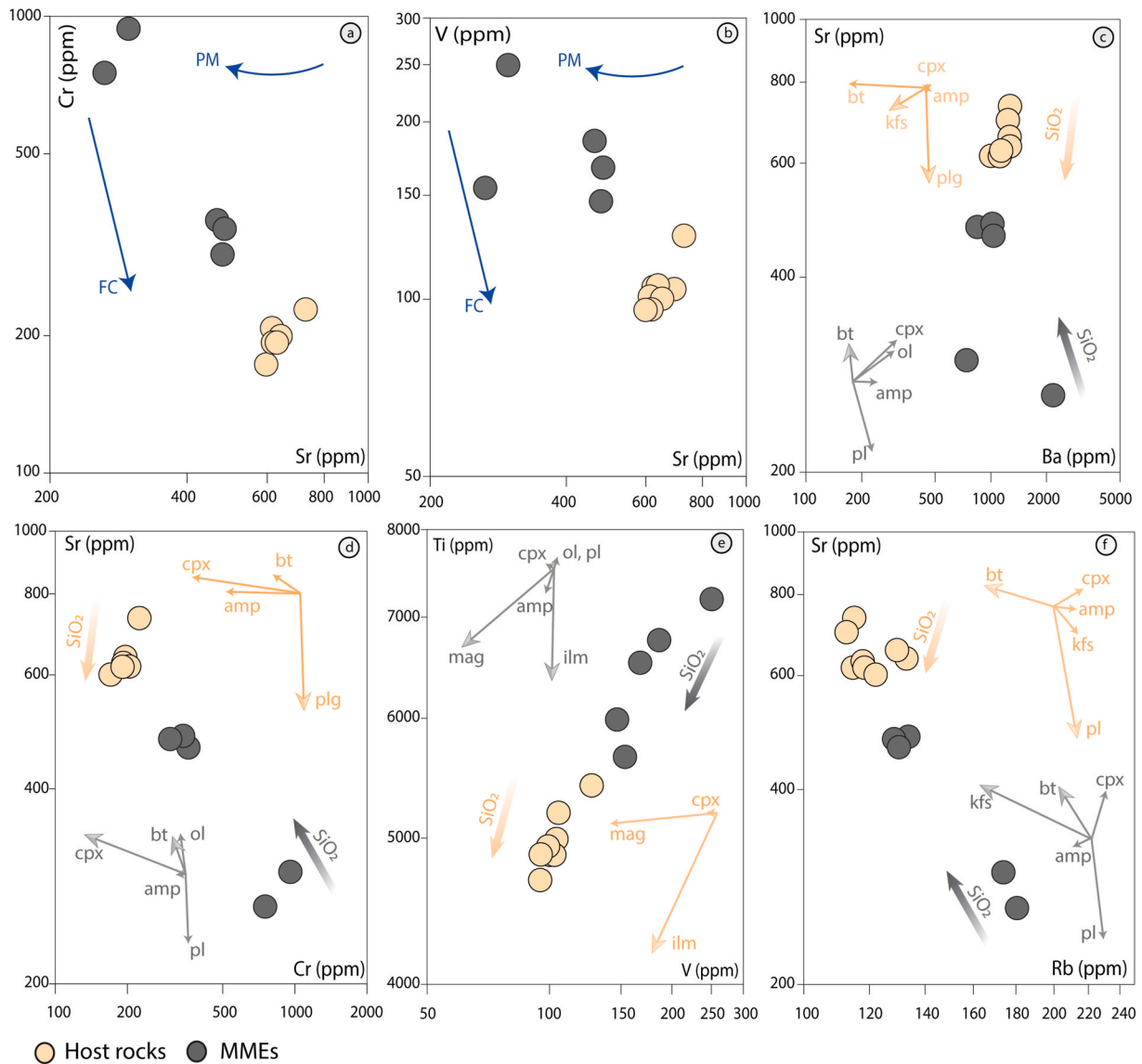


Fig. 11. Petrogenetic discrimination diagrams for rocks of the Lagoa do Roçado Stock. Log-log plots of (a) Cr vs. Sr and (b) V vs. Sr showing trends associated with partial melting (PM) and fractional crystallization (FC). Vector log-log plots of (c) Sr vs. Ba, (d) Sr vs. Cr, (e) Ti vs. V, and (f) Sr vs. Rb illustrating the influence of fractional crystallization of clinopyroxene (cpx), biotite (bt), plagioclase (pl), K-feldspar (kfs), olivine (ol), amphibole (amp), ilmenite (ilm), and magnetite (mag).

the proportion of the mafic component required to account for the composition of the host granodiorites and quartz monzodiorites can reach 50%.

This interpretation is further reinforced by mixing models based on major oxide compositions (Fig. 12e and f). To evaluate whether the host rocks and enclaves follow the expected mixing relationships, we applied the approach of Fourcade and Allegre (1981). In the plot of $C_m^i - C_B^i$ vs. $C_A^i - C_B^i$, the concentrations of oxide i in the m (hybrid component), A (least evolved component) and B (most evolved component), define a straight line whose slopes (0.54 and 0.65) are interpreted as the proportions of the mafic component in the mixture. As demonstrated by experimental studies (De Campos et al., 2011), non-strictly linear trends observed in binary mixing models are a common feature of products of chaotic mixing. In this process, diffusive fractionation between the end-members tends to generate highly heterogeneous pockets that may be preserved as MMEs with contrasting compositions. These features indicate a high degree of hybridization and support the interpretation that magma mixing was the main differentiation process controlling the composition of the Lagoa do Roçado Stock.

5.5. Integrated model

We propose a model in which partial melting of a metasomatized lithospheric mantle, crustal anatexis, and subsequent mixing between compositionally contrasting magmas together governed the compositional diversity of the Lagoa do Roçado pluton (Fig. 13).

As discussed previously, the MMEs are interpreted to have formed by low-grade partial melting of a phlogopite-bearing, metasomatized peridotitic source. Geochemical and isotopic evidence led Pereira et al. (2023, 2024) to propose that subduction-related sediment influx during the Rhyacian Orogeny was responsible for metasomatizing the sub-lithospheric mantle beneath the ancient Borborema Province basement. This fertilized mantle was then involved in the Brasiliano/Pan-African Orogeny, giving rise to the pre-to early-collisional mafic plutons emplaced into the Macururé Domain between 640 and 628 Ma. Although no mafic plutons younger than 628 Ma have been identified in the SOS, the potassic magmas are preserved as mafic enclaves within several late-collisional intrusions of the Macururé, Poço Redondo, and Canindé domains (Lisboa et al., 2019; Sousa et al., 2022). These findings suggest that a previously enriched mantle remained fertile and prone to

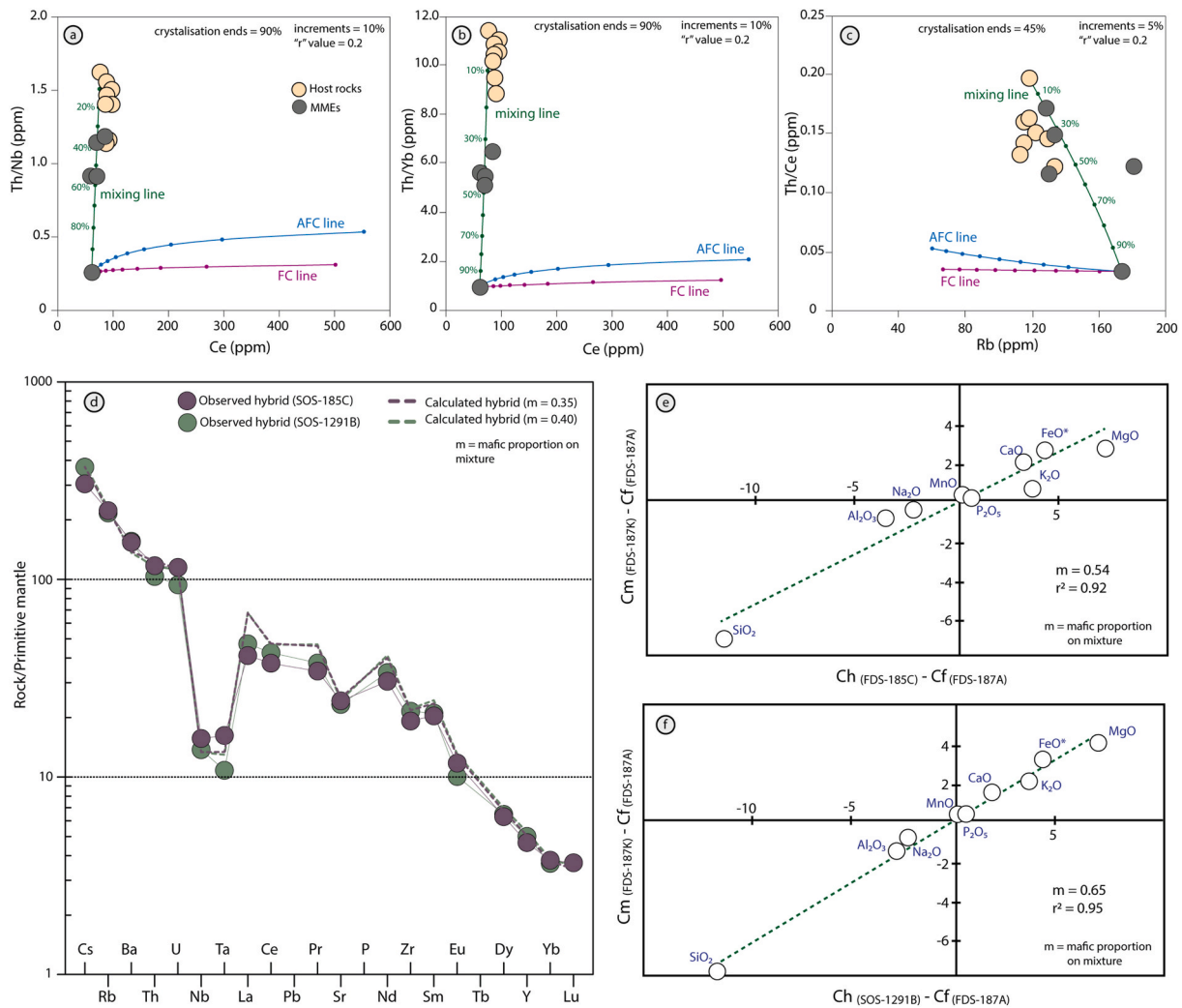


Fig. 12. Differentiation processes in the Lagoa do Roçado Stock. (a) Th/Nb vs. Ce, (b) Th/Yb vs. Ce, and (c) Th/Ce vs. Rb diagrams illustrating the trends associated with fractional crystallization (FC), assimilation and fractional crystallization (AFC), and magma mixing. The proportion of each mineral phase involved in the fractional crystallization model was based on the semiquantitative modal composition of the enclaves and the fractionation vectors derived from log-log trace element diagrams: 50% biotite + 30% clinopyroxene + 15% plagioclase + 5% ilmenite and magnetite. (d) Calculated and observed trace elements generated by mixing between a mafic magma (SOS-187K) and a differentiated felsic magma (FDS-187A). (e) and (f) Major element mixing models testing the hypothesis that the quartz monzodioritic (Ch = FDS-185C) and dioritic (Ch = SOS-1291B) compositions can be generated by mixing between a mafic magma (Cm = SOS-187K) and a differentiated felsic magma (Cf = FDS-187A).

melting throughout the Brasiliano orogenic cycle.

Following the intracontinental extension and later inversion during the continental collision, regional relaxation allowed emplacement of the late-collisional magmatism (Pereira et al., 2023). The high contents of modal biotite support that it originates from a hydrous basaltic magma, which would have favored ascent to higher crustal levels (Condamine and Médard, 2014; Murphy, 2020). Sustained accumulation of such mafic magmas at the base of the crust may have triggered partial melting of amphibolitic/basaltic sources (Huppert and Sparks, 1988; Annen et al., 2015), generating the felsic magmas that now constitute the host granitoids.

Field and microscopic evidence indicate that interaction between felsic magmas and injections of mafic magma occurred at various stages of crystallization in the magma chamber. Disequilibrium features indicate that the felsic magma had already begun to crystallize when the pulses of hot mafic magmas were intruded. Furthermore, the presence of similar textures within the enclaves further supports the hypothesis of repeated recharge events. Limited interaction and hybridization between these compositionally distinct magmas generated intermediate compositions. In addition, fractional crystallization of diopside, biotite,

and plagioclase took place may have further contributed to the differentiation.

The presence of syn-plutonic dikes indicates that recharge events persisted even after the felsic magma had cooled and attained substantial crystallinity. Under these conditions, the strong thermal and rheological contrasts between the two magmas would inhibit efficient mixing (Barbarin and Didier, 1991; Wiebe and Collins, 1998; Perugini, 2021). We therefore interpret MMEs displaying reaction rims and sharp contacts as products of the later stages of crystallization or inefficient mixing in the Lagoa do Roçado Stock.

Angular xenoliths from the Macururé Complex, enclosed in MMEs, demonstrate that mafic injections persisted even at the depths of final emplacement, underscoring the influence of mantle-derived magmas in the late-collisional stage of the SOS.

5.6. Tectonic implications

Two main geodynamic models have been proposed to explain the geodynamic evolution of the Borborema Province and, consequently, the SOS. The intracontinental model suggests that the basement of the

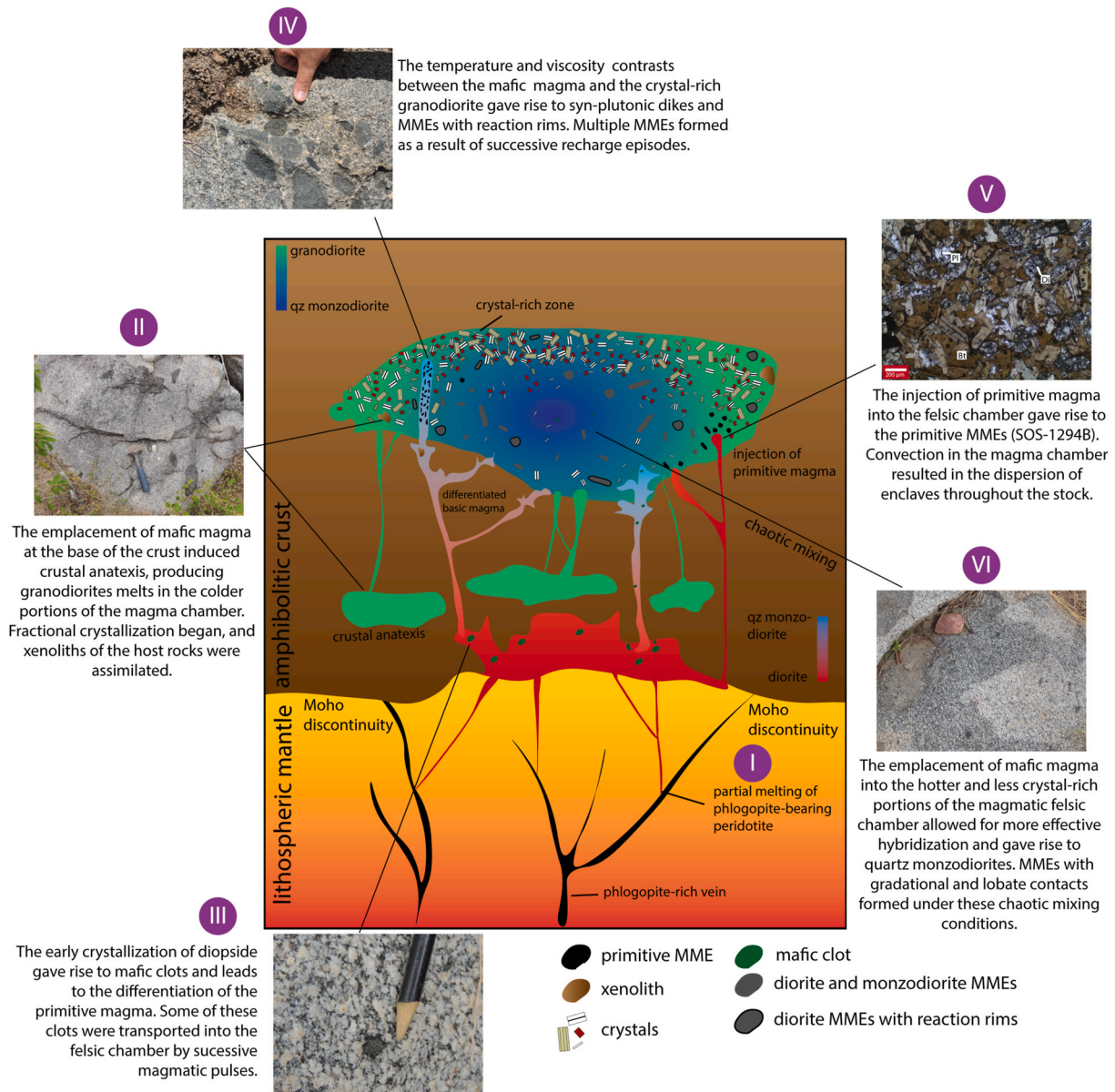


Fig. 13. Integrated petrogenetic model illustrating the genesis of the Lagoa do Roçado Stock. (I) Partial melting of phlogopite-bearing peridotitic veins generates an enriched basaltic magma that ponds at the base of the lower crust near the Moho discontinuity. (II) Heat supplied by this primitive magma triggers partial melting of the lower crust, forming a dacitic magma reservoir. (III) Fractional crystallization of early phases from the basaltic magma produces mafic clots that are entrained and dispersed into the felsic chamber during successive mafic recharge pulses. Differentiation of the primitive magma yields andesitic compositions that form dioritic enclaves. (IV) Thermal exchange between the margins of the felsic magma chamber and the surrounding country rocks leads to the development of a crystal-rich zone. Owing to rheological contrasts between interacting magmas, emplacement of mafic magma within this zone results in the formation of synplutonic dikes. (V) New mafic injections from less differentiated portions of the basaltic reservoir produce microgranular mafic enclaves with compositions similar to those of the enriched primitive magma, which are dispersed throughout the felsic chamber by convection. (VI) Emplacement of mafic pulses into hotter and less crystal-rich portions of the chamber promotes more efficient magma mixing, leading to the formation of hybrid enclaves with variable contact relationships that reflect different degrees of hybridization.

province was part of a large lithospheric block that was stabilized during the Paleoproterozoic Orogeny at ca. 2.0 Ga (Neves, 2003; Neves et al., 2006). This block comprised the Amazonian, São Francisco-Congo, and West African-São Luís paleocontinents. According to this model, the Borborema Province and the São Francisco Craton shared a continuous basement that underwent intracontinental extension shortly before the Brasiliano/Pan-African Orogeny and subsequent decratonization. As a result, intracontinental basins were formed, which were later inverted and involved in a collisional setting (Neves et al., 2015; Neves, 2021; Pereira et al., 2023). Conversely, the most widespread model states that the cratonic blocks were separated by wide oceans, which were

consumed into subduction zones during the Neoproterozoic in complete Wilson cycles (Oliveira et al., 2010, 2017; Caxito et al., 2020; Ganade et al., 2021).

The late Cryogenian-Ediacaran magmatism intruding the SOS is characterized by uniform high-K calc-alkaline and shoshonitic geochemical signatures (Conceição et al., 2016; Fernandes et al., 2020; Pereira et al., 2020; Sousa et al., 2022). This signature is further supported by the data presented in this study for the Lagoa do Roçado Stock. Such potassic granitoids are commonly associated with periods of orogenic relaxation and are typical of post-collisional stages, when the tectonic regime shifts from compressional to extensional (Barbarin,

1999; Pe-Piper et al., 2006; Couzinié et al., 2016). However, even the pre- to early-collisional mafic rocks of the Macururé Domain display potassic affinity and a crustal-like isotopic signature (Pereira et al., 2023, 2024), which requires the presence of a sediment-metasomatized lithospheric mantle prior to the onset of the Brasiliano Orogeny. According to Pereira et al. (2024), these features support an extensional model for the SOS, in which the mantle source represents a long-term fertilized domain associated with the hyperextended margin of the São Francisco Craton.

The least evolved samples of the Lagoa do Roçado Stock, represented by the MMEs, share several geochemical similarities in major and trace elements with the mafic plutons studied by Pereira et al. (2023, 2024), suggesting derivation from a common mantle source. These findings indicate that the input of mantle-derived magmas remained active throughout the Brasiliano Orogeny.

The rocks of the Lagoa do Roçado Stock are predominantly isotropic and show no evidence of solid-state deformation, even at the microscopic scale. These characteristics suggest emplacement under a

Table 3

Summary of geochemical characteristics and available geochronological data for late-collisional plutons of the SOS.

Plutonic unit	U-Pb crystallization age	Host lithology	Geochemical features	Enclave	Geochemical features	Reference
MACURURÉ DOMAIN						
Coronel João Sá	625 ± 2 Ma	Granodiorite, granite	Metaluminous to peraluminous, high-K calc-alkaline	Tonalite, mafic clots	Metaluminous, high-K calc-alkaline	^a
Fazenda Lagoas	623 ± 4 Ma	Monzogranite, qz monzonite, granodiorite	Metaluminous, shoshonite, and high-K calc-alkaline	Diorite	Metaluminous, shoshonite, and high-K calc-alkaline	^b
Glória Norte	621 ± 2 Ma	Monzogranite, granodiorite, qz monzonite	Metaluminous, shoshonite	Monzonite, monzodiorite, diorite, lamprophyre, phlogopite-tremolite cumulate, and phlogopite-diopside cumulate	Metaluminous, ultrapotassic	^c
Santa Helena	619 ± 2 Ma	Monzogranite, granodiorite	Metaluminous, high-K calc-alkaline	MMEs, biotitic surmicaceous enclaves		^c
Lagoa do Roçado	618 ± 4 Ma	Qz monzodiorite, granodiorite	Metaluminous, shoshonite, and high-K calc-alkaline	Qz monzodiorite, qz diorite, diorite, mafic clots	Metaluminous, shoshonite, and high-K calc-alkaline	^d
Propriá	615 ± 6 Ma	Syenogranite	Metaluminous to peraluminous, shoshonite, and high-K calc-alkaline	Qz syenite	Metaluminous, shoshonite, and high-K calc-alkaline	^e
Mocambo	614 ± 7 Ma	Qz monzodiorite, qz diorite	Metaluminous to peraluminous, shoshonite	MMEs		^f
Graccho Cardoso	603 ± 8 Ma	Syenogranite				^g
Amparo do São Francisco		Monzogranite, qz monzonite, qz syenite	Metaluminous, shoshonite, and high-K calc-alkaline	Syenite, qz syenite, qz monzonite	Metaluminous, shoshonite, and high-K calc-alkaline	^e
Frutuoso		Qz diorite	Metaluminous, shoshonite	Diorite	Metaluminous, shoshonite	^f
POÇO REDONDO DOMAIN						
Poço Redondo	623 ± 7 Ma	Granite				^h
Queimada Grande	618 ± 4 Ma	Granodiorite	Metaluminous, high-K calc-alkaline	MMEs		^h
Rio Jacaré	617 ± 4 Ma	Monzogranite, granodiorite, qz monzonite	Metaluminous, shoshonite, and high-K calc-alkaline	Granodiorite, qz monzonite, qz monzodiorite, qz diorite	Metaluminous, shoshonite, and high-K calc-alkaline	ⁱ
Curituba	617 ± 7 Ma	Syenogranite, qz syenite, monzogranite	Metaluminous, peraluminous, shoshonite	Diorite, mafic clots		^j
Serra do Brejo		Granite, syenite	Metaluminous, peraluminous, shoshonite, and high-K calc-alkaline	Gabbro, diorite	Metaluminous, shoshonite	^k
CANINDÉ DOMAIN						
Lajedinho	619 ± 3 Ma	Monzogranite, granodiorite		Amphibolite		^h
Santa Maria	611 ± 4 Ma	Granite	Metaluminous, peraluminous, shoshonite, and high-K calc-alkaline	MMEs		^l

Data source.

^a Long et al. (2005).

^b Fernandes et al. (2020).

^c Pereira et al. (2023).

^d This study.

^e Santos et al. (2019).

^f Oliveira (2020).

^g Sousa (2020).

^h Oliveira et al. (2015)

ⁱ Sousa et al. (2022)

^j Lima (2016).

^k Gentil (2013).

^l Soares et al. (2019).

relaxation regime following the collisional stage (Bonin, 2004). The emplacement of biotite and two-mica leucogranites in the SOS occurred between 630 and 624 Ma, a period interpreted as the collisional stage of the Brasiliano Orogeny (Pereira et al., 2023). Therefore, our new SHRIMP U-Pb zircon age of 618 ± 8 Ma for the Lagoa do Roçado Stock is consistent with emplacement during the late-collisional stage of the orogeny.

Table 3 summarizes geochemical and geochronological data for the late-to post-collisional magmatism within the SOS. Several plutons emplaced within the Macururé Domain, such as Coronel João Sá (625 ± 2 Ma), Fazenda Lagoas (623 ± 4 Ma), Glória Norte (621 ± 2 Ma), Santa Helena (619 ± 2 Ma), Propriá (615 ± 6 Ma), and Mocambo (614 ± 7 Ma), display similar geochemical characteristics, typically ranging from high-K calc-alkaline to shoshonitic affinities. Comparable magmatic activity is also recognized in the Poço Redondo Domain, where plutons such as Poço Redondo (623 ± 7 Ma), Queimada Grande (618 ± 4 Ma), Rio Jacaré (617 ± 4 Ma), Curituba (617 ± 7 Ma), and Lajedinho (619 ± 3 Ma) record similar emplacement ages. In the Canindé Domain, the Santa Maria intrusion (611 ± 4 Ma) represents one of the youngest expressions of this magmatic episode. Notably, mafic microgranular enclaves have been described in many of these intrusions, indicating that magma mixing processes were widespread during this magmatic stage. Taken together, these data indicate that the Lagoa do Roçado Stock forms part of a regional late-collisional magmatic pulse affecting several domains of the SOS during the final stages of the Brasiliano Orogeny.

6. Conclusion

The Lagoa do Roçado Stock is predominantly composed of granodiorites and quartz monzodiorites that contain abundant MMEs, which record varying degrees of magmatic hybridization. The isotropic fabric, absence of solid-state deformation, and geochronological constraints indicate that the Lagoa do Roçado Stock belongs to the late-collisional plutonic suite of the SOS. The host felsic magmas were generated by partial melting of a lower crust with amphibolitic to basaltic composition and were subsequently modified by intracrustal magmatic processes.

The parental magmas of the MMEs were likely derived from partial melting of a phlogopite-bearing mantle source. Magma mixing between mantle-derived magmas and crustal dacitic magmas constituted the main differentiation process controlling the compositional variability of the Lagoa do Roçado Stock, whereas fractional crystallization played a subordinate role. Field and petrographic evidence, including syn-plutonic mafic dikes and the widespread occurrence of MMEs with broad compositional variation and diverse contact relationships with the host rocks, suggest multiple episodes of mafic magma recharge into the felsic magma chamber. These features are best explained by chaotic magma mixing operating during the emplacement and crystallization of the stock. These results highlight the importance of recurrent mantle input and magma hybridization in the evolution of igneous bodies in late-to post-collisional settings.

CRediT authorship contribution statement

Luis Felipe dos Santos Rodrigues: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Fábio dos Santos Pereira:** Conceptualization, Methodology, Validation, Visualization, Writing – review & editing. **Clevertton Correia Silva:** Data curation, Investigation. **Jean-Michel Lafon:** Methodology, Validation. **Rômulo Machado:** Methodology, Validation. **Herbet Conceição:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Validation, Writing – review & editing. **Maria de Lourdes da Silva Rosa:** Formal analysis, Funding acquisition, Methodology, Project administration, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsames.2026.106052>.

Data availability

Data will be made available on request.

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