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Chemical compositions of biotite as a petrogenetic discriminator: Rio Jacaré Batholith, Borborema Province, NE Brazil

Composições químicas de biotita como discriminador petrogenético: Batólito Rio Jacaré, Província Borborema, NE do Brasil

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Abstract: Biotite is the most common mica in igneous rocks, but until the beginning of this century, researchers used amphibole and pyroxene more frequently to estimate the conditions of magma crystallization. Currently, biotite has become a useful petrogenetic tool and its primary chemical composition can also be used to infer magmatic crystallization conditions. Primary and reequilibrated biotite are found in the Rio Jacaré Batholith (RJB) rocks. Primary crystals mainly occur as inclusions in plagioclase and have a composition of crystals formed in calc-alkaline orogenic magmas. The crystallization temperature of biotite primary of the RJB ranged from 678 to 745ºC. Pressure during magmatic crystallization of biotite ranges from 1.2 to 2.9 kbar. This is consistent with the crystallization temperature and pressure of biotite in granitic systems. The compositions of the primary crystals indicate that they were formed from magmas with H_2O contents between 5 and 7%. The fO_2 during the formation of these crystals range from -16.3 to -13.9. When correlating temperature variation and fO_2 variation of the primary crystals in the different enclaves samples, it is possible to infer the presence of several mafic magmatic pulses during the evolution of the RJB.

Keywords: Primary crystals; Sergipano Orogenic System; Reequilibrated crystals.

Resumo: A biotita é a mica mais comum nas rochas ígneas, porém até o início deste século, os pesquisadores utilizavam com maior frequência o anfibólio e o piroxênio para estimar as condições de cristalização do magma. Atualmente, a biotita tornou-se uma ferramenta petrogenética importante e sua composição química primária também pode ser usada para inferir condições de cristalização magmática. Biotita primária e reequilibrada são encontradas nas rochas do Batólito Rio Jacaré (BRJ). Cristais primários ocorrem principalmente como inclusões em plagioclásio e têm uma composição de cristais formados em magmas orogênicos calcioalcalinos. A temperatura de cristalização da biotita primária do BRJ variou de 678 a 745ºC. A pressão durante a cristalização magmática da biotita variou de 1,2 a 2,9 kbar. Esses resultados são consistentes com a temperatura de cristalização e a pressão da biotita em sistemas graníticos. As composições dos cristais indicam que foram formados a partir de magmas com teores de H_2O entre 5 e 7%. A fO_2 durante a formação desses cristais varia de -16,3 a -13,9. Ao correlacionar a variação de temperatura e variação de fO_2 dos cristais primários nas diferentes amostras de enclaves, é possível inferir a presença de vários pulsos magmáticos máficos durante a evolução do BRJ.

Palavras-chave: Cristais primários; Sistema Orogênico Sergipano; Cristais reequilibrados.

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1. Introduction

The determination of the chemical composition of minerals plays an important role in igneous petrology (BINELE BETSI; LENTZ, 2013). The main factors responsible for the crystallization and mineralogy in rocks are the chemical composition of the magma, pressure, temperature, oxygen fugacity, content, and nature of the volatile phase (e.g., MARTIN, 2007; YU *et al.,* 2021). Thus, the inference of these parameters is relevant to understanding the processes responsible for forming plutons.

Granitic plutons are formed through the addition of small pulses of magma (GLAZNER *et al.,* 2004). According to Cashman *et al.* (2017), igneous processes occur throughout the crust and the magma chamber occupies only the top of a much larger transcrustal magma system. In recent decades, researchers have preferentially used amphibole chemical compositions (e.g. ANDERSON; SMITH, 1995; RIDOLFI; RENZULI, 2012) and pyroxene (e.g., PUTIRKA *et al.,* 1996) to estimate the magmatic crystallization conditions. However, these minerals have early crystallization in granitic systems, that is, they register higher temperatures and pressure. On the other hand, biotite crystallizes in later magmatic stages that may represent the final placement conditions of the magmatic chamber. Therefore, it is also important to estimate the physicochemical conditions of crystallization from the biotite composition.

Biotite is a very common mafic mineral in plutonic rocks. It can be formed under different crystallization conditions and has the ability to register in its chemical composition the changes in oxygen fugacity, temperature, pressure and chemical composition of magma (e.g., SPEER, 1984). Besides, the tectonic environment and the nature of the magma that generated it influences the composition of biotite (NACHIT *et al.,* 1985; ABDEL-RAHMAN, 1994). However, biotite tends to reequilibrate at subsolidus temperatures or due to hydrothermal alteration (e.g. LI *et al.,* 2019a). For these reasons, only primary biotite can be used to infer the physicochemical conditions present in magmas when they crystallize (e.g., DONG *et al.,* 2014).

The Sergipano Orogenic System (SOS – CONCEIÇÃO *et al.,* 2016) has several plutons where reequilibrated biotite crystals are more common. Biotite is the most abundant mafic mineral in the Rio Jacaré Batholith (RJB), SOS. In this work, petrographic data and the mineral chemistry of biotite crystals will be presented and discussed, aiming to identify the primary biotite crystals and infer intensive parameters (temperature, pressure, oxygen fugacity) during the crystallization of this mineral.

2. Geological context

2.1 Regional Geology

The SOS is in the southern portion of the Borborema Province (ALMEIDA *et al.,* 1977), northeast Brazil, and represents the result of collision between the Sanfranciscana Plate and the Pernambuco-Alagoas Superterrain during the Brasiliano Orogeny (DAVISON; SANTOS, 1989; D'EL REY SILVA, 1992; OLIVEIRA *et al.,* 2010). During this collision, shear zones that limit the different geological domains of the SOS were generated (DAVISON; SANTOS, 1989; SILVA FILHO; TORRES, 2002) and correspond to: Estância, Vaza-Barris, Macururé, Marancó, Poço Redondo, Canindé and Rio Coruripe.

In the Macururé, Marancó, Poço Redondo and Canindé Domains, several different plutons occur (e.g. CONCEIÇÃO *et al.,* 2016; LIMA *et al.,* 2017; PINHO NETO *et al.,* 2019; SOARES *et al.,* 2019). They show high-K to shoshonitic calc-alkaline magmatic affinities, some intrusions being emplaced before to the Brasiliano collision and some following it.

2.1 Local Geology

The RJB (Figure 1) intrudes rocks of the Poço Redondo Domain, Tonian migmatites of the Poço Redondo Migmatitic Complex, and other Ediacaran granites (CARVALHO, 2005; OLIVEIRA *et al.,* 2015; SOUSA *et al.,* 2019). This batholith shows a U-Pb$_{\text{SHRIMP}}$ zircon crystallization age of 617 ± 4 Ma (SOUSA *et al.,* 2019) and presents two petrographic facies, inequigranular (IF) and porphyritic (PF), which are composed of granodiorites, monzogranites and quartz monzonites. Microgranular enclaves (ME) are ubiquitous in the RJB and correspond to diorites, quartz diorites, quartz monzodiorites and granodiorites. The contact relationships between the MEs and the host granites preserve evidence of interaction between magmas during the evolution of the RJB (SOUSA *et al.,* 2022). Magma mixing is a relevant petrogenetic process that conformed these rocks, as shown by the presence of feldspar xenocrysts, chilled margins and sinuous to embayed contacts and linear chemical evolution with the enclosing felsic rocks in Harker diagrams for the RJB samples (SOUSA *et al.*, 2019).

The mineralogy of the RJB rocks is composed of quartz, plagioclase, alkali feldspar, biotite, Mg-hornblende, epidote, titanite, apatite, zircon, magnetite and ilmenite. RJB rocks are metaluminous, magnesian high-K rocks of calc-alkaline and shoshonitic series and have the geochemical signature of post-collisional magmas (SOUSA *et al.,* 2019).

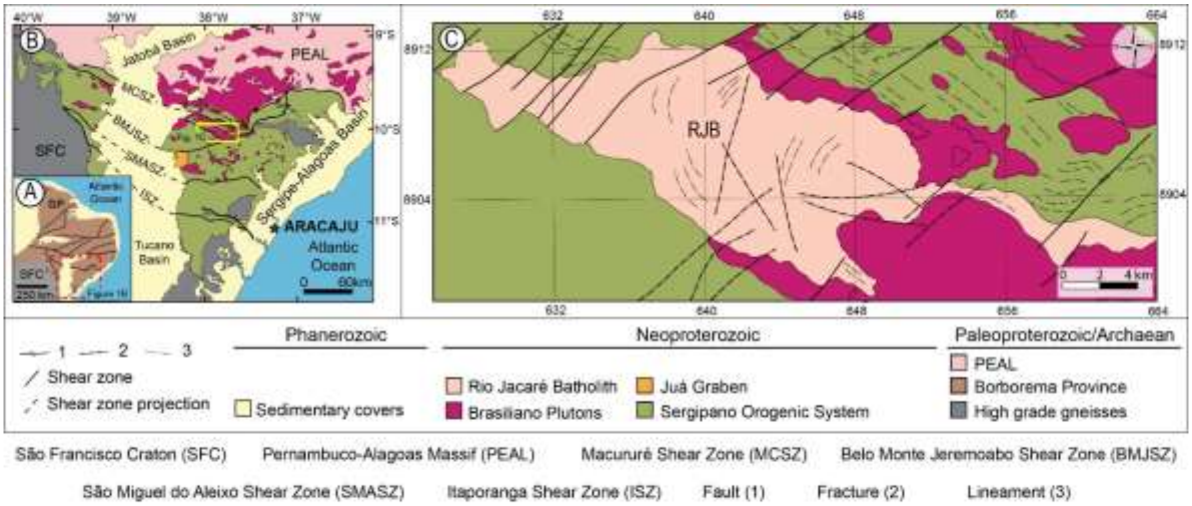

Figure 1 – Schematic maps contextualizing the regional geology and the RJB. (A) Simplified map of the Borborema Province in the Northeast of Brazil (VAN SCHMUS et al., 2008). (B) Map of the SOS (PINHO NETO et al., 2019). (C) Geological map of the RJB
Fonte: Sousa et al. (2019)

3. Materials and methods

The mineralogy of the RJB was investigated using polished thin sections from representative samples. Thirty-three polished thin sections were studied, eight from the IF, ten from the PF and fifteen from the ME. Minerals and textures were identified under an OPTON (TNP - 09NT) microscope with transmitted and reflected light at the Laboratory of Microanalysis of Condominium of Multiuser Laboratories of Geosciences (CLGeo), Universidade Federal de Sergipe (UFS).

The polished thin sections were coated with carbon (8-10 nm thick) with a Quorum® metallizer, model Q150R ES, so that the crystals could be imaged and analyzed. The spot chemical analysis of biotite was determined with X-Act energy dispersive spectrometer (EDS) from Oxford Instruments®, with a resolution of 125 eV and a silicon solid state detector (SSD, 10mm²). This spectrometer is installed in a scanning electron microscope (SEM), brand Tescan - VEGA LMU3 of the CLGeo-UFS. The reliability and reproducibility of the percentages of oxides obtained with the EDS were verified using international standards from Astimex Scientific Ltd® and CLGeo-UFS internal standards. The EDS from the CLGeo-UFS is regularly calibrated using copper energy. The Quant routine of the Aztec 4.0 software, from Oxford Instruments®, was used to convert the intensities of energy to oxide percentage with the ZAF automatic correction factors. Analytical conditions used were: 20 kV voltage, 17 nA beam intensity, 400 nm electron beam diameter, mean analysis time per point of 60s; analysis distance 15 mm.

The internal calibration of the EDS was carried out using standards, energy spectrum and with precision (2σ): albite, NaKα (±0.2); corundum, AlKα (±0.2); metallic chromium, CrKα (±0.4); fluorite, FKα (±0.3); metallic iron, FeKα (±0.4); halite, ClKα (±0.3); metallic manganese, MnKα (±0.2); metallic nickel, NiKα (±0.3); orthoclase, KKα (±0.2); periclase, MgKα (±0.4); quartz, SiKα (±0.4); metallic titanium, TiKα (±0.2); wollastonite, CaKα (±0.2) and barium fluoride, BaLα (±0.3). The comparison between the data obtained with the EDS and those from international Astimex and internal laboratory standards is presented in Sousa (2022). The differences observed between the values provided by the standards and those obtained with the EDS are very small.

Calculations of the structural formula were carried out based on 22 oxygens and the Fe^{2+} and Fe^{3+} content obtained was based on the empirical equation of Wones (1972), using the Geo-fO_2 software from Li *et al.* (2019b).

4. Results

4.1 Petrography

Biotite is one of the mafic minerals found in the RJB rocks. Its volume varies from <1.0 to 15.4% in the IF, from 2.5 to 11.4% in the PF and from 8.5 to 33.5% in the ME.

Biotite crystals of the IF and PF show similar textures, being subhedral or euhedral, with diameter between 0.1 and 2.5 mm, those with diameter around 0.8 mm being predominant. They show pleochroism varying from brown to yellow (Figures 2A and 2D). Occasionally the pleochroism can range from brown to brownish green. Usually, biotite occurs associated with hornblende, and sometimes, these minerals form agglomerates of crystals with diameters between 2 and 7 mm (Figures 2B and 2C). In places they mark the magmatic flow texture with other minerals. Contacts with the other minerals in the rock are clear-cut, straight or curved. It commonly contains inclusions of zircon, apatite, titanite, opaque minerals and, less often, hornblende. Anhedral magnetite, ilmenite and titanite crystals occur in the cleavage or on grain limits (Figure 2E). Plagioclase, alkali feldspar and quartz crystals have biotite inclusions. However, biotite inclusions in plagioclase phenocrysts have larger sizes when located close to grain limits. On some grains, chlorite is formed as a product of biotite alteration.

The biotite crystals of the ME differ from those of the host rocks by their finer grain size (Figure 2F), which varies from 0.1 to 1.7 mm, with 0.3 mm crystals predominating. As in the PF and IF, plagioclase, alkali feldspar and quartz include biotite. While in the plagioclase phenocrysts biotite inclusions are preferentially located close to grain boundaries, in the matrix plagioclase crystals biotite inclusions are distributed throughout the plagioclase grains.

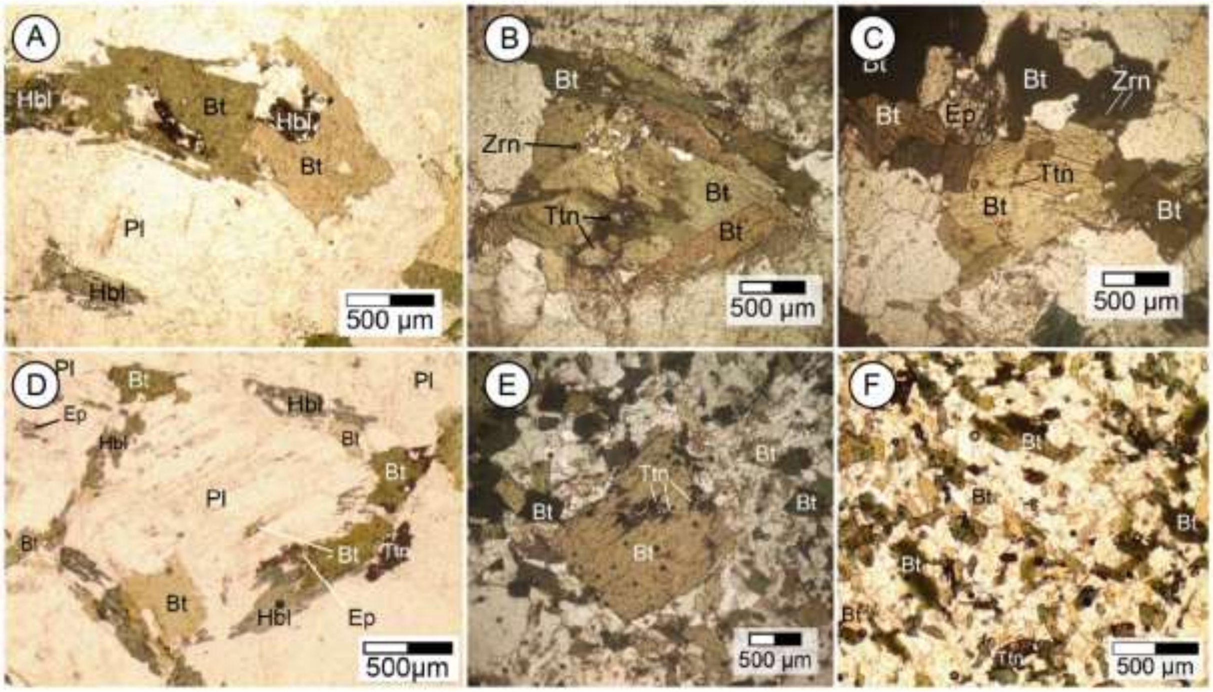

Figure 2 – Images with textures observed in biotite crystals of the RJB rocks. (A) Contact between biotite crystals. Hornblende inclusions are observed. (B and C) Cluster of biotite crystals with a diameter around 1,5 mm. The presence of titanite among the biotite crystals is identified. (D) Biotite and hornblende crystals surrounding plagioclase. Note the inclusion of biotite in the plagioclase. (E) Biotite with titanite in cleavage planes. (F) Fine-grained biotite crystals in a microgranular enclave. Note the abundance of these crystals.
Source: Authors (2024)

4.2 Biotite chemistry

In this study, 360-point analyses of biotite crystals were obtained (data available in SOUSA (2022)), 63 of these in the IF, 122 in the PF and 175 in the ME. Out of the 360 analyses, 93 correspond to primary crystals (12 in the IF, 5 in the PF and 76 in the ME) and 267 correspond to reequilibrated primary crystals (51 in the IF, 117 in the PF and 99 in the ME).

The representative results of chemical analyses show that the RJB biotite crystals contain similar MgO concentrations between the IF and the ME, of 10.3 to 14.1% and 9.8 to 14.5%, respectively, while the crystals of the PF have a greater variation of MgO, of 9.4 to 18.4%. This similarity is also observed in the Mg/(Fe + Mg) ratios, which vary between 0.46 and 0.64 for the IF crystals and between 0.49 and 0.66 for the ME crystals, while those of the PF vary between 0.46 and 0.81. The TiO_2 contents are similar between the IF and PF crystals (1.0 to 3.5% and 0.9 to 3.4%, respectively), and with greater variation in the ME crystals (1.1 to 4.2%). The Al_2O_3 contents (IF: 14.9 to 17.9%; PF: 14.4 to 19.4%; ME: 14.4 to 19.7%), FeO (IF: 13.6 to 19.5%; PF: 7.6 to 20.0%; ME: 12.5 to 20.0%) and the Fe/(Fe + Mg) ratio (IF: 0.35 to 0.51; PF: 0.18 to 0.53; ME: 0.33 to 0.51) are similar among those crystals of the IF, the PF and the ME.

5. Discussion

5.1 Classification and compositional variation

Trioctahedral micas have varied composition (e.g. DEER *et al.*, 1992). The Mg, Mn, Fe^{2+}, Fe^{3+}, Ti, Si^{4+} and Al^{VI} contents of the RJB micas allow classifying them predominantly as Mg-biotite (Figure 3). A trend is observed (Figure 3) formed in the direction of the Mg and (Fe^{2+} + Mn) poles, suggesting a linear correlation between the concentration of these elements in the studied crystals. This correlation is mainly due to the variation of the Fe^{2+} e Mg contents once the Mn values are low and have little influence in the formation of this trend. According to Li *et al.* (2014), the important variation of Mg/(Mg+Fe) in micas suggests that they are not primary.

Nachit *et al.* (2005) suggest that the distinction between primary/magmatic, reequilibrated and secondary/newly formed biotite crystals can be made using the TiO_2, FeO, MnO and MgO contents (Figure 4). The TiO_2 contents of the RJB analyzed crystals have an important variation (IF: 1.0-3.5%; PF: 0.9-3.4%; ME: 1.1-4.2%) and are typical of primary and reequilibrated crystals, with predominance of reequilibrated grains (Figure 4). The decrease in TiO_2 content in the studied crystals tends to keep the ratio (FeO+Mn)/MgO relatively constant (Figure 4). This evolution can reflect crystal reequilibration. The magmatic biotite crystals of the RJB occur mainly as inclusions in plagioclase. This fact suggests that these crystals have been preserved from the action of hydrothermal fluids. Magmatic biotite is more abundant in the ME. Probably the faster cooling process responsible for the fine graining of these rocks also preserved the magmatic crystals. In the next sections the inferences of intensive parameters on biotite crystallization were made using only the primary/magmatic crystals.

The composition of biotite has also been used to infer the nature of the magma from which it crystallized (e.g. ANDERSON *et al.*, 2008). The Fe/(Fe+Mg) and total Al parameters of the RJB crystals are characteristic of crystals formed in magmas of the magnetite series (Figure 5), which indicates the crystallization under conditions of high oxygen fugacity.

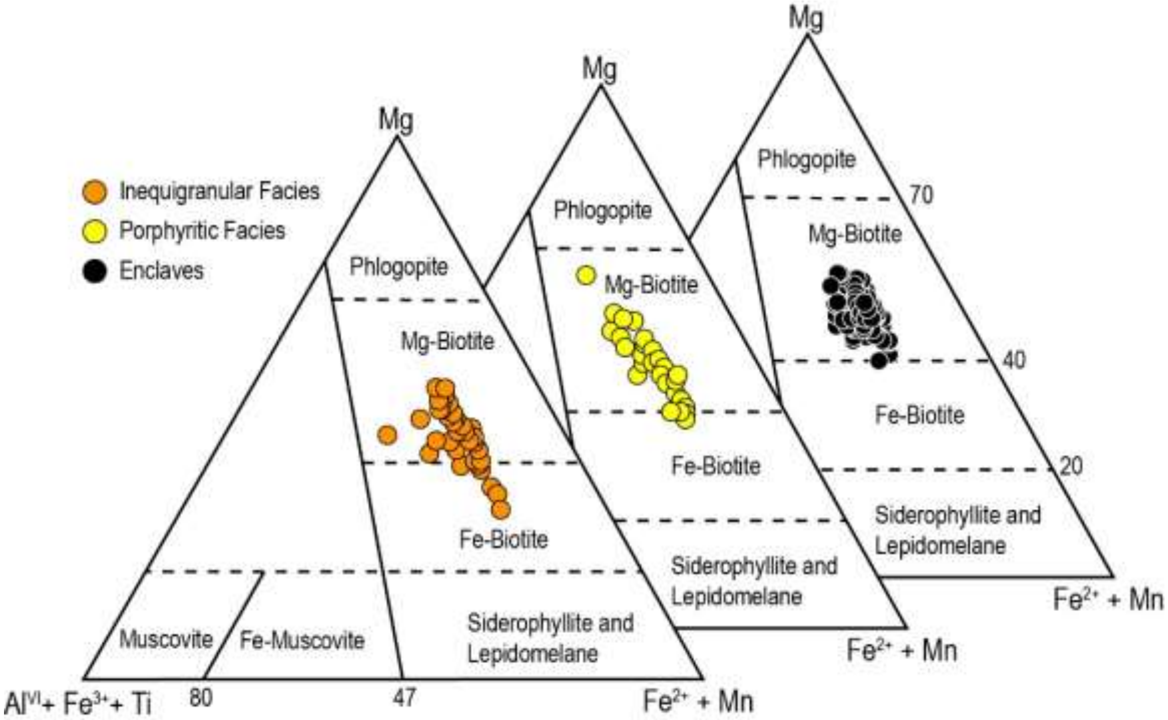

Figure 3 – Diagram Mg versus (Fe^{2+} + Mn) versus (Al^{VI} + Fe^{3+} + Mn) applied to the biotite crystals of the RJB.
Source: Foster (1960)

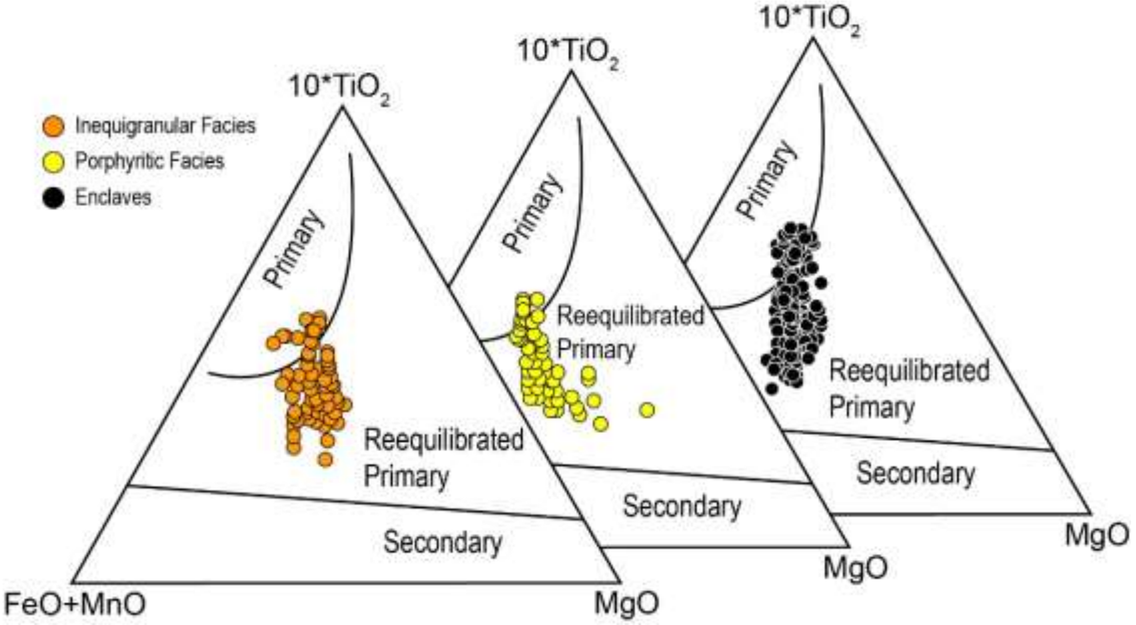

Figure 4 – Diagram for discrimination of primary, reequilibrated and secondary biotite applied to biotite crystals from the RJB.
Source: Nachit et al. (2005)

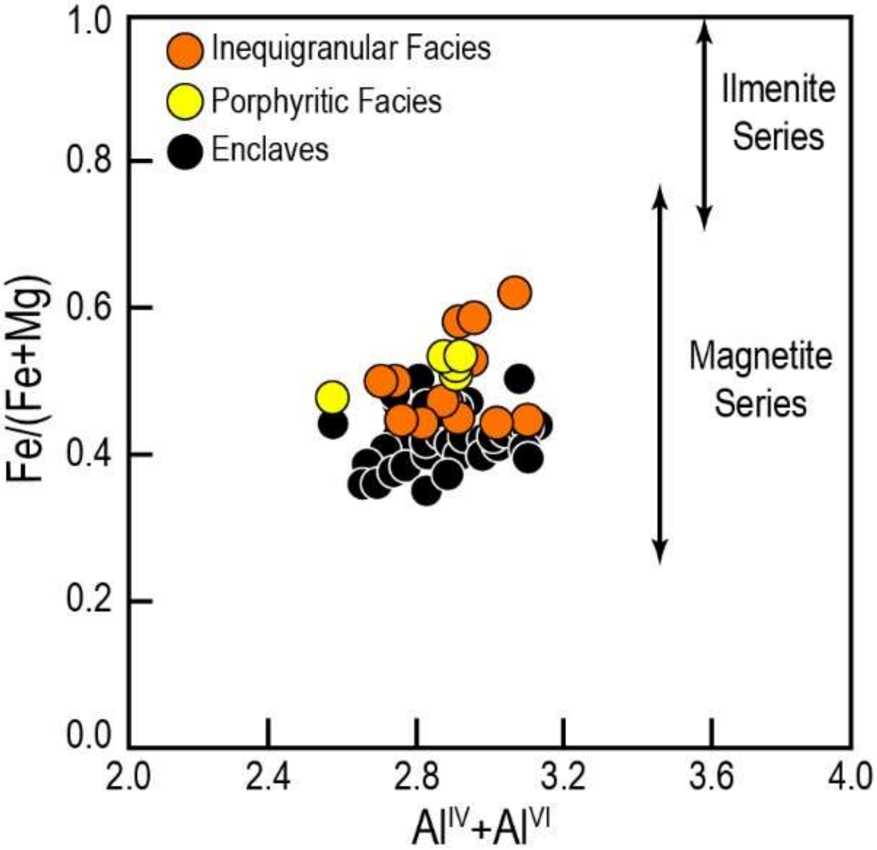

Figure 5 – Fe/(Fe+Mg) versus Al^{IV}+Al^{VI} diagram to discriminate between ilmenite and magnetite series magmas applied to primary biotite crystals from the RJB.
Source: Anderson et al. (2008)

5.2 Nature of magmas

Biotite found in the RJB rocks is brown-colored. According to Lalonde and Bernard (1993), the green or brown color in biotite may be related to the Mg and Fe^{3+} contents and to granites with a magmatic arc signature. The primary biotite crystals of the RJB have a FeO*/MgO ratio that varies from 1.42 to 1.49 in the IF crystals, from 1.65 to 2.08 in the PF crystals and from 1.00 to 1.85 in the ME crystals. According to Abdel-Rahman (1994), biotite with FeO*/MgO ratio around 1.76 is characteristic of I-Type calc-alkaline granites with orogenic signature. The values of Fe/(Fe+Mg) and total Al values of the studied primary crystals have compositions like those of biotite from magmatic arc-related metaluminous granites (Figure 6).

The MgO, FeO and Al_2O_3 contents of the RJB primary biotite crystals are like those of crystals formed by calc-alkaline orogenic signature magmas (Figure 7) studied by Abdel-Rahman (1994). It is therefore suggested that the RJB biotite was crystallized in Type-I, calc-alkaline metaluminous magma, that being consistent with the available data on the regional geological context of the RJB (e.g. OLIVEIRA *et al.,* 2015; SOUSA *et al.,* 2019).

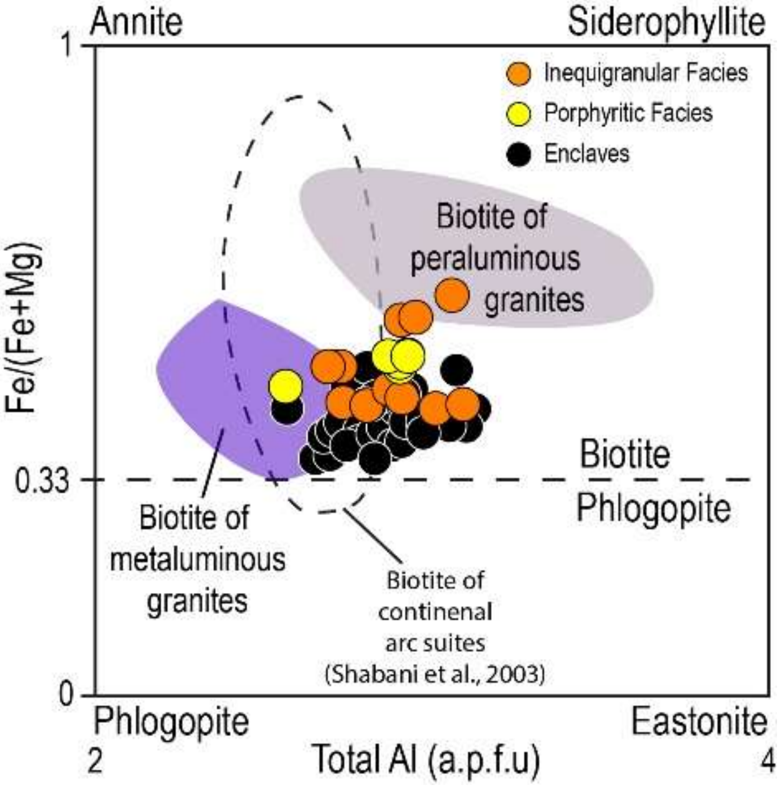

Figure 6 – Diagram Fe/(Fe+Mg) versus total Al applied to primary biotite crystals from the RJB.
Source: Lalonde and Bernard (1993)

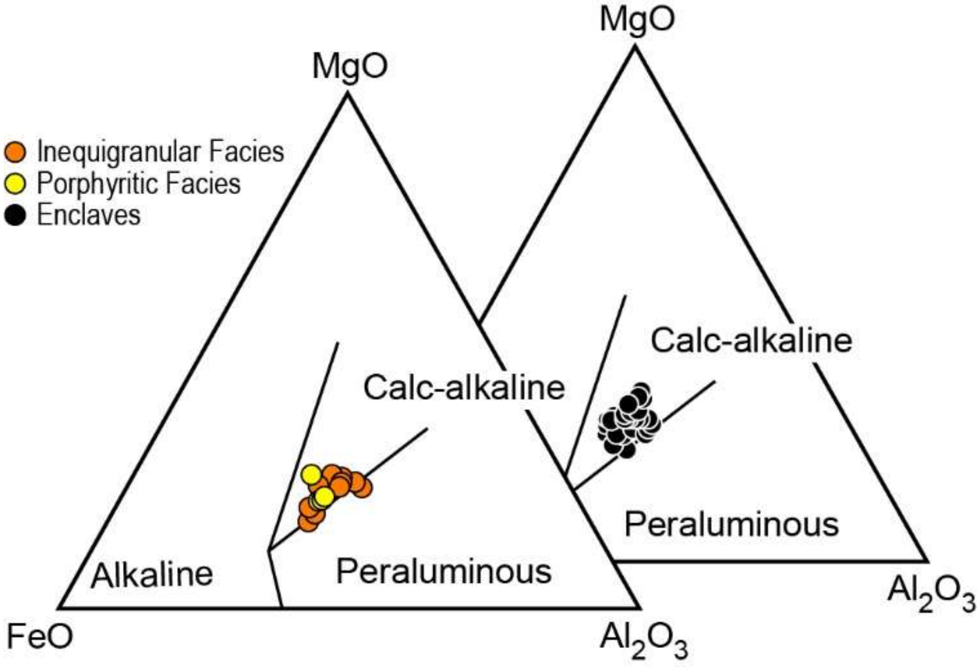

Figure 7 –Ternary diagram FeO-MgO-TiO$_2$ applied to primary biotite crystals from the RJB.
Source: Abdel-Rahman (1994)

5.3 Crystallization conditions and processes involved

The contents of Ti in biotite seem to follow Le Chatelier's principle (when a force is applied to a system in equilibrium, it tends to readjust itself, seeking to reduce the effects of this force), as some authors describe (e.g. HENRY *et al.,* 2005) that the concentration of Ti in biotite is sensitive to changes in temperature and for this reason it can be used to infer the crystallization or reequilibration temperature. The Ti geothermometer in biotite by Henry *et al.* (2005) was applied to the studied crystals. Although this calculation was initially based on biotite compositions from metamorphic rocks, Li *et al.* (2019b) showed that it is possible to apply it to biotite from granites, as good results have been obtained when used in experimental work on magmatic biotite (e.g., ANDÚJAR; SCAILLET, 2012) and in various intrusions in different terrains (e.g., HOSSAIN; TSUNOGAE, 2014).

The BRJ primary biotite crystals of the IF and PF facies register similar temperature ranges, from 682 to 713°C and from 678 to 704°C, respectively. The primary crystals from the ME provided higher temperatures, from 685 to 745°C. The temperatures obtained for the reequilibrated crystals, with this same geothermometer, were variable and similar between facies (IF: 500 to 682°C; PF: 514 to 681°C; ME: 499 to 690°C).

According to Uchida *et al.* (2007), it is possible to use the chemical composition of biotite as a geobarometer, as there is a positive correlation between the total aluminum content of biotite and the crystallization pressure of this mineral. By using the calculations proposed by Uchida *et al.* (2007), crystallization pressures for the primary crystals of 1.8 to 2.7 kbar in IF, 1.2 to 2.2 kbar in PF and 1.2 to 2.9 kbar in ME were obtained. Considering the value of 1 kbar equal to 3.7 km of depth in the continental crust (e.g., TULLOCH; CHALLIS, 2000), biotite crystallization depths are estimated to be between 6.6 and 9.9 km in the IF, between 4.4 and 8.1 km in the PF and between 4.4 and 10.7 km in the ME. In the BRJ rocks, Sousa *et al.* (2019) identified variation in amphibole crystallization pressure from 2 to 6 kbar. The integration of biotite and amphibole geobarometry data suggests that biotite began to crystallize at the final moments of amphibole crystallization, at shallower levels of the continental crust. This hypothesis is supported by the observed textures, due to the presence of amphibole inclusions in the biotite crystals.

Naney (1983) carried out an experimental study in which he observed the crystallization of a granitic system under conditions of 2 kbar (pressure similar to those found in this work). In this experimental study, when the H_2O contents were higher than 4%, there was the crystallization of the paragenesis biotite + plagioclase + alkali feldspar + liquid + vapor between approximate temperatures of 700 and 750°C and the paragenesis biotite + plagioclase + alkali feldspar + quartz + vapor between 670 and 700°C. These temperatures are similar to those obtained with the RJB primary biotite crystals and suggest that they represent crystallization temperatures.

The temperatures obtained for the reequilibrated crystals (499-690°C) match those of metamorphic biotite (PANCHUK, 2019). Petrik and Broska (1994) interpret the low values of TiO_2 in biotite as reequilibration temperatures, and that can be explained by the release of Ti from the crystalline structure of biotite, forming titanite crystals. In the cleavage planes of the RJB biotite, anhedral titanite is found, which may reflect the reequilibration of the studied crystals. According to Shau *et al.* (1991), during the process the release of biotite components requires that the volume of reagents is equal to the sum of the products. These reactions require dissolution or recrystallization of at least a portion of the original biotite, with gain or loss of components. Also, according to Shau *et al.* (1991), Ti and Ca are stable in the structure of magmatic biotite. It also implies that if magmatic biotite is metamorphosed under conditions of greenschist or amphibolite facies, the Ti and Ca present can be released. Shau *et al.* (1991) also propose that the destabilization of primary biotite and the topotactic release of Ti is possible leading to formation of titanite during metamorphism. Yui *et al.* (2001) agree that biotite can provide sufficient Ti, but Ca would need to be provided by an external source (e.g., plagioclase) for the formation of titanite. According to Sousa *et al.* (2019), the rocks of the BRJ do not have evidence of metamorphism/deformation in the solid state. However, Sousa *et al.* (2019) when describing saussuritized plagioclase crystals, suggested that they result from the action of late fluids. In this context, it is likely that the formation of titanite in the biotite cleavage in the RJB is not related to regional metamorphism, but to a hydrothermal process at the end of the crystallization process of this batholith.

Holtz *et al.* (2001) suggest a diagram to estimate the minimum H_2O content dissolved in granitic magma. To use this diagram, only the temperatures and crystallization pressures of the IF and PF biotite crystals were considered. The RJB ME crystals were not used, as they are considered to be of mantle origin (OLIVEIRA *et al.*, 2015; SOUSA *et al.*, 2019), thus not attending the requirements for using this diagram. The values obtained in the FP and FI crystals were similar and according to this estimate, the minimum water content in the magma during the crystallization of biotite was between 5 and 7% (Figure 8).

Biotite composition is very sensitive to changes in $f\text{O}_2$, so it has been used as indicator of redox conditions of granitic magmas (e.g., WONES, 1972; HOSSAIN; TSUNOGAE, 2014). When performing Wones (1972) calculations with the data of the primary biotite crystals studied, similar values of log $f\text{O}_2$ were obtained between the IF and PF, that is, -16.3 to -15.0 and -15.9 to -15.4, respectively, whilst those found for the ME showed greater variation, -15.6 to -13.9. The results were plotted on the Temperature versus ΔNNO diagram (Figure 9) and were in an array above the NNO buffer (O'NEIL; POWNCEBY, 1993) showing a trend of increasing $f\text{O}_2$ with temperature decrease. Based on the NNO buffer, $f\text{O}_2$ values range from +0.7 to +1.3 in the IF, between +0.7 to +0.8 in the PF, and from +0.4 to +1.6 in the ME.

It was noted that the ME primary crystals show variations in $f\text{O}_2$ and temperature values. Given this fact, it was decided to analyze these variations in the different samples of the ME (Figure 9). It is observed that the set of analyses of each sample of ME presents different variation of temperature and $f\text{O}_2$. Due to the trends of increasing $f\text{O}_2$ with decreasing temperature, formed with different initial and final values of these parameters in the samples (Figure 9), it is suggested that these variations may indicate the presence of mafic magma (ME) pulses at different stages of the crystallization of the RJB magmatic chamber. Sousa *et al.* (2019, 2022) also inferred the existence of several pulses of mafic magma during the evolution of the RJB magmatic chamber, based on: (i) the identification of a variety of enclave types (dark, light, or showing varying shades of gray) in the RJB; (ii) the presence of different shapes and contacts of enclaves with the host granites (indicating differences between the viscosities of the magmas) and (iii) oscillatory zoning in plagioclase crystals.

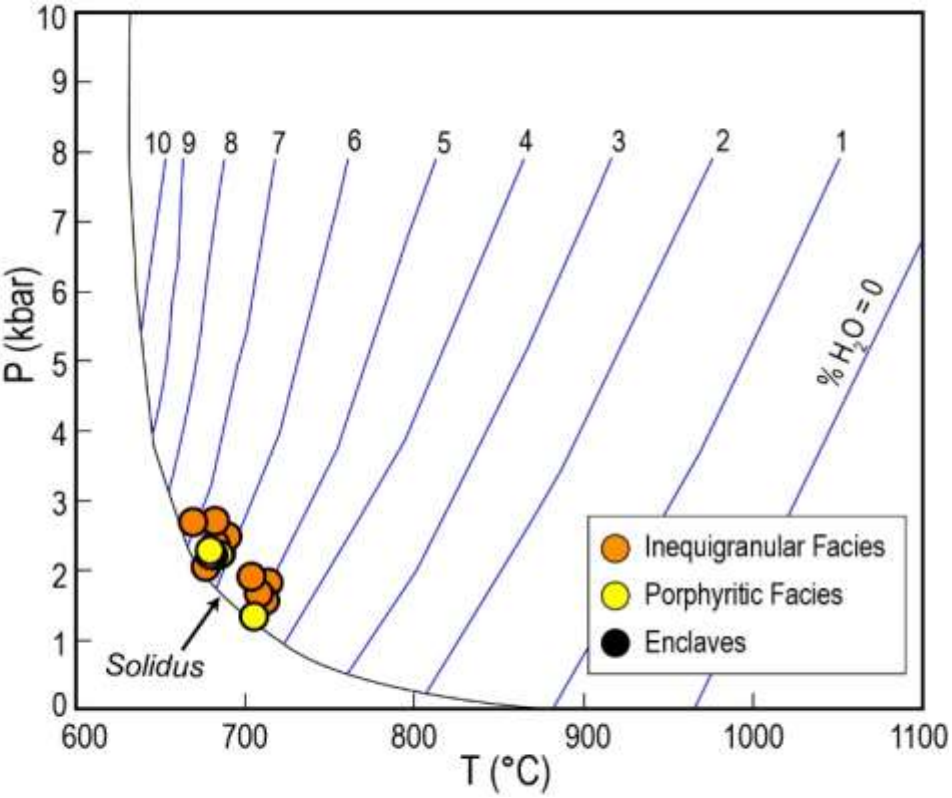

Figure 8 – Temperature versus pressure diagram to estimate the minimum content of H_2O dissolved in magma applied to primary biotite of the RJB. Blue lines represent the percentage of water content.
Source: Holtz et al. (2001)

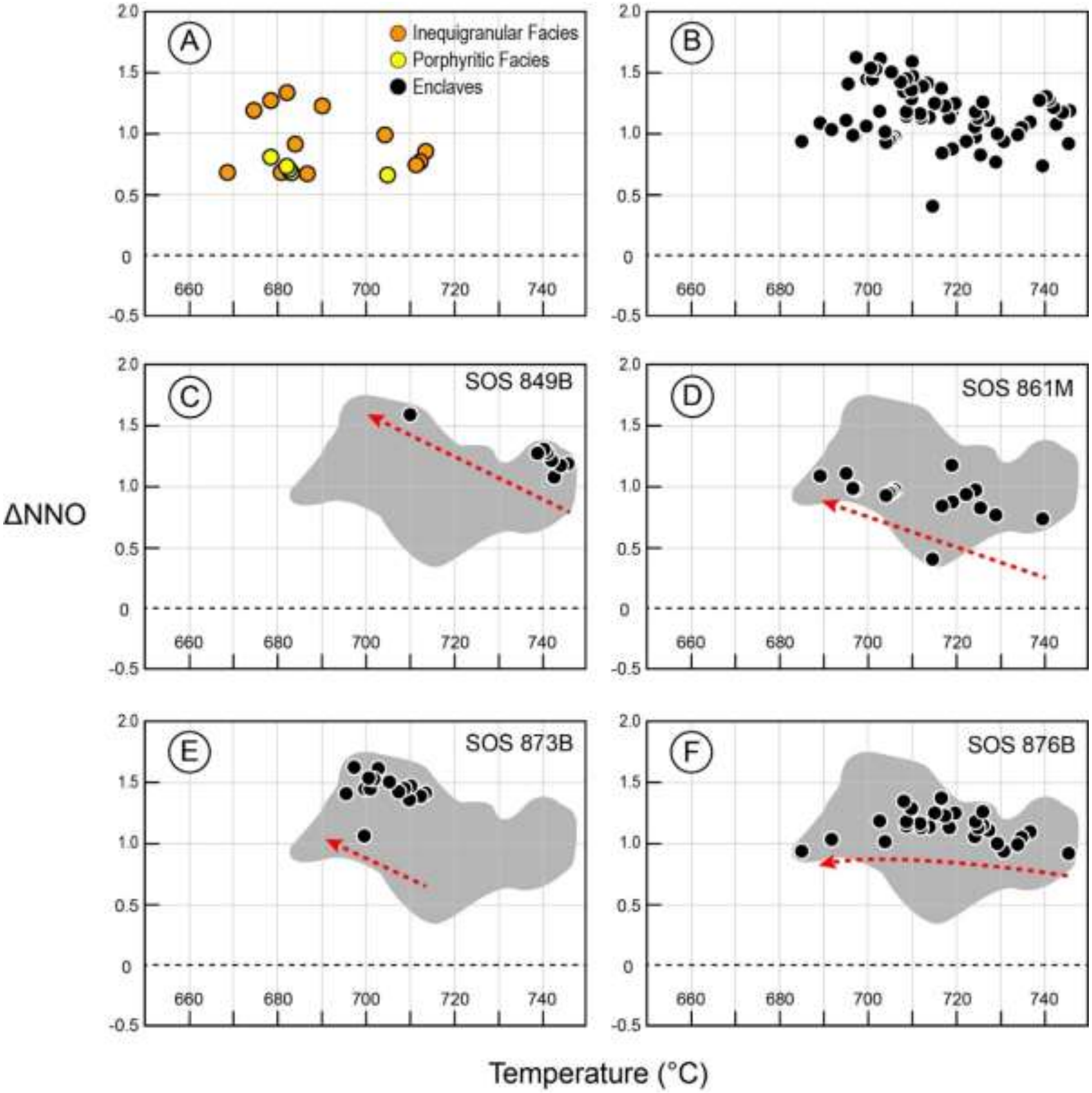

Figure 9 – ΔNNO versus temperature diagram applied to primary biotite from the RJB. The gray area represents the composition of all analyzed MEs. Trends indicated by red arrow.
Source: Authors (2024)

6. Conclusions

The textures and mineral chemistry of biotite crystals allowed us to identify in the RJB the presence of two groups of biotite crystals: a primary (magmatic) and a reequilibrated (magmatic rebalanced). The magmatic crystals are present in rocks of all three petrographic facies of the RJB (ineguigranular and porphyritic facies, and in the microgranular enclaves). However, primary biotite is more abundant in the MEs. Probably the faster cooling process responsible for the fine graining of these rocks preserved the magmatic crystals.

Primary biotite crystals occur mainly as inclusions in plagioclase crystals, indicating early crystallization. The occurrence as inclusions is probably what allowed the biotite to be preserved from the action of hydrothermal fluids common in plutonic systems and which in the case of the batholith studied are responsible for the saussuritization of plagioclase and partial alteration of biotite to chlorite.

The primary biotite corresponds to Mg-biotite and its chemical composition indicates that the rocks of the RJB are granites of the Magnetite Series, metalluminous and with a calc-alkaline geochemical signature. These data agree with conclusions based on total rock chemical data available for the RJB rocks.

The maximum temperature obtained for the crystallization of Mg-biotite from RJB is 745°C and is compatible with experimental results available in the literature for granitic magmas. In the RJB this temperature overlaps with the end of amphibole crystallization of these rocks. The onset of crystallization of biotite in the mafic magmas (enclaves) was estimated at a depth of 10.7 km (2.9 kbar) and crystallization in the granites at 9.9 km (2.7 kbar). The temperature (500-690°C) ranges obtained for the reequilibrated biotite crystals suggest that this reequilibrium does not reflect the regional metamorphism in the amphibolite facies (500-700°C) present in the studied sector, but the effect of hydrothermal fluids.

It was estimated that during the crystallization of primary Mg-biotite the dissolved H_2O content of the magma was 5-7% and the oxygen fugacity ranged from -16.3 to -13.9 (log fO_2). The variations in temperature and fO_2 values found in different enclaves may reflect the input of different pulses of mafic magmas present during the evolution of the RJB and suggested in previous studies.

The use of primary biotite crystal chemistry in granites, such as the case studied, has proven efficient for estimating magmatic temperatures, pressure, percent H_2O, and oxygen fugacity at late stages of crystallization in a plutonic system.

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