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# Petrology of volcanic rocks of the Serra Sul mine, Carajás Province, Pará

Hélio Junior Lima Monteiro<sup>1,2\*</sup> (D, Artur Corval<sup>1</sup> (D, Débora Grala Roldão<sup>3</sup> (D, Benevides Aires Filho<sup>2</sup> (D, Luighi Santos Rinaldi<sup>2</sup> (D, Letícia Martins<sup>4</sup> (D, Gustavo Diniz Oliveira<sup>5</sup> (D)

#### Abstract

The Parauapebas Formation and Igarapé Cigarra Formation constitute two Neoarchean extrusive units inserted in the metavolcanosedimentary sequence (~2.76 Ga) of the Grão Pará Group, Itacaiúnas Supergroup, being represented by basaltic seeps underlain and overlain by jaspillites, rhyolites, volcanoclastic rocks, and gabbro dikes/sills, thus being inserted in the Serra Sul district in the Mineral Province of Carajás, Pará. This study aimed to understand the igneous processes involved in the genesis of these basalts from both geological formations, supported by field, petrographic, and geochemical data. Inserted in the metavolcanosedimentary sequence of the Grão Pará Group (Carajás Domain), the basalts and basalt andesites, the most abundant types of the Parauapebas and Igarapé Cigarra Formations, occur as successions of massive and amygdaloidal lava flows. The study of core samples from nine stratigraphic holes that intersected basaltic rocks of the two geological formations in body S11D (Serra Sul) showed that these rocks reach thick layers with different characteristics, ranging from aphanitic to phaneritic. The basalts are dark green, aphanitic, phaneritic, thin to medium, and hypocrystalline. They show preserved igneous texture being commonly seriated as inequigranular, intersertal, ophitic, subophytic, intergranular, branching, and swallow tail. Its essential primary constituents are plagioclase, orthopyroxene, and clinopyroxene, and its accessory constituents are titanite and apatite. Chlorite, epidote, quartz, and calcite occur as secondary phases and are interpreted as the products of ocean-bottom hydrothermal alteration and/or incipient metamorphism. In general, the studied volcanic rocks stand out for SiO, content between 47.00 and 56.04%, high alkali contents (4.70-7.50%), K,O contents between 0.40 and 3.97%, TiO, (< 1.0%), and MgO between 4.90 and 8.16%. In the classification diagrams, the samples are situated in the fields of basalts, basalt andesites, trachyandesite, and trachybasalt basalts, in the transition of the toleitic and calc-alkaline series. The basalts of the Parauapebas and Igarapé Cigarra Formations were probably formed in an intraplate continental environment influenced by subduction zones. Therefore, the Grão-Pará Basin was probably formed in a convergent regime related to a subduction-type environment. The geochemical data indicate that the studied rocks of the Parauapebas Formation and the Igarapé Cigarra Formation correspond to basalts of calc-alkaline affinity. Two facies were identified in the Parauapebas Formation, namely, the Amendoim and Violão facies. In the Igarapé Cigarra Formation as well, the following facies were identified: Jacaré and Três Marias. Based on the geochemical interpretation, it is assumed that the rocks studied are arc-like continental basalts, which are formed in a subduction environment with influence from a possible asthenospheric source and modified by crustal contamination.

KEYWORDS: Serra Sul; Carajás; Brazil; high-pressure melting; petrology; geochemistry.

#### INTRODUCTION

The Carajás Mineral Province (CMP) (Santos 2003) is notorious for gathering large deposits of iron (Fe) and copper (Cu), as well as important occurrences of Mn, Au, PGE, Ni, Cr, and rare earth elements (REE). Since its discovery in the 1960s, CMP has been the target of several studies, mainly exploratory. But even today, there are few publications focused

\*Corresponding author.



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on basic geological and structural mapping. The long and complex geological history of the CMP is still lacking information that needs to be revealed.

The studies mentioned earlier have shown that it is possible to obtain important data related to the genesis of the rocks, type of geotectonic environment, and characteristics of the magmatic sources, besides evidencing the successive deformation events that affected these rocks (Gibbs *et al.* 1986, Olszewski *et al.* 1989, Machado *et al.* 1991, Meirelles and Dardenne 1991, Teixeira and Eggler 1994, Pinheiro and Holdsworth 2000, Lobato *et al.* 2005, Zucchetti *et al.* 2007). Recent studies by Martins *et al.* (2017) pointed out that the Grão Pará Group basaltic rocks are derived from the subcontinental lithospheric mantle and affected by upper continental crustal components. These authors interpret a rift setting based on regional geology but do not discard the fact that volcanism is originated by the opening of a back-arc continental basin.

Since the 1970s, several petrogenetic and geochemical studies have been developed in order to characterize the different signatures of the basic magmas and correlate them with the respective tectonic environments. From these studies, numerous tectonic

<sup>&</sup>lt;sup>1</sup>Universidade Federal Rural do Rio de Janeiro – Rio de Janeiro (RJ), Brazil. E-mails: geohelio@yahoo.com.br, helio.monteiro@vale.com, corvalgeo@ufrrj.br

<sup>&</sup>lt;sup>2</sup>Vale S.A. – Canaã dos Carajás (PA), Brazil. E-mails: benevides.aires@ vale.com, luighi.santos.rinaldi@vale.com

 <sup>&</sup>lt;sup>3</sup>Vale S.A. – Nova Lima (MG), Brazil. E-mails: debora.roldao@vale.com
<sup>4</sup>Vale S.A. – Parauapebas (PA), Brazil. E-mail: leticia.martins@vale.com
<sup>5</sup>Vale S.A. – Santa Luzia (MG), Brazil. E-mail: gustavo.diniz.oliveira@vale.com

discrimination diagrams were proposed (e.g., Pearce and Cann 1973, Pearce and Norry 1979, Wood 1980, Shervais 1982, Meschede 1986, Humphris and Thompson 1989), aiming to identify and understand the processes involved in the generation and evolution of magmas and thus unveil the tectonic affinity of ancient basic rocks. Currently, most of the studies developed in this area have used a combination of different diagrams to satisfactorily determine the sources, processes, and tectonic environments in which ancient basic rocks were generated (Pearce 2014, Saccani 2015).

This study presents and discusses the petrographic and geochemical data of the basic rocks of the Parauapebas Formation (FP) and Igarapé Cigarra Formation (FIC), with the objective of discussing the igneous processes involved in the generation of these rocks in order to contribute to the understanding of the tectonic environment of the formation and the main evolutionary aspects of the Grão Pará Group.

The studied area comprises the Serra Sul plateaus that are composed of targets S11A, S11B, S11C, and S11D and are positioned on the southern flank of the Bocaina syncline. The S11 plateau, which is compartmentalized into targets A, B, C, and D (CVRD-CMM 1972), represents the main target, presenting 28 km in length, 1 km in width, and a known depth of 600 m (Fig. 1).

#### **GEOLOGICAL SETTING**

The Carajás Basin, which is also known as the central sigmoid of Carajás (Araújo *et al.* 1988, Araújo and Maia 1991, Pinheiro 1997, Pinheiro and Holdsworth 1997, 2000), is situated in the eastern portion of the Amazonian craton in northern Brazil (Fig. 2). This basin is located in the Carajás block, which, along with the Transition subdomain and Rio Maria block, constitutes the Carajás Province (Dall'Agnol *et al.* 1997, 2006, Althoff *et al.* 2000). The basement of the Carajás Basin comprises ~2.85 Ga Mesoarchean igneous and metamorphic rocks, which include granite and gneiss of tonalite-trondhjemite-granodiorite type, belonging to the Xingu Complex (Machado *et al.* 1991). Besides that, the Pium Diopside-Norite Complex, which comprises norite, gabbro, and diorite of ~3.0 Ga (Pidgeon *et al.* 2000), and the Chicrim-Cateté orthogranulite unit are considered by many authors (Araújo and Maia 1991, Vasquez *et al.* 2008) to be part of the basement assembly of this basin as well.

The limits of the Carajás Basin are difficult to establish. During the Transamazonian cycle that took place at ~2.0 Ga (Cordani *et al.* 1984, Machado *et al.* 1991, Macambira *et al.* 2009, Tavares *et al.* 2018), a large part of the Carajás Basin was segmented into different compartments that present a complex history of deformation and metamorphism. Currently, the Carajás Basin is limited by the Bacajá block to the north and by the Transition subdomain to the south (Dall'Agnol *et al.* 2006, Feio *et al.* 2013). The ~1.88 Ga Carajás granite and dike swarms (Machado *et al.* 1991, Teixeira *et al.* 2018, Giovanardi *et al.* 2019) cross-cut the Carajás Basin, post-dating the deposition within the basin.

The Grupo Grão Pará (CVRD-CMM 1972, Docegeo 1988) was divided into three units by Beisiegel *et al.* (1973), originally described as follows:



Figure 1. (A) Brazil and study area maps. (B) Total gradient amplitude (TGA) map S11D. (C) Geological map modified from Justo and Lopes (2014) of the iron plateau S11D.



**Figure 2.** (A) South America map showing the location of the Amazonian craton and the Carajás Province in northern Brazil. (B) Carajás Province map showing the location of the Carajás Basin in the Carajás block. (C) Geological map (Justo and Lopes 2014), showing the location of the study area. The polygon highlights the deposit of S11D.

- Lower volcanic sequence is represented by mafic volcanic rocks, hydrothermally altered, and with preserved primary features, such as amygdalas and intergranular texture. The primary structures suggest the occurrence of several spills and pyroclastic contributions that form a stratiform body in concordant contact with the Carajas Formation above. In mine N4, the thickness is inferred to be more than 150 m;
- Carajás Formation is formed by banded iron formation (BIF) and its alteration products occurring in tabular form between the mafic rocks. All the stratigraphic contacts are concordant when observed. The Carajás Formation has an average thickness of 200–250 m in the North ridge and above 300 m in the South ridge and is cut by dikes and sills of mafic rocks;
- Upper volcanic sequence is formed by basic volcanic rocks similar to those of the lower volcanic sequence, from which

it is differentiated by lenticular intercalations of the ironrich formation.

The rocks of the lower and upper units occur in the form of several spills, representing a submarine volcanic event, and show two petrographic types, namely, very fine-grained rocks, without phenocrystals and intergranular texture and coarse grained rocks that are partly phaneritic and locally porphyritic (Hirata 1982).

The lower volcanic sequence is named FP (Meirelles et al. 1984, Docegeo 1988), and besides the already known features - volcanism in several basaltic spills, amygdaloidal zones, and porphyritic texture — intercalations of felsic volcanic rocks with porphyritic texture and an aphanitic matrix are observed. These may present flow structures and fragmentary portions. In the basal portion of the unit, subordinate zones of laminated argillaceous metasedimentary rocks and rocks formed by biotite and quartz are described. The felsic volcanic rocks are described by Gibbs et al. (1986) as rhyolites in homogeneous, lapilli tuffs, and tuff to crystal and vitreous spills. The authors estimated that felsic volcanic rocks constitute about 10--15% of the volcanic rock outcrops in the Northern Sierra. The basalts of the lower unit have brecciated and scoriaceous tops with chlorite, quartz, pyrite, and other secondary minerals filling amygdales (Gibbs and Wirth 1990, Martins et al. 2017). The Carajás Formation is in contact with the FP and shows intercalations between mafic volcanic rocks and the BIF (Gibbs and Wirth 1990). The BIF is described as jaspilite (Coelho 1986, Beisiegel 1982), meso- and microbanded, formed by bands of jasper and iron oxides. It is important to note that jasper is a chert impregnated with microcrystalline hematite. In addition to compositional banding, the Carajás jaspilites preserve other depositional structures, such as planar-parallel internal lamination, scour-and-fill structures, and spherulites/granules of probable organic origin (Meireles 1986, Macambira 2003). The jaspilites formed by chemical precipitation on shallow-water marginal platforms during a period of tectonic calm and near fumaroles with a wide areal distribution (Lindenmayer et al. 2001). Detailed descriptions on the jaspilites were done by Meireles (1986), Lindenmayer et al. (2001), Klein and Ladeira (2002), Macambira (2003), and Figueiredo and Silva (2004).

The upper volcanic sequence is named FIC by Macambira *et al.* (1990) and Macambira (2003). According to the authors, this unit is composed of basalts with tuff intercalations covered by clastic sediments (quartz wackes and quartz sandstone) and chemical sediments (BIF and chert), presenting concordant contact against the Carajás Formation and a thickness that varies from 1 to 3 km. The upper volcanic sequence is questioned by some authors, either by the lithotypes that compose it or by its occurrence as a unit belonging to the Grão Pará Group. In the first case, Gibbs *et al.* (1986) and Gibbs and Wirth (1990) named it the Superior Sequence, constituted by tuffs, siltstone, phyllites, cherts, grauvaca, and subordinately, mafic spills. In the second case, Meireles (1986), Meirelles and Dardenne (1991), and Lindenmayer *et al.* (2001) considered the top and bottom relations of the volcanic rocks with the jaspillites

as of structural character, questioning their stratigraphic value. Teixeira and Eggler (1994) and Teixeira *et al.* (1997) considered only the Parauapebas and Carajás formations as belonging to the Grão Pará Group. The upper volcano-sedimentary sequence would belong to the Igarapé Bahia Group, positioned just above the Grão Pará Group.

The age of volcanism of the lower unit of the Grão Pará Group is about  $2758 \pm 39$  Ma by means of U-Pb analyses on zircons from rhyolites related to the FP by Wirth *et al.* (1986). This age is ratified by U-Pb analyses of zircons from rhyodacites of the same unit (Machado *et al.* 1991), which provides an age of <sup>207</sup>Pb/<sup>206</sup>Pb of  $2759 \pm 2$  Ma.

Trendall *et al.* (1998) dated rocks of the Grão Pará Group and of the Águas Claras Formation by the U-Pb/SHRIMP method based on zircons. In the first unit, rhyolites associated with lower volcanism provided extrusion ages between  $2760 \pm 11$  Ma and  $2757 \pm 7$  Ma. An age of  $2740 \pm 8$  Ma was obtained for a diabase sill. However, according to Lindenmayer (2003), the second lithotype belongs to the upper volcanic rocks. Sandstones of the Águas Claras Formation present two zircon populations. The main population provided an age of  $2681 \pm 5$  Ma, interpreted by the authors as the age of syndepositional volcanism in sedimentary rocks.

Paleoarchean crustal contribution to this domain's basement is indicated by detrital zircon of up to 3.6 Ga and rocks with model ages ( $T_{DM}$ ) greater than 3.20 Ga (Mougeot 1996, Mougeot *et al.* 1996, Macambira *et al.* 2001, Galarza and Macambira 2002, Dall'Agnol *et al.* 2005).

Krymsky (2002) dated zircons (U-Pb method) from the same felsic volcanic rock sample analyzed by Trendall *et al.* (1998). The obtained age of  $2751 \pm 4$  Ma was interpreted as the age of crystallization of the volcanic rock.

The Itacaiúnas Supergroup is formed by the volcanosedimentary sequences Grão Pará, Igarapé Salobo, Igarapé Pojuca, Igarapé Bahia, and Buritirama. These units have in common the lithological association dominated by mafic volcanism intercalated with chemical sedimentary rocks, overlain by clastic sedimentary rocks. However, at the same time, the sequences present differences among themselves as to the metamorphic degree, the intensity of deformation, and the types of mineral deposits they host. To date, there is no clear definition about the contemporaneity or not of these units (Docegeo 1988, Machado *et al.* 1991, Pinheiro and Holdsworth 2000).

In relation to the environment of formation of the volcanosedimentary sequences, which implies in the tectonics of the Mineral Province of Carajás itself, there are two basic ideas as follows:

- The units of the Itacaiúnas Supergroup are volcanic and sedimentary rocks on the continental crust adjacent to rift zones or intracratonic basins (Gibbs *et al.* 1986, Olszewski *et al.* 1989, Machado *et al.* 1991, Lindenmayer 1992, Santos 2003, Tallarico *et al.* 2005, Grainger *et al.* 2007);
- The volcanosedimentary sequences are formed in arc environments and involve subduction zones (Meirelles and Dardenne 1991, Teixeira and Eggler 1994, Lobato *et al.* 2004, Lobato *et al.* 2005, Rosière *et al.* 2006, Martins *et al.* 2017).

Olszewski *et al.* (1989) suggested that the volcanic and sedimentary rocks of the Grão Pará Group developed over continental crust adjacent to rift zones. According to the authors, the absence of pillow lavas, the intimate association of mafic volcanics with quartz-rich clastic sedimentary rocks, and the evidence for crustal contamination ( $\varepsilon_{Nd}(t)$  with negative values) suggested formation on or near the continental crust. They concluded that the mafic rocks of the Grão Pará Group have chemical characteristics of continental basalts (Martins *et al.* 2017).

The volcanic rocks studied by Gibbs *et al.* (1986), Olszewski *et al.* (1989), Machado *et al.* (1991), Meirelles and Dardenne (1991), Lindenmayer (1992), Teixeira and Eggler (1994), Santos (2003), Lobato *et al.* (2004), Lobato *et al.* (2005), Tallarico *et al.* (2005), Rosière *et al.* (2006) and Grainger *et al.* (2007) differ from those of subduction zones by presenting bimodal volcanism without intermediate andesitic composition.

As for the greenstone belts, Olszewski *et al.* (1989) stated that the volcanic rocks of the Grão Pará Group are chemically distinct from the greenstone belts, because the alkali enrichment in the latter is much lower than that present in the Carajás rocks.

According to Meirelles and Dardenne (1991), the basaltic rocks of the Grão Pará Group represent predominantly shoshonitic magmatism, which possibly ascended to the surface through a rift system formed in a continental crustal environment genetically linked to a neighboring orogeny.

Based on the geochemical characteristics of REE, Teixeira and Eggler (1994) suggested that the mafic rocks of the Grão Pará Group formed in a magmatic arc environment, generated by partial fusion over a subduction zone. According to the schematic drawing presented by the author, the volcanism would have occurred in the arc region. Lindenmayer *et al.* (2001) and Silva *et al.* (2005) followed the proposal of Teixeira and Eggler (1994) for a magmatic arc environment and subduction zone.

## MATERIALS AND METHODS

The research method proposed in the present research will essentially involve the following stages: field, laboratory, and office work.

The laboratory stage involved the following main items:

- Acquisition of the database from an exploration diamond drill holes realized in 1986. These data were used for the selection, as well as: (a) analysis of the profiles of the nine selected diamond drill holes (Fig. 3) (where the relevance of each hole for the study was considered) and (b) according to the number of selected holes, it was determined that the selection of 86 sample intervals that were used in the study;
- Confection of 39 thin-section slides for petrographic-petrological analysis of the unaltered samples, including study under transmitted light (transparent phase microscopy);
- Sample selection and preparation: based on the petrographic phase, unaltered rocks were selected for crushing and grinding, to be carried out at the ALS Limited laboratory in Brazil. These samples were destined for lithogeochemical analyses of major, trace, and REE to be performed at the ALS Limited laboratory in Peru. A total of 21 samples were forwarded and used for this purpose.

## RESULTS

#### Field data

The S11D mine is approximately 6 km long in the W-E direction. It has been divided into mining systems numbered 1-5 (Fig. 4). The pits in systems 1, 2, and 4 are well developed



**Figure 3.** Geological map of the S11D mine, with primary lithologies, showing the layout of the boreholes selected for the study. Terms, such as chemical canga, structural canga, and manganese iron ore, used in the mine geology in Carajás, are explained in the map "Mesoscopic classification of the iron ore profile."

with large exposures of iron ore. The mining in system 3 is partially paralyzed by the deposition of waste rock piles. System 5 is located in the western portion of the S11D deposit, south of the Violão Lagoon. This system is in the implementation phase, and its natural surface is a red bed plateau.

#### Lithostratigraphic units

During the mapping of the S11D deposit, only lithologies of the Grão Pará Group were observed. These occur roughly elongated along a W-E direction with dips predominantly to the north. The iron formation, which occurs in this deposit, can be summarized as hematite and jaspelite. The S11D deposit is capped at the base and top by mafic and felsic rocks of volcanic origin. The bedrock of S11D is covered by a crust of laterite material, sometimes detrital, rich in iron oxides and hydroxides, called canga.

## Parauapebas Formation and Igarapé Cigarra Formation

The volcanic rocks of the Grão Pará Group were observed in the southern and northern portions of the S11D plateau, capping the base and top, respectively, of the iron formation layer. The volcanics located at the base of the formation were characterized along the slope cuts in systems 1–4. It is a predominantly reddish, silty-clayey, cohesive saprolite (Fig. 5).

The volcanic rock occurring on top of the ferrous formation layer was characterized only on the north slope of containment dike 3. At this point, the volcanic rock presents itself as a friable, poorly cohesive, yellowish saprolite with a foliated structure (Fig. 6).

#### Carajás Formation

Rocks of volcanic origin were also observed interspersed in the iron formation layer. These are rhyolites, with a maximum



Figure 4. Aerial image of the S11D deposit. The location of the mining systems is indicated in the image.



**Figure 5.** Photographs showing volcanic rock that occurs at the base of the iron formation layer. (A) Reddish volcanic rock saprolite. (B) Layered levels of volcanic rock saprolite of different colors.

thickness of 2 m (Fig. 7) and of kilometric persistence, as this layer of volcanoclastic rock was observed and followed from system 2 to system 4. The tuffs are generally altered to friable, red saprolite with a silty-sandy texture. The rhyolite shows preserved compact to semi-compact portions (Fig. 8A), a red matrix, and a framework composed mainly of quartz and rock fragments 2–5 mm in diameter (Fig. 8B).

The S11D deposit is basically composed of jaspelite and hematite and is in sharp contact with the volcanic bedrock FP and FIC. The largest exposures of the iron formation occur in the pits of systems 1, 2, and 4 according Fig. 4.

This lithology is exposed in compact, metric bodies, enveloped by friable hematite, or in large compact bodies, hundreds of meters long, in the floors of the system 1 and 4 pits, always



**Figure 6.** Photographs showing the aspects rock of volcanic rock saprolite occurring on top of the ferrous formation layer.



**Figure 7.** Photographs showing rhyolite layer fitted concordantly with the banding of the iron formation.

oriented in a NE-SW trend. In system 1, the jaspelite occurs in larger proportions in the northwestern portion, near the belvedere. In system 4, the outcropping bodies of jaspelite are grouped in the southern portion of this system.

The S11D jaspelite is a gray rock (Fig. 9A), banded, composed of alternating gray bands composed of iron oxides, and predominantly white siliceous bands (chert) and jaspes. However, it was observed in portions of ochre jaspelite where the banding is characterized by alternating bands of iron oxides with a yellowish mass, apparently limonitized (Fig. 9B).

The orebody of S11D consists of a predominantly friable hematite rock substrate and is capped by red beds. This substrate is bounded to the south and north by volcanic rocks and, at depth, by compact jaspelites. The hematite of S11D envelops metric to decametric cores of compact jaspelites, preserved remnants of the mineralization process.

The hematite is a gray-banded rock, but ochre-colored limonitized portions (Fig. 10) occur throughout the S11D complex. It has a predominantly friable, semi-compact (medium), and compact consistency. The friable hematite is generally composed of the sheet and powdery types. The sheet type is characterized by alternating bands forming "sheet" plates and bands of pulverulents (Fig. 11A). In the powdery type, there is no heterogeneity between the strengths of the bands, since the material crumbles evenly (Fig. 11B).

Hematite with medium to compact compactness (Fig. 12) presents occurrences restricted to dikes 1 and 3, southern portion of system 2.

### **Covering units**

The structured canga has the largest areal expression, covering much of the southern portion of the Violão Lagoon and around the present S11D pits. The structural canga is formed simply by the penetration of supergene fluids along the structural planes of the rocks. The direction and dip of the structural planes and axes can be recorded as representative of bedrock, but this usually exhibits high magnetism (Fig. 13A).

Ore canga occurs mainly around the guitar pond and in the southern part of system 3. It consists of irregular fragments of iron formation cemented by iron hydroxides.



Figure 8. Photographs showing volcanic rock. (A) Detail of rhyolite layer near the iron formation in regular contact. (B) Detail of the rhyolite grain size.

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Figure 9. Photographs showing of jaspelites from S11D. (A) Gray variety. (B) Ochre variety.



Figure 10. General view of slope exhibiting limonitized hematite.

Chemical canga occurs in a continuous band in the W-E direction, mainly in the northern portion of the S11D area, overlying the top volcanic rock. This unit was poorly characterized during mapping.

Roll-front deposits were observed making up small basins formed in the side of NE-SW-directed synformal structures in the S11D mine. The basins were observed in the central portion of system 1 and the southern portion of system 2. These are composed of pebbles and rounded blocks, predominantly of iron formation (Fig. 13B).

#### Petrography

Microscopic description of petrographic slides obtained from samples collected from boreholes revealed the existence of at least two distinct groups of rocks in the study region.

Two of these are basalts of the FP and FIC, and the other is a rhyolite existing in the Carajás Formation. These rocks are described below.

#### Basalts Igarapé Cigarra Formation

These rocks are part of the FIC, at the top of the Grāo Pará Group. As with most Archean rocks, they are hydrothermally altered at different intensities, regardless of the lithological type. However, a large number of primary textural features are preserved. Samples showing amygdaloidal texture are frequent in the thin section.

Macroscopically, the basalt is dark gray to greenish, mesoto melanocratic, fine-grained, with a general homogeneous aspect, without apparent structures, except for some spots where amygdaloidal and micro-fractures filled by carbonate and quartz are present (Fig. 14).

Under the microscope, the basalts present the following textures: seriate inequigranular, hypocrystalline, intersertal, ophitic, subophytic, intergranular, branching, and swallow tail (Fig. 15), with fine grains of < 1 mm. The basalts are composed essentially of plagioclase (Pl), clinopyroxene (Cpx), and orthopyroxene (Opx), and in some sections there is the presence of quartz (Qtz) in the form of venules. Opaque minerals, such as apatite and titanite, occur as accessory minerals. It is worth noting that grains of opaque minerals occur in plagioclase grains. Finally, chlorite, serpentine, calcite, epidote, and amphibole are observed as secondary minerals.

Plagioclase crystals are present in about 100% of the samples with an average frequency of 40% and are smaller than < 1 mm in size, with the predominance of the smaller ones in slaty form and the medium ones with a tabular to prismatic habit. These plagioclase grains vary from sub-hedral to euhedral, making straight contacts with quartz, opaque minerals, chlorite, and calcite. Basalts of FIC show inclusions of quartz and opaque minerals in plagioclase and, locally, dovetail texture, thus corroborating the rapid cooling of the magma.

The orthopyroxene and clinopyroxene grains are present, basically filling the interstices left by the euhedral plagioclase grains. In general, the pyroxene (Px) grain has irregular shapes, varying from subhedral to anhedral. In addition, pyroxene grains are circular and quadratic, showing slaty crystals with irregular edges. The amphibole grains are also observed under the pyroxene alteration product.

Quartz, in a proportion of 1%, has a subhedral to anhedral form with undulating extinction and it occurs in about 5% of the studied slides. It is found locally in the form of crystals dispersed in the matrix and as venules, and in the latter, the crystals are anhedral, agglomerated, and recrystallized, with sizes varying from small (0.1 mm), which are the recrystallized ones, to medium (0.2 mm).

Titanite presents an anhedral form and is always associated with opaque minerals, which also occur as isolated crystals or in aggregates.



Figure 11. Photographs showing friable hematite. (A) Detail of sheet type. (B) Overview of pulverulent type.



**Figure 12.** Photograph showing compact, highly fractured hematite showing verticalized structuring.

Calcite (Cal), quartz (Qtz), and epidote (Ep) are found filling elongated to irregularly shaped amygdaloidal cavities, micro-fractures, or as alteration products (Fig. 16).

The most common alterations found are orthopyroxene changing to amphibole, saussuritized plagioclase, epidotization, and carbonation in the form of venules.

#### **Basalts Parauapebas Formation**

These rocks are part of the PF, the basis of the Grão Pará Group. Macroscopically, the basalt is dark gray to greenish, meso- to melanocratic, fine-grained (< 1 mm), with a general homogeneous aspect, without apparent structures, except in some cases where there is the occurrence of amygdala and micro-fractures filled by calcite, quartz, and epidote (Fig. 17).

Under the microscope, the basalts present as main textures the intergranular, intersertal, ophitic, subophytic, hypocrystalline, and serial inequigranular (Figs. 18 and 19). They are essentially composed of plagioclase (Pl), orthopyroxene (Opx), clinopyroxene (Cpx), and quartz (Qtz). Accessory minerals are opaque minerals such as rutile, biotite, and titanite. As secondary minerals, we observe the occurrence of chlorite (Chl), calcite (Cal), epidote (Ep), chloritoid, serpentine, and amphibole. Precisely, there is the presence of chloritoid grains. Plagioclase crystals are present in about 100% of the samples with an average frequency of 40% and are of varying sizes from small to very small (from 1 to 0.05 mm), presenting in the form of laths and with a tabular to prismatic habit. Plagioclase grains vary from subhedral to euhedral, making straight contacts with quartz, chlorite, and calcite. It is worth noting that it is possible to observe grains of opaque minerals included in plagioclase grains.

Orthopyroxene is present in 70% of the sections. It has an irregular shape, subhedral and anhedral crystals, with irregular edges, and is usually altered to amphibole.

The most occurrence form of amphibole grains in the basalts is registered as a pyroxene alteration product.

Quartz, in a proportion of 4–15%, has a subhedral to anhedral form with undulating extinction and it occurs in about 60% of the studied sections. It is found in the form of both crystals and veins, and in the latter, the crystals are agglomerated and recrystallized with sizes varying from small (0.1 mm), which are the recrystallized ones, to medium (0.2 mm), forming triple points due to the recrystallization in the formation of subcrystals.

Titanite presents an anhedral form and is always associated with opaque minerals, which also occur as isolated crystals or in aggregates. Chlorite, chloritoid, calcite, quartz, and amphibole are found filling amygdaloidal cavities of elongated to irregular shape, micro-fractures, or as a product of alteration, except for quartz, often in concentric arrangement.

The most common alterations observed are amphibole to chlorite, pyroxene to amphibole, as well as chloritization, epidotization, and carbonation. Biotite is recognized in a few slides with subhedral and anhedral shapes and with a very small representation, most of them already altered to chlorite.

#### Chloritites

Subordinately, some rocks were recognized as *Chloritites*. The presence of chlorite in 70% of the samples indicates that chloritization was one of the most important alteration processes acting on these rocks. Completely altered to chlorite, there are three rocks in which the presence of chlorite



Figure 13. Photographs showing the aspects of the covering materials. (A) Structured canga. (B) Rolled deposit.



**Figure 14.** Photographs showing the aspects of the collected core samples from Cigarra Formation.

is 60% (SSD-FD00932-L02, SSD-FD01027-L02, and SSD-FD00831-L02) (Fig. 20). According to Zucchetti *et al.* (2007), due to hydrothermal alteration, there is the presence of chloritites. The mention of these rocks was cited in the doctoral thesis of Zucchetti *et al.* (2007) entitled "Mafic rocks of the Grāo Pará Group and their relation to the iron mineralization of the N4 and N5 deposits, Carajás-PA."

The petrographic data show that the rocks are basalts due to the presence of large quantities of minerals such as plagioclase, clinopyroxene, and orthopyroxene. The mineralogical study indicates a probable involvement of hydrothermalism, marked mainly by the presence of calcite, quartz, and epidote veins (Fig. 19). This process was possibly induced by the entrance of hydrothermal fluid in fault and contact planes between jaspilites and basalts, with the latter forming alteration zones dominated by chlorite (distal) and hematite (proximal). In the basalts, the amygdalites served as the main channel for the passage and diffusion of the hydrothermal fluid (Zucchetti *et al.* 2007) and the percolation of fluids from shear zones, which was found to be intense in the basaltic rocks of the Grão Pará Group.

The presence of plagioclase in large quantities and the ophitic and subophytic textures of the plagioclase grains demonstrate that they had high temperatures, which is typical of basaltic magmas; the intersectional texture points to the fact of the presence of volcanic glass. The presence of opaque minerals included in plagioclase grains suggests that these mineral phases have early crystallization, which is typical of an oxidizing environment.

The rocks most affected by hydrothermal alteration present almost total replacement by chlorite and are classified as chlorites according to Zucchetti *et al.* (2007). Teixeira and Eggler (1994) observed the intense chloritization of mafic rocks and that the chlorite content in altered rocks can reach 90% of the modal proportion.

In chloritites, the plagioclase is still partially preserved, but the mafic minerals are replaced by chlorite. Chlorite, carbonate, quartz, and plagioclase are the most common alteration minerals. Chlorite occurs replacing the rock matrix and amygdales, while carbonate, quartz, and epidote appear preferentially in veins and amygdales. One can also observe elongate, skeletal, opaque minerals and the presence of interstitial volcanic glass in the basalts from **PF** and FIC. Macroscopically, the samples from FIC are more granular compared to those from PF.

# Rock classification, lithogeochemical data treatment, and facies discrimination

Total rock chemical analysis was performed on 21 samples (Table 1), considering the different weathering stages of the rocks collected from the drill holes. They were selected after petrographic characterization and analyzed by Analytical Laboratories (ALS Limited), Lima, Peru, and the concentrations of major, minor, and trace elements, including REE, were obtained. Major and minor elements (SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, MgO, CaO, Na,O, P,O, Cr,O, BaO, K,O, and SrO) were determined by Inductively Coupled Plasma - Atomic Emission Spectrometry (ICP-AES) and trace elements (Ba, Ce, Co, Cr, Cs, Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Lu, Mo, Nb, Nd, Pb, Pr, Rb, Sm, Sn, Sr, Ta, Tb, Th, Tl, Tm, U, V, W, Y, Yb, Zn, and Zr) by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). In this study, major elements were expressed as weight percent (%wt), while trace elements were expressed as parts per million (ppm). Geochemical interpretation was based primarily on the use of software suitable for series discrimination, rock classification, CIPW standard calculation, and petrogenetic interpretation.



Figure 15. Photomicrographs showing the main features of the studied basalt samples of the FIC: (A) intergranular texture (B) intersertal texture with swallow tail in plagioclase (C) ophitic and subophytic texture, and (D) branching texture.



**Figure 16.** Photomicrographs showing the venules of the samples from the FIC: (A) quartz and calcite venule, (B) epidote and calcite venule, (C) quartz and epidote venule, and (D) epidote venule.

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The packages ME-ICP06, TOT-ICP06, OA-GRA05, ME-MS81, ME-MS42, and ME-4ACD81 use data from international rock standards to evaluate the accuracy of the obtained data. Standards SY-4, OREAS 146, NCSDC71301, BXSP-1, BCS-348, MRGe008, GBM908-10, and OREAS 24b were used as references due to their similarity with the rocks of the study area.

The analytical precision for the major elements ranges from 0 to 1.66%. The analytical precision for the minor elements (trace and rare earths) ranges from 0 to 14.75% (check the value). Note that exceptionally, the accuracy calculated for Pb was 20%; because of this fact, special attention will be given to diagrams using this element.



**Figure 17.** Photographs showing the aspects of the collected core samples from PF.

The analytical accuracy for the major elements ranges from 0 to 6.87%. The analytical accuracy of the minor elements, rare earths, and trace elements varies between 0 and 9.86%.

The iron in all samples studied in this study was analyzed as total iron expressed as ferric iron  $(Fe_2O_3^t)$ .

The loss on ignition (LOI) values of the basaltic rocks selected for this study are generally above 2%wt (average 3.72%wt) (Table 2). As an approximation, the LOI value of the rocks can be an indication of the degree of alteration. Rocks with high LOI values are generally more altered than those with lower values (Valente *et al.* 2002). PF > 2% rocks of the Grão Pará Group may have been extensively affected by hydrothermal alteration and weathering. However, LOI values can be used as a criterion for selection of altered samples with some confidence in the case of rocks containing relatively small volumes of hydrated phases such as basalts. Combining this fact with the results from petrography, we consider the volcanic rocks studied in this article to be partially altered.

Samples, such as SSD-FD00612-AM04, SSD-FD00932-AM01, SSD-FD01009-AM02, SSD-FD01058-AM01, SSD-FD01059-AM02, and SSD-FD01008-AM02, present total oxides equal to 98.81%wt, 101.96%wt, 98.44%wt, 101.52%wt, 98.96%wt, and 98.76%wt, respectively. These sums are outside the range (between 99 and 101%wt) generally considered satisfactory for geochemical analyses of the total rock.



**Figure 18.** Photomicrographs showing the main features of the studied basalt samples of the FP: (A) intergranular texture, (B) intersertal texture, (C) hypocrystalline texture, and (D) ophitic and subophytic texture.



**Figure 19.** Photomicrographs showing the venules of the FP samples: (A) venule of calcite, epidote, and chloritoid; (B) serpentine; (C) venule of calcite and epidote; and (D) venule of rutile, chloritoid, epidote, biotite, and quartz.



Figure 20. Photomicrograph showing the chloritite from the FP.

Nevertheless, these samples were used in this study, although special attention was given to them with regard to detecting possible discrepancies. An estimate of the quality of the analyses used in this study was made by calculating the coefficients of variation (coefficient of variation = standard deviation/ mean) (Table 2).

High values of coefficients of variation are indicative of:

• Analytical error (this can be tested with precision and accuracy data);

- Alteration (this can be tested by checking LOI values and variations in incompatible immobile trace elements; e.g., Y, Zr, and Nb);
- Existence of more than one magmatic suite.

Relatively high values observed for other elements (e.g., Ce = 1.04, La = 1.05, Nb = 1.01, Sn = 1.13, Th = 1.04, As = 1.19, Bi = 1.84, and TI = 1.55; Table 2) may be due to the concentrations very close to the detection limits of the analytical instruments.

#### Rock classification

The series discrimination diagram used in this study (Fig. 21) was the TAS (Total Alkalis ' Silica; Irvine and Baragar 1971).

The mafic rock samples of both the FP and the FIC characterize a subalkaline series (Fig. 21).

The basalts studied from the FIC and FP, considering the curve of Kuno (1966) and the curve of Irvine and Baragar (1971), are characterized as a calc-alkaline transitional series (Fig. 22). It is important to highlight that two samples are plotted in the tholeiitic series. It is important to point out that these two samples (SSD-FD00932-AM02, SSD-FD01027-AM02, and SSD-FD00831-AM02) were classified according to the petrography as chloritites. These rocks present a high LOI and are also altered.

	FORMATION	-				-		ARAUAPEBA	S	-	-	× 11		
	ASSAY/ SAMPLE	SSD- FD00931- AM03	SSD- FD01027- AM02	SSD- FD00831- AM04	SSD- FD00932- AM01	SSD- FD00831- AM03	SSD- FD00612- AM03	SSD- FD00612- AM04	SSD- FD00932- AM02	SSD- FD01027- AM01	SSD- FD00612- AM06	SSD- FD00931- AM02	SSD- FD00612- AM07	SSD- FD00831- AM02
	SiO,	47	49	49.1	49.2	49.5	51.2	51.6	53.2	53.3	53.8	53.8	53.9	55.5
	TiO	0.74	0.85	0.86	1.22	0.83	0.83	0.81	1.02	0.82	0.85	0.8	0.8	0.79
	Al <sub>2</sub> O <sub>3</sub>	12.65	13.2	13.8	14.7	14.3	14.8	14.45	13.65	13.15	13.65	13.05	13.55	13.85
	$Fe_2O_3$	12.1	17.55	20.4	15.5	14.95	13.35	13.2	12.85	16.9	13.4	12.3	12.5	13.2
	MgO	5.9	4.9	8.16	6.2	5.99	7.64	7.66	6.33	5.54	5.97	5.47	5.51	6.31
	MnO	0.26	0.14	0.18	0.28	0.14	0.13	0.13	0.19	0.05	0.21	0.22	0.19	0.13
	CaO	10.1	4.98	0.99	8.61	2.42	2.94	2.44	5.2	0.44	5.02	7.18	5.56	1.91
	$Na_2O$	1.61	0.78	0.41	2.21	3.13	1.51	1.35	3.69	1.5	3.47	2.46	3.53	2.95
	K <sub>2</sub> 0	1.67	2.13	0.67	1.92	1.88	3.12	3.34	0.4	3.97	1.23	1.06	1.69	2.33
Bio     012     007     003     007     003     007     003     003     003     004     003       Cry0     001     0001     0010     0011     0003     0017     003     00	P <sub>2</sub> O,	0.08	0.1	0.09	0.1	0.09	0.08	0.11	0.08	0.1	0.08	0.1	0.09	0.06
	BaO	0.12	0.07	0.02	0.07	0.03	0.07	0.07	0.01	0.05	0.03	0.03	0.04	0.05
5400010010010010010010010010010010010010010010011017.797.765.98195.943.953.612.863.473.1510.379.333.53100100101710710660190.910.9659.819.953.612.863.612.923.639.910.039.939.33Rb29234519.66765.729.6110.6691.1110.1149137.59.00Rb2923.6611717.953.327.670.610.697.110.119.137.339.69Rb2922.661.171.751.691.741.731.873.02.143.133.739.69Rf2.522.661.352.6317.41.731.873.02.142.132.333.65Y2.043.151.741.731.873.02.142.171.991.373.63Y2.043.181.741.731.873.02.141.793.753.44Th3.181.671.631.741.731.873.02.142.171.373.28La0.110.351.411.731.411.731.411.731.411.751.951.61Th <th>Cr<sub>3</sub>O<sub>3</sub></th> <td>0.01</td> <td>0.009</td> <td>0.01</td> <td>0.025</td> <td>0.012</td> <td>0.019</td> <td>0.025</td> <td>0.007</td> <td>0.009</td> <td>0.017</td> <td>0.008</td> <td>0.02</td> <td>0.011</td>	Cr <sub>3</sub> O <sub>3</sub>	0.01	0.009	0.01	0.025	0.012	0.019	0.025	0.007	0.009	0.017	0.008	0.02	0.011
	SrO	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01
Total $100.04$ $101.37$ $100.67$ $101.96$ $99.21$ $99.65$ $98.81$ $99.5$ $99.3$ $100.89$ $100.63$ $99.73$ $100.62$ <b>B</b> $2922$ $345$ $1965$ $612$ $269$ $588$ $687$ $108$ $504$ $274$ $321$ $378$ $420$ <b>Sr</b> $9922$ $266$ $511$ $75$ $572$ $961$ $1006$ $9$ $101$ $49$ $1775$ $544$ <b>Zr</b> $82$ $106$ $103$ $87$ $98$ $99$ $100$ $125$ $104$ $107$ $99$ $99$ $509$ <b>Y</b> $204$ $32.5$ $133$ $253$ $174$ $178$ $18.7$ $30$ $214$ $177$ $544$ <b>Y</b> $204$ $32.5$ $133$ $263$ $174$ $178$ $18.7$ $30$ $214$ $107$ $99$ $99$ $92$ <b>H</b> $2.5$ $218$ $2.8$ $2.8$ $2.8$ $2.9$ $3.2$ $1064$ $177$ $544$ $325$ <b>Ga</b> $148$ $167$ $163$ $1775$ $169$ $107$ $99$ $92$ $26$ <b>H</b> $2.5$ $108$ $107$ $912$ $212$ $103$ $325$ $1064$ $107$ $99$ $92$ <b>Ga</b> $148$ $167$ $163$ $1775$ $169$ $107$ $209$ $215$ $106$ <b>H</b> $3.8$ $492$ $163$ $157$ $102$ $121$ $102$ $101$ $107$ $99$ $92$ <b>H</b> <th>LOI</th> <td>7.79</td> <td>7.66</td> <td>5.98</td> <td>1.9</td> <td>5.94</td> <td>3.95</td> <td>3.61</td> <td>2.86</td> <td>3.47</td> <td>3.15</td> <td>4.13</td> <td>2.33</td> <td>3.53</td>	LOI	7.79	7.66	5.98	1.9	5.94	3.95	3.61	2.86	3.47	3.15	4.13	2.33	3.53
Ba     1090     684     186.5     612     269     588     687     108     504     274     321     378     420       Rb     2922     34.5     19.6     76     57.2     96.1     106     9     131     33.3     69.9     33.2     69.9     33.2     69.9     33.2     69.9     33.2     69.9     33.2     69.9     33.2     69.9     33.2     69.9     33.2     69.9     33.2     69.9     33.4     23.5     19.4     137.5     54.4     33.5     69.9     33.2     767     61.9     69.7     33.2     76.7     99.9     101     19.9     137.5     54.4       T     2.04     13.5     16.3     17.4     17.8     18.7     30     21.4     20.9     21.5     25     19       Hf     2.5     2.8     2.8     2.8     5.8     2.8     2.8     2.6     11.5       Ga     14.1     3.5     16.9     16.9     16.9	Total	100.04	101.37	100.67	101.96	99.21	99.65	98.81	99.5	99.3	100.89	100.63	99.73	100.62
Rb $292$ $345$ $196$ $76$ $572$ $961$ $106$ $9$ $131$ $323$ $329$ $403$ $699$ Sr $992$ $266$ $51$ $1795$ $332$ $767$ $619$ $697$ $2111$ $101$ $149$ $1375$ $544$ Yr $204$ $32.5$ $133$ $263$ $174$ $178$ $87$ $99$ $99$ $197$ $53$ $544$ Yr $204$ $32.5$ $133$ $263$ $174$ $178$ $187$ $30$ $214$ $209$ $215$ $25$ $99$ Hf $2.5$ $248$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.6$ Th $0.4$ $0.5$ $0.4$ $0.4$ $0.4$ $0.5$ $0.5$ $0.6$ $0.4$ $0.5$ $0.4$ $0.5$ Ga $148$ $167$ $163$ $175$ $169$ $165$ $155$ $161$ $167$ $163$ $157$ $0.24$ $0.24$ $0.5$ C $0.11$ $0.35$ $0.36$ $0.24$ $0.25$ $117$ $1.09$ $0.6$ $0.4$ $0.5$ $0.4$ $0.5$ U $10.8$ $1.38$ $1.22$ $0.24$ $0.24$ $0.24$ $0.24$ $0.24$ $0.24$ $0.24$ U $10.0$ $1.03$ $0.24$ $3.21$ $2.13$ $2.13$ $2.13$ $1.11$ $1.33$ $1.76$ $1.15$ U $10.0$ $1.03$ $1.23$ $2.24$ $3.23$ $2.24$ $3.24$	Ba	1090	684	186.5	612	269	588	687	108	504	274	321	378	420
Sr     99.2     266     51     179.5     33.2     76.7     61.9     69.7     21.1     101     149     137.5     544       Zr     82     106     103     87     98     99     100     125     104     107     99     99     92       T     0.4     0.5     0.4     0.4     0.3     17.4     17.8     18.7     30     21.4     20.9     99     99     99     92     93     94     93     94     95     94     95     94     95     94     107     99     99     90     90     91     91     93     34     21     23     23     34     23     23     35     93     95     94     95     95     95     95     95     95     96     97     90     90     90     90     95     93     95     94     97     96     97     96       T1      T1<	Rb	29.2	34.5	19.6	76	57.2	96.1	106	6	131	32.3	32.9	40.3	6.69
Zr8210610387989910012510410799999992Y2043251352631741781873021420921.5252826Hf2.52.82.82.6317417.818.73021.420921.52.82.82.9Ga14816716316.915.516.116.915.516.116.915.315.32.82.82.82.6Ga14816.716.317.516.915.516.11.90.051.40.50.40.5Co1103.884.924.930.754.774.794.895.694.824.994.774.64.79U1.081.381.220.231.011.561.532.121.391.411.351.761.15U2.412.512.343.37 $2.42$ 2.343.38 $2.36$ $4.77$ $4.6$ $4.79$ V2.412.512.312.332.121.151.391.411.351.761.15U3.88 $4.92$ $4.72$ $5.92$ $4.73$ $6.92$ $4.73$ $6.92$ $4.73$ $6.92$ $4.79$ V2.412.512.312.322.322.322.322.352.36 $2.36$ $2.36$ $2.36$ <th>Sr</th> <td>99.2</td> <td>26.6</td> <td>5.1</td> <td>179.5</td> <td>33.2</td> <td>76.7</td> <td>61.9</td> <td>69.7</td> <td>21.1</td> <td>101</td> <td>149</td> <td>137.5</td> <td>54.4</td>	Sr	99.2	26.6	5.1	179.5	33.2	76.7	61.9	69.7	21.1	101	149	137.5	54.4
Y $204$ $3.5$ $13.5$ $263$ $17.4$ $17.8$ $18.7$ $30$ $21.4$ $209$ $21.5$ $25$ $19$ Hf $2.5$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.8$ $2.6$ Ta $0.4$ $0.5$ $0.4$ $0.4$ $0.4$ $0.4$ $0.5$ $0.6$ $0.4$ $0.5$ $0.4$ $0.5$ Ga $14.8$ $16.7$ $16.3$ $17.5$ $16.9$ $16.9$ $15.5$ $16.1$ $16.9$ $15.2$ $15.9$ $16.3$ $16.7$ Th $3.38$ $4.92$ $4.93$ $0.75$ $4.77$ $4.79$ $4.89$ $5.69$ $4.82$ $4.99$ $4.77$ $4.79$ U $1.08$ $1.38$ $1.22$ $0.24$ $0.92$ $1.17$ $1.09$ $0.05$ $1.48$ $1.35$ $1.76$ $1.15$ U $2.41$ $2.51$ $2.24$ $32.12$ $1.99$ $4.82$ $4.99$ $4.77$ $4.79$ $4.79$ V $2.41$ $2.51$ $2.24$ $32.12$ $1.99$ $1.41$ $1.35$ $1.76$ $1.15$ V $2.41$ $2.51$ $2.24$ $32.12$ $1.39$ $1.44$ $1.35$ $1.76$ $1.15$ V $2.41$ $2.51$ $2.24$ $3.28$ $2.62$ $2.43$ $2.62$ $2.43$ $2.66$ V $2.41$ $2.51$ $2.54$ $3.93$ $2.42$ $2.43$ $2.66$ $1.15$ V $2.41$ $3.5$ $4.44$ $4.3$ $4.4$ $4.3$ <th>Zr</th> <td>82</td> <td>106</td> <td>103</td> <td>87</td> <td>98</td> <td>66</td> <td>100</td> <td>125</td> <td>104</td> <td>107</td> <td>66</td> <td>66</td> <td>92</td>	Zr	82	106	103	87	98	66	100	125	104	107	66	66	92
Hf $2.5$ $2.8$ $2.8$ $2.8$ $2.8$ $2.9$ $3$ $3.4$ $2.8$ $2.8$ $2.8$ $2.6$ Ta $0.4$ $0.5$ $0.4$ $0.4$ $0.4$ $0.5$ $0.6$ $0.4$ $0.5$ U $1.08$ $1.12$ $0.22$ $1.01$ $1.56$ $1.53$ $2.122$ $1.53$ $1.61$ $1.53$ $1.25$ $0.27$ $0.38$ $0.96$ V $2.11$ $2.51$ $2.54$ $2.92$ $4.73$ $3.78$ $3.79$ $4.48$ $5.39$ $5.44$ $4.73$ $2.43$ $2.26$ V $2.11$ $2.11$ $2.122$ $2.24$ $2.34$ $2.32$ $2.43$ $2.354$ $5.04$ V $3.5$ $4.44$ $4.3$ $3.37$ $4.48$ $5.39$ $5.4$ $4.43$ $7.3$	Y	20.4	32.5	13.5	26.3	17.4	17.8	18.7	30	21.4	20.9	21.5	25	19
Ta $0.4$ $0.5$ $0.4$ $0.4$ $0.6$ $0.4$ $0.5$ $0.6$ $0.4$ $0.5$ $0.4$ $0.5$ Ga $14.8$ $16.7$ $16.3$ $17.5$ $16.9$ $16.9$ $15.5$ $16.1$ $16.9$ $15.2$ $15.9$ $16.3$ $15$ Cs $0.11$ $0.35$ $0.36$ $0.24$ $0.92$ $1.17$ $1.09$ $0.05$ $1.58$ $0.37$ $0.27$ $0.38$ $0.96$ Th $3.88$ $4.92$ $4.92$ $4.77$ $4.77$ $4.79$ $4.89$ $5.69$ $4.82$ $4.99$ $4.77$ $4.6$ $4.79$ U $1.08$ $1.38$ $1.22$ $0.23$ $1.01$ $1.56$ $1.53$ $2.12$ $1.39$ $1.41$ $1.35$ $1.76$ $1.15$ V $241$ $251$ $254$ $321$ $238$ $242$ $254$ $308$ $258$ $262$ $250$ $243$ $226$ V $241$ $251$ $224$ $321$ $238$ $242$ $254$ $308$ $258$ $262$ $250$ $243$ $226$ V $35$ $4.4$ $4.3$ $4$ $4.1$ $4.4$ $4.8$ $53.9$ $54$ $453$ $554$ $504$ Wb $3.5$ $4.4$ $4.3$ $3.7$ $4.4$ $4.8$ $5.3$ $4.7$ $4.7$ $4.7$ $7.3$ Wb $3.5$ $4.4$ $4.3$ $5.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$ $2.2$	Hf	2.5	2.8	2.8	2.5	2.8	2.9	3	3.4	2.8	2.8	2.8	2.8	2.6
Ga14.816.716.317.516.916.915.516.116.915.215.916.315Cs0.110.350.360.240.921.171.090.051.580.370.270.380.96Th3.884.924.930.754.774.794.895.694.824.994.774.64.79U1.081.381.220.231.011.561.532.121.391.411.351.761.15V241251224321238242254308258262250243226V24125122432123824223737.837.944.853.95445.356.450.4V2412512243015070100601411.351.761.15V241251224337.837.944.853.95450.456.4Nb354.44.344.14.44.85.34.54.74.47.3Mb354.44.344.14.44.85.34.74.74.47.3Mb35555552222232Mb1255555554.74.4	Ta	0.4	0.5	0.4	0.4	0.4	0.5	0.5	0.6	0.4	0.5	0.5	0.4	0.5
Cs0.110.350.360.240.921.171.090.051.580.370.270.380.96Th3.884.924.930.754.774.794.895.694.824.994.774.64.79U1.081.381.220.231.011.561.532.121.391.411.351.761.15V241251224321238242254308258262250243256Co $42.6$ 49.2473321238242254308258262250243256Co $42.6$ 49.247.259.245.337.837.944.853.95445.356.476Ch8060601909015019050701006014080Mb3.54.44.344.14.44.85.34.54.74.77.3Mo222222222334.54.74.77.3Mb3.54.44.334.44.85.34.54.74.47.3Mb3.555522222232Mb125555522232	Ga	14.8	16.7	16.3	17.5	16.9	16.9	15.5	16.1	16.9	15.2	15.9	16.3	15
Th $3.88$ $4.92$ $4.93$ $0.75$ $4.77$ $4.79$ $4.89$ $5.69$ $4.82$ $4.99$ $4.77$ $4.6$ $4.79$ U $1.08$ $1.38$ $1.22$ $0.23$ $1.01$ $1.56$ $1.53$ $2.12$ $1.39$ $1.41$ $1.35$ $1.76$ $1.15$ V $241$ $251$ $224$ $321$ $238$ $242$ $254$ $308$ $258$ $262$ $250$ $243$ $226$ Co $42.6$ $492$ $47.2$ $592$ $45.3$ $37.8$ $37.9$ $44.8$ $53.9$ $54$ $45.3$ $55.4$ $50.4$ Co $80$ $60$ $60$ $190$ $90$ $150$ $190$ $50$ $70$ $100$ $60$ $140$ $80$ Nb $3.5$ $4.4$ $4.3$ $4$ $4.1$ $4.4$ $4.8$ $5.3$ $4.5$ $4.7$ $4.7$ $50.4$ Nb $3.5$ $4.4$ $4.3$ $4.7$ $4.8$ $5.3$ $4.5$ $4.7$ $4.7$ $50.4$ Nb $3.5$ $4.4$ $4.3$ $4.4$ $4.8$ $5.3$ $4.5$ $4.7$ $4.7$ $50.4$ Nb $3.5$ $4.4$ $4.3$ $4.4$ $4.8$ $5.3$ $4.5$ $4.7$ $4.7$ $5.4$ $5.6$ Nb $3.5$ $4.4$ $4.8$ $5.3$ $4.5$ $4.7$ $4.3$ $4.4$ $7.3$ Nb $12$ $5$ $5$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ </th <th>Cs</th> <td>0.11</td> <td>0.35</td> <td>0.36</td> <td>0.24</td> <td>0.92</td> <td>1.17</td> <td>1.09</td> <td>0.05</td> <td>1.58</td> <td>0.37</td> <td>0.27</td> <td>0.38</td> <td>0.96</td>	Cs	0.11	0.35	0.36	0.24	0.92	1.17	1.09	0.05	1.58	0.37	0.27	0.38	0.96
U1.081.381.220.231.011.561.532.121.391.411.351.761.15V241251224321238242242254308258262250243226Co42.649.247.259.245.337.837.944.853.95445.3266Cr8060601909015019050701006014080Nb3.54.44.344.14.44.85.34.54.74.34.47.3Mo2222222222234.54.74.7 $7.3$ Mo222222222223 $7.3$ $7.3$ Mo125591 $4.4$ $4.8$ $5.3$ $4.5$ $4.7$ $4.3$ $4.4$ $7.3$ Mo2222222223 $3.5$ $4.5$ $4.7$ $4.7$ $4.7$ $4.7$ $7.3$ Mo22222222223 $3.5$ $4.7$ $4.7$ $4.7$ $4.7$ $7.3$ Mo125552222223 $3.5$ $5.5$ $3.5$ $3$	П	3.88	4.92	4.93	0.75	4.77	4.79	4.89	5.69	4.82	4.99	4.77	4.6	4.79
V $241$ $251$ $224$ $321$ $238$ $242$ $254$ $308$ $258$ $262$ $250$ $243$ $226$ Co $42.6$ $49.2$ $47.2$ $59.2$ $45.3$ $37.8$ $37.9$ $44.8$ $53.9$ $54$ $45.3$ $55.4$ $50.4$ Cr $80$ $60$ $60$ $190$ $90$ $150$ $190$ $50$ $70$ $100$ $60$ $140$ $80$ Nb $3.5$ $4.4$ $4.3$ $4$ $4.1$ $4.4$ $4.8$ $5.3$ $4.5$ $4.7$ $4.3$ $4.4$ $7.3$ Mo $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $3$ $4.7$ $4.7$ $3.6$ Nb $3.5$ $4.4$ $4.3$ $4.4$ $4.8$ $5.3$ $4.5$ $4.7$ $4.4$ $7.3$ Mo $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $3$ $3.4.5$ $4.7$ $3.4.4$ $7.3$ Mo $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $3$ $3.4.5$ $4.7$ $3.4.4$ $7.3$ Mo $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $3$ $3.4.5$ $4.7$ $4.3$ $4.4$ $7.3$ Mo $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $2$ $3$ $2$ $3$ $3.4.4$ $7.3$ Mo $11$	U	1.08	1.38	1.22	0.23	1.01	1.56	1.53	2.12	1.39	1.41	1.35	1.76	1.15
Co     42.6     49.2     47.2     59.2     45.3     37.8     37.9     44.8     53.9     54     45.3     56.4     50.4       Cr     80     60     60     190     90     150     190     50     70     100     60     140     80       Nb     3.5     4.4     4.3     4     4.1     4.4     4.8     5.3     4.5     4.7     4.3     4.4     7.3       Mo     2     2     2     2     2     2     2     3     4.5     4.7     4.3     4.4     7.3       Mo     2     2     2     2     2     2     3     2     3     2       Pb     12     5     5     5     5     7     5     3     2     5	V	241	251	224	321	238	242	254	308	258	262	250	243	226
Cr     80     60     60     190     50     70     100     60     140     80       Nb     3.5     4.4     4.3     4     4.1     4.4     4.8     5.3     4.5     4.7     4.3     4.4     7.3       Mo     2     2     2     2     2     2     2     2     3     4.5     4.7     4.3     4.4     7.3       Mo     2     2     2     2     2     2     2     3     4.5     4.7     4.3     4.4     7.3       Mo     2     2     2     2     2     2     2     3     2     3     2     3     2     3     2     2     3     2     3     2     3     2     3     2     3     2     3     2     3     2     3     2     3     2     3     2     3     2     3     3     2     3     2     3     2 <th>Co</th> <td>42.6</td> <td>49.2</td> <td>47.2</td> <td>59.2</td> <td>45.3</td> <td>37.8</td> <td>37.9</td> <td>44.8</td> <td>53.9</td> <td>54</td> <td>45.3</td> <td>55.4</td> <td>50.4</td>	Co	42.6	49.2	47.2	59.2	45.3	37.8	37.9	44.8	53.9	54	45.3	55.4	50.4
Nb     3.5     4.4     4.3     4     4.1     4.4     4.8     5.3     4.5     4.7     4.3     4.4     7.3       Mo     2     2     2     2     2     2     2     4.5     4.7     4.3     4.4     7.3       Mo     2     2     2     2     2     2     2     3     2       Pb     12     5     5     5     5     7     5	C.	80	60	60	190	90	150	190	50	70	100	60	140	80
Mo     2     2     2     2     2     2     2     3     2       Pb     12     5     5     9     5     5     7     5     2     2     3     2       Sn     1     3     1     1     3     2     2     3     2     3     2	Nb	3.5	4.4	4.3	4	4.1	4.4	4.8	5.3	4.5	4.7	4.3	4.4	7.3
Pb     12     5     5     9     5     5     5     7     5     5     10     5     1     1     1	Мо	2	2	2	2	2	2	2	2	2	2	2	ю	2
Sn     1     3     1     1     3     2     2     1     14     2     2     1	Pb	12	5	5	6	5	S	5	7	5	5	10	S	5
	Sn	1	3	1	1	3	2	2	1	14	2	2	2	1

Braz. J. Geol. (2023), **53**(2): e20220053

	Table 1. Ccontir       FORMATION	uation.						ARAUAPEBA						
	ASSAY/ SAMPLE	SSD- FD00931- AM03	SSD- FD01027- AM02	SSD- FD00831- AM04	SSD- FD00932- AM01	SSD- FD00831- AM03	SSD- FD00612- AM03	SSD- FD00612- AM04	SSD- FD00932- AM02	SSD- FD01027- AM01	SSD- FD00612- AM06	SSD- FD00931- AM02	SSD- FD00612- AM07	SSD- FD00831- AM02
W2433 <th< th=""><th>TI</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th><th>0.5</th></th<>	TI	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	W	2	4	ŝ	ŝ	ŝ	ŝ	ŝ	c,	e,	2	2	2	2
	Zn	169	42	119	140	78	126	144	173	40	131	199	109	66
C28.657.51014.421126.738.457.433.456.936.928.3N1125.81172112.637.431.537.737.637.637.637.637.3N1125.81090.331.332.533.063.015.2.53.063.015.3.32.593.7.63.7.73.7.73.7.63.7.13.7.83.7.3N110.51.110.130.231.140.330.561.132.2.63.015.3.32.593.7.63.7.73.7.73.7.73.7.73.7.73.7.73.7.83.7.83.7.7N0.731.110.730.410.330.7.70.470.430.7.70.470.470.47N0.731.110.730.410.330.350.7.70.370.373.7.73	La	14.5	30.1	4.6	5.9	10.3	13.4	13.2	24.5	13.9	16.1	16.2	19	16.3
	Ce	28.6	57.5	10	14.4	22.1	29.7	28.8	49.4	28.4	32.4	33.4	36.9	28.2
Mit $127$ $256$ $46$ $98$ $103$ $142$ $131$ $226$ $131$ $236$ $144$ $158$ $153$ $145$ $145$ Ru $111$ $128$ $129$ $233$ $233$ $233$ $233$ $233$ $236$ $213$ $236$ $213$ $236$ $231$ $236$ <	Pr	3.32	6.72	1.17	2.11	2.6	3.74	3.45	5.7	3.25	3.79	3.76	4.14	3.53
Mot311544109303225346301533295346336331295Ho3135491031140.681140.681140.681140.691150.970.770.941110.47Th0.661010.281041030.70.690.770.940.710.940.710.47Th0.661010.280.770.970.930.660.630.650.630.740.470.47Th0.661010.280.770.941030.770.930.770.930.710.470.47Th0.351110.441732.930.470.331362.030.330.360.340.410.35Th0.350.440.310.360.330.460.330.360.330.440.31Th0.330.440.330.330.360.330.360.330.360.330.440.31Th0.330.440.310.330.330.330.330.330.330.330.340.330.340.33Th0.330.440.310.330.330.330.330.330.330.330.340.330.340.33Th0.330.340.300030.000030.000030.000030.000030	PN	12.7	25.6	4.6	9.8	10.5	14.2	13.1	22.6	12.5	14.6	14.4	15.8	14.5
He1121490.331140.681410.911.550.770.941.210.757 $\mathbf{D}$ 0.531.914.552.733.163.163.163.150.770.941.210.757 $\mathbf{D}$ 0.531.110.441.030.730.553.210.603.750.720.970.730.830.413.5670.731.914.653.113.563.210.500.770.350.413.564.413.6670.330.440.290.450.310.360.320.410.350.330.410.3570.330.440.290.450.310.360.320.410.350.340.340.3680.000130.000140.000110.00030.000110.00030.000010.000030.000030.000030.000030.000030.000030.0000390.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.0000390.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.0000390.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.0	Sm	3.11	5.84	1.09	3.03	2.25	3.06	3.01	5.23	2.95	3.45	3.36	3.81	2.95
	Eu	1.2	1.49	0.28	1.14	0.68	1.41	0.91	1.55	0.97	0.77	0.94	1.21	0.75
Tb161010.280.720.470.580.510.530.510.530.710.47Dy3755.541.910.441.030.70.530.510.530.710.440.43He0.733.041.752.931.982.012.223.022.332.382.42.641.13He2.390.440.290.450.330.350.320.350.330.350.340.410.35He2.390.440.340.420.330.350.372.332.382.42.641.13Me0.000130.000140.000110.000110.000110.000110.000130.000030.000030.000010.00013He0.000130.000010.000010.000010.000010.000010.000030.000030.000030.000030.00003He0.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.00003He0.000030.000030.000030.000030.000030.000030.000030.000030.000030.000030.00003He0.000030.000030.000030.000030.000030.000030.000030.000030.000030.00003He0.000030.000030.000030.000030.000030.000030.000030.000030.000030.00003 <th>Gd</th> <th>3.33</th> <th>5.98</th> <th>1.53</th> <th>4.26</th> <th>2.78</th> <th>3.16</th> <th>3.16</th> <th>6.4</th> <th>3.48</th> <th>3.72</th> <th>3.7</th> <th>4.29</th> <th>3.62</th>	Gd	3.33	5.98	1.53	4.26	2.78	3.16	3.16	6.4	3.48	3.72	3.7	4.29	3.62
	Tb	0.6	1.01	0.28	0.72	0.47	0.58	0.51	0.95	0.6	0.63	0.58	0.71	0.47
Ho $0.75$ 1.11 $0.44$ $1.03$ $0.7$ $0.69$ $0.72$ $1.03$ $0.82$ $0.94$ $0.64$ Fr $0.33$ $0.44$ $1.75$ $2.93$ $1.98$ $2.01$ $2.22$ $3.02$ $2.38$ $2.44$ $2.64$ $1.35$ Th $0.33$ $0.44$ $1.75$ $0.33$ $0.31$ $0.23$ $0.33$ $0.32$ $0.33$ $0.34$ $0.32$ $0.32$ $0.34$ $0.32$ $0.32$ $0.31$ $0.32$ $0.33$ $0.34$ $0.33$ $0.32$ $0.33$	Dy	3.75	5.54	1.91	4.65	3.1	3.56	3.27	6.02	3.82	4.01	3.65	4.41	3.08
H2193041752931982012.223.022.332.382.42.641.85Tm $0.38$ $0.44$ $0.29$ $0.45$ $0.31$ $0.35$ $0.32$ $0.41$ $0.35$ $0.38$ $0.44$ $0.31$ Lm $0.38$ $0.44$ $0.29$ $0.45$ $0.31$ $2.27$ $2.86$ $2.37$ $2.34$ $2.54$ $1.85$ Lm $0.38$ $0.0004$ $0.00011$ $0.0005$ $0.00007$ $0.00005$ $0.00007$ $0.00019$ $0.00019$ $0.00019$ $0.00019$ H $0.00005$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00019$ $0.00019$ H $0.000015$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ H $0.000015$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ H $0.000015$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ H $0.000015$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ H $0.000015$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ H $0.000015$ $0.000015$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ $0.00007$ H $0.00001$ $0.000015$ $0.000015$ $0.00007$ $0.00007$ $0.00007$	Но	0.75	1.11	0.44	1.03	0.7	0.69	0.72	1.09	0.77	0.82	0.82	0.94	0.64
Th $0.38$ $0.44$ $0.29$ $0.45$ $0.31$ $0.36$ $0.32$ $0.41$ $0.35$ $0.38$ $0.38$ $0.44$ $0.31$ Th $2.39$ $3.08$ $2.06$ $2.77$ $1.93$ $2.31$ $2.27$ $2.86$ $2.37$ $2.34$ $2.56$ $1.91$ Th $0.00018$ $0.00014$ $0.0011$ $0.0003$ $0.00014$ $0.00011$ $0.00019$ $0.000019$ <	Er	2.19	3.04	1.75	2.93	1.98	2.01	2.22	3.02	2.3	2.38	2.4	2.64	1.85
Yh $2.39$ $3.08$ $2.06$ $2.77$ $1.93$ $2.31$ $2.27$ $2.86$ $2.37$ $2.23$ $2.34$ $2.56$ $1.91$ As $0.00016$ $0.00014$ $0.0001$ $0.00013$ $0.00013$ $0.00013$ $0.00014$ $0.00014$ $0.00013$ $0.00003$ He $0.000166$ $0.000046$ $0.000016$ $0.000016$ $0.000016$ $0.000014$ $0.000014$ $0.000019$ $0.000019$ He $0.000005$ $0.000007$ $0.000005$ $0.000005$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ He $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ Se $0.00003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ $0.000003$ He $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ Se $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ $0.00003$ Ag $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ Ag $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.00003$ Ag $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ $0.5$ <th>Tm</th> <td>0.38</td> <td>0.44</td> <td>0.29</td> <td>0.45</td> <td>0.31</td> <td>0.36</td> <td>0.32</td> <td>0.41</td> <td>0.35</td> <td>0.38</td> <td>0.38</td> <td>0.4</td> <td>0.31</td>	Tm	0.38	0.44	0.29	0.45	0.31	0.36	0.32	0.41	0.35	0.38	0.38	0.4	0.31
	Yb	2.39	3.08	2.06	2.77	1.93	2.31	2.27	2.86	2.37	2.22	2.34	2.56	1.91
As $0.00018$ $0.00014$ $0.00011$ $0.00013$ $0.00013$ $0.00013$ $0.00013$ $0.00013$ $0.00013$ $0.00013$ $0.00013$ $0.00013$ $0.00003$ $0$	Lu	0.3	0.4	0.34	0.42	0.28	0.33	0.28	0.36	0.32	0.32	0.34	0.32	0.27
Hi $0.000006$ $0.00004$ $0.00004$ $0.00003$ $0.00004$ $0.00003$ $0.00004$ $0.00003$ $0.00004$ $0.00003$	As	0.00018	0.00004	0.00011	0.0005	0.00005	0.00011	0.0000	0.00021	0.00005	0.00004	0.00029	0.00019	0.00015
Hg0.00000050.000005	Bi	0.000006	0.000004	0.000003	0.000007	0.000002	0.000007	0.000006	0.000004	0.000001	0.000003	0.000004	0.00001	0.000009
No     0.00005     0.	Hg	0.0000005	0.0000005	0.0000006	0.0000005	0.0000005	0.0000005	0.0000005	0.0000005	0.0000005	0.0000005	0.0000005	0.0000005	0.0000005
Ke     0.0003     0.0004     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0003     0.0004     0.0003 <th>Sb</th> <th>0.000005</th> <th>0.000005</th> <th>0.000005</th> <th>0.000015</th> <th>0.000005</th> <th>0.000005</th> <th>0.000005</th> <th>0.00001</th> <th>0.000005</th> <th>0.000008</th> <th>0.000006</th> <th>0.00000</th> <th>0.000008</th>	Sb	0.000005	0.000005	0.000005	0.000015	0.000005	0.000005	0.000005	0.00001	0.000005	0.000008	0.000006	0.00000	0.000008
TI $0.000002$ $0.000004$ $0.000002$ $0.000014$ Cu $25$ $0.$	Se	0.00003	0.00004	0.00003	0.00005	0.00004	0.00004	0.00003	0.00003	0.00003	0.00002	0.00005	0.00004	0.00003
Ag $0.5$ $0$	Ш	0.000002	0.000003	0.000004	0.000002	0.00001	0.00004	0.000043	0.000002	0.000019	0.000008	0.000002	0.00008	0.000014
Cd0.5	Ag	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Co41554753463940466150435452Cu251446124613188428026122105221Li202020202020202010101010Mo11111111111Ni71748190787981598075668080Ni71748190787981598075668080Ni71748190787981598075668080Sc33393333363642413436353537Li15153510712765123138168301161799597	Cd	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Cu251446124613188428026122105221Li202020202020202020101010Mo111111111111Ni7171748190787981598075668080Ni71748190787981598075668080Pb1122210102429336363636363636Sc333933393636133168301161793739Sa151515157153138168301161799590	Co	41	55	47	53	46	39	40	46	61	50	43	54	52
Ii     20     20     20     20     10	Cu	25	144	9	124	6	13	18	84	280	26	122	105	221
Mo     1	Li	20	20	20	20	10	20	20	20	20	10	10	10	10
Ni     71     74     81     90     78     79     81     59     80     75     66     80<	Мо	1	1	1	1	1	1	1	1	1	1	1	1	1
Pb     11     2     2     10     2     4     2     9     2     3     10     3     2     2       Sc     33     39     33     39     36     36     42     41     34     36     35     34       Zn     155     35     107     127     65     123     138     168     30     116     179     95     90	Ni	71	74	81	06	78	79	81	59	80	75	66	80	80
Sc     33     39     36     36     42     41     34     36     35     34     34     35     35     34     34     36     35     34     34     36     35     34     34     36     35     34     34     36     35     34     34     34     36     35     34     34     36     35     34     34     36     35     34     34     34     36     35     34     34     36     35     34     34     36     35     34     36     36     36     36     30     316     179     35     34     30     36     36     30     36     36     30     36     36     30     36     36     30     36     36     36     30     36     36     30     36     36     30     36     36     30     36     36     30     36     36     30     36     36     30     3	Pb	11	2	2	10	2	4	2	6	2	ŝ	10	Э	2
Zn     155     35     107     127     65     123     138     168     30     116     179     95     90	Sc	33	39	33	39	36	36	42	41	34	36	35	35	34
	Zn	155	35	107	127	65	123	138	168	30	116	179	95	06

Table 1. (	Continue
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FORMATION				IGARAPÉ	CIGARRA			
	SSD-							
ASSAY/	FD01059-	FD01009-	FD01009-	FD01009-	FD01008-	FD01059-	FD01008-	FD01058-
SAMPLE	AM02	AM02	AM01	AM03	AM01	AM01	AM02	AM01
SiO <sub>2</sub>	51	53	53.3	53.9	54	54.3	55	56.4
TiO <sub>2</sub>	0.46	0.48	0.46	0.48	0.51	0.48	0.52	0.64
Al <sub>2</sub> O <sub>3</sub>	14.35	14.9	15.1	14.4	14.95	14.8	15.05	14.65
Fe <sub>2</sub> O <sub>3</sub>	9.19	10.85	11.2	11.05	9.39	9.19	9.37	10.1
MgO	6.04	5.56	5.81	6.98	5.69	6.2	6.04	5.07
MnO	0.23	0.21	0.24	0.17	0.14	0.2	0.15	0.21
CaO	7.47	4.19	5.19	6.84	7.4	8.21	7.58	7.81
Na <sub>2</sub> O	2.02	3.17	3.33	4.05	2.55	2.71	2.65	2.16
K <sub>2</sub> O	3.25	2.04	2.08	1.2	1.81	2.35	1.82	1.99
$P_2O_5$	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.1
BaO	0.13	0.1	0.13	0.03	0.05	0.1	0.15	0.06
Cr <sub>2</sub> O <sub>3</sub>	0.012	0.002	0.002	0.012	0.014	0.007	0.012	0.005
SrO	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.03
LOI	4.72	3.85	2.91	2.32	2.16	2.15	2.2	1.58
Total	98.96	98.44	99.84	101.52	98.76	100.8	100.64	100.81
Ba	1185	872	1230	329	518	880	1300	614
Rb	96.8	55.4	51.8	24.1	90	60.1	81.6	73.9
Sr	154	154	170	133	194	212	219	226
Zr	66	66	67	69	75	67	75	97
Y	11.3	13.2	12.7	13.5	12.4	11.7	12.5	16
Hf	1.7	1.7	1.7	1.6	1.9	1.8	1.9	2.5
Ta	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Ga	13.3	13.5	14	12.4	14.3	13.1	13.8	15.3
Cs	0.3	0.1	0.11	0.07	0.42	0.25	0.37	0.72
Th	3.16	3.08	3.17	3.37	3.58	3.27	3.63	4.33
U	0.71	0.66	0.78	0.83	0.82	0.81	0.78	1.11
V	157	162	181	159	173	170	174	198
Со	37.8	41.6	46	39.9	36.3	41.1	35.7	46.8
Cr	90	10	150	100	100	50	90	30
Nb	2.7	2.8	2.8	2.7	2.9	2.7	2.9	3.9
Мо	2	2	2	2	2	2	2	2
РЬ	6	5	5	5	5	5	5	5
Sn	1	1	1	1	1	1	1	1
Tl	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
W	1	1	2	1	2	1	2	2
Zn	114	210	163	107	70	134	72	204
La	12.1	12.6	12.3	17.2	12.9	12.2	13.3	17.6
Ce	25.5	21.9	23.8	35.1	27.9	26.2	27.8	36.2
Pr	2.9	2.72	2.79	3.99	3.23	2.93	3.21	4.12
Nd	10.8	10.9	11	15.4	12.3	11.9	12.2	15.2
Sm	1.89	1.87	1.93	2.92	2.16	2.27	2.24	2.83
Eu	0.75	0.51	0.57	2.35	0.61	0.56	0.6	0.86
Ga Th	2.22	2.35	2.22	3.22	2.17	2.1	2.37	3
10 D	0.33	0.33	0.30	0.48	0.35	0.29	0.34	0.45
Dy Ho	1.98	1.98	2	2.08	1.99	1.93	0.44	2.94
HU Fa	1.21	0.42	0.49	1.42	1.20	0.42	1.24	1.97
EI Tm	0.10	0.10	1.55	1.45	1.37	1.42	1.50	1.07
тш Vb	1.19	1 41	1.48	1.43	1.47	1.35	1.58	1 79
Lu	0.10	0.18	0.17	0.2	0.18	0.10	0.22	0.28
As	0.13	0.10	0.17	0.2	0.10	0.17	0.22	0.20
Ri	0.00008	0.00003	0.00003	0.00007	0.00044	0.00012	0.00091	0.00013
Ы	0.000012	0.000007	0.000007	0.000009	0.000000	0.000000	0.000007	0.000005
rig Sh	0.0000005	0.0000009	0.0000005	0.0000000	0.0000005	0.0000000	0.0000005	0.0000005
Se	0.000007	0.000003	0.000003	0.000007	0.000003	0.000003	0.000007	0.00004
TI	0.000002	0.000002	0.000002	0.000002	0.000002	0.000002	0.000002	0.000012

Continue...

Table 1. Continue

FORMATION				IGARAPÉ	CIGARRA			
ASSAY/ SAMPLE	SSD- FD01059- AM02	SSD- FD01009- AM02	SSD- FD01009- AM01	SSD- FD01009- AM03	SSD- FD01008- AM01	SSD- FD01059- AM01	SSD- FD01008- AM02	SSD- FD01058- AM01
Ag	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Cd	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Со	42	42	45	43	37	44	48	48
Cu	70	84	101	19	58	65	72	93
Li	20	20	10	10	10	10	20	10
Мо	1	1	1	1	1	1	1	1
Ni	81	78	59	70	74	73	91	50
Pb	8	2	3	2	4	5	4	2
Sc	30	31	32	29	32	32	37	33
Zn	116	203	161	111	63	138	80	203

**Table 2.** Maximum and minimum values, means, standard deviations, and coefficients of variation of oxides and elements of basalts ( $Fe_2O_3^{t}$  is total iron in the form of ferric iron; LOI is loss on fire; and n is the number of samples).

Element	Minimum	Maximum	Mean	Standard Deviation	Coefficient of variation	n
Al <sub>2</sub> O <sub>3</sub>	12.65	15.10	14.14	0.74	0.07	21
BaO	0.01	0.15	0.07	0.04	0.64	21
CaO	0.44	10.10	5.36	2.70	0.89	21
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.03	0.01	0.01	0.78	21
Fe <sub>2</sub> O <sub>3</sub>	9.19	20.40	12.79	2.98	0.26	21
K <sub>2</sub> O	0.40	3.97	2.00	0.88	0.46	21
MgO	4.90	8.16	6.14	0.84	0.56	21
MnO	0.05	0.28	0.18	0.05	0.64	21
Na <sub>2</sub> O	0.41	4.05	2.44	0.99	0.81	21
P <sub>2</sub> O <sub>5</sub>	0.06	0.11	0.09	0.01	0.27	21
SiO	47.00	56.40	52.43	2.49	0.11	21
SrO	0.01	0.03	0.02	0.01	0.41	21
TiO <sub>2</sub>	0.46	1.22	0.73	0.21	0.36	21
LOI	1.58	7.79	3.72	1.79	0.41	21
Total	98.44	101.96	100.10	0.99	0.01	21
Ba	108.00	1,300.00	621.40	353.90	0.60	21
Ce	10.00	57.50	29.72	10.30	1.04	21
Co	35.70	59.20	45.15	6.71	0.52	21
Cr	10.00	190.00	92.40	48.20	0.81	21
Cs	0.05	1.58	0.49	0.42	0.96	21
Dy	1.91	6.02	3.25	1.22	0.66	21
Er	1.31	3.04	2.01	0.58	0.61	21
Eu	0.28	2.35	0.96	0.47	0.68	21
Ga	12.40	17.50	15.22	1.47	0.15	21
Gd	1.53	6.40	3.29	1.22	0.74	21
Hf	1.60	3.40	2.44	0.54	0.92	21
Но	0.42	1.11	0.68	0.23	0.63	21
La	4.60	30.10	14.68	5.50	1.05	21
Lu	0.17	0.42	0.28	0.08	0.64	21
Мо	2.00	3.00	2.05	0.22	0.09	21
Nb	2.70	7.30	3.97	1.12	1.01	21
Nd	4.60	25.60	13.55	4.33	0.99	21
Pb	5.00	12.00	5.91	1.97	0.30	21
Pr	1.17	6.72	3.48	1.16	1.03	21
Rb	9.00	131.00	60.37	32.27	0.52	21
Sm	1.09	5.84	2.92	1.09	0.90	21
Sn	1.00	14.00	2.05	2.82	1.13	21
Sr	5.10	226.00	117.90	69.50	0.94	21
Ta	0.30	0.60	0.40	0.09	0.80	21
Tb	0.28	1.01	0.53	0.20	0.68	21
Th	0.75	5.69	4.10	1.09	1.04	21

Continue...

Table 2. Continution

Element	Minimum	Maximum	Mean	Standard Deviation	Coefficient of variation	n
Tl	0.50	0.50	0.50	_	-	21
Tm	0.19	0.45	0.31	0.09	0.59	21
U	0.23	2.12	1.13	0.43	0.88	21
V	157.00	321.00	223.40	47.80	0.61	21
W	1.00	4.00	2.24	0.83	0.61	21
Y	11.30	32.50	18.46	6.12	0.67	21
Yb	1.25	3.08	2.04	0.54	0.60	21
Zn	40.00	210.00	125.90	49.40	0.63	21
Zr	66.00	125.00	89.67	16.98	0.94	21
As	0.000030	0.000910	0.000182	0.000210	1.19	21
Bi	0.000001	0.000012	0.000006	0.000003	1.84	21
Hg	-	0.000001	0.000001	-	-	21
Sb	0.000005	0.000015	0.000007	0.000002	0.35	21
Se	0.000020	0.000050	0.000033	0.000009	0.33	21
Tl	0.000002	0.000043	0.000009	0.000012	1.55	21
Ag	0.5	0.5	0.5	-	-	21
Cd	0.5	0.6	0.5	0.021820	4.32	21
Co	37.0	61.0	46.5	6.0	12.92	21
Cu	6.0	280.0	82.7	70.2	84.94	21
Li	10.0	20.0	15.2	5.1	33.58	21
Мо	1.0	1.0	1.0	-	-	21
Ni	50.0	91.0	74.8	9.9	13.25	21
Pb	2.0	11.0	4.4	3.2	71.99	21
Sc	29.0	42.0	34.7	3.5	9.98	21
Zn	30.0	203.0	119.2	49.1	41.17	21



Figure 21. TAS series discrimination diagram (Irvine and Baragar 1971) for the basalts studied. Data recalculated to 100% on an anhydrous basis.

According to Ross and Bédard (2009), the rocks were classified as calc-alkaline magmatic affinity (Fig. 23).

The samples studied in this study were classified based on their chemical composition. The lithogeochemical classification was done on a TAS diagram (Lemaitre 1989). However, classification diagrams based on trace elements (Winchester and Floyd 1977, Pearce 1996, Stanley 2017) were also used in order to reduce the effects related to alteration processes. These rocks were classified as basalts, and esite-basalts, and basaltic trachyandesites (Fig. 24A).

## Evolutionary processes and mantle sources

In the lithogeochemical study of igneous rocks, one of the most important aspects to be noted is related to the evaluation of the elements' mobility in order to understand the effects of alteration processes (i.e., weathering, diagenesis, and hydrothermalism) on the original geochemical compositions. Zircon in igneous rocks is generally considered the most immobile element during hydrothermal alteration (Pearce and Cann 1973, Weaver and Tarney 1981, Sheraton *et al.* 1984, Li *et al.* 2008, Pearce 2014). Crustal contamination processes and magma mixing can interfere with the distribution of chemical elements, and these must be considered when assessing element mobility (Wilson 1989).

Elements of different geochemical behaviors, such as Nb, Hf, Ta, Y, Ce, Sm,  $\text{TiO}_2$ , Th, V, Rb, Sr, and Ba, were plotted against Zr to evaluate the mobility of these elements in samples from the **PF** and FIC (Fig. 25). In these, the high ionic potential elements (HFSEs, such as Nb and



**Figure 22.** AFM diagram of tholeiitic and calc-alkaline series discrimination (Kuno 1966, Irvine and Baragar 1971) for the basalts studied. A = Na<sub>2</sub>O + K<sub>2</sub>O; F = Fe<sub>2</sub>O<sub>3</sub>t; M = MgO (in %wt). Data recalculated to 100% on an anhydrous basis.

Hf) and most of the REE show strong correlations with Zr, suggesting that these elements remained immobile during the alteration processes. In the large ionic radius lithophile elements (LILEs), represented by Rb, Sr, and Ba, only Rb showed poor dispersion; the others showed very good correlation with Zr, implying different degrees of mobility during alteration processes. Th presents a low dispersion, which can be interpreted later as coming from the magma generation process.

From the evaluation of the mobility of LILEs, HFSEs, and ETR, it was possible to identify the elements that remained immobile during possible alteration processes and thus select the elements to be used in petrogenetic classifications and discussions.

Three samples were described petrographically as chloritites (Fig. 20). These samples are originated from hydrothermal processes, such as those described in the areas studied by Beisiegel *et al.* (1973) and Beisiegel (1982), where the authors stated that they are mafic rocks affected by low-temperature hydrothermal activity with intense chloritization, interpreted as autometamorphism or metasomatism. Therefore, these three samples in the present study were not considered in the petrogenetic study in question for having another genesis.

The 18 basalt samples studied in this scientific article were placed within a low-TiO<sub>2</sub> suite (Table 3) based on the criteria presented in the literature (2%wt < TiO<sub>2</sub> < 2.00%wt, 310 < Ti/Y < 310; Bellieni *et al.* 1984, Hergt *et al.* 1991). To fit into this low-TiO<sub>2</sub> suite, at least one parameter had to be complied with according to the adopted criteria. All samples have TiO<sub>2</sub> values < 2.00%wt, and only one of the 18 samples has Ti/Y > 310. Therefore, all samples were considered low-TiO<sub>2</sub>.

The basalts of the Grão Pará Group have at least two low-TiO<sub>2</sub> facies, namely FP and Igarapé Cigarra, discriminated on a geochemical basis according to the variation diagrams based on immobile incompatible trace elements (Figs. 26A and 26B). According to Macambira (2003), the Grão Pará Group fills



Figure 23. Magmatic affinity ranking diagram for the samples studied (Ross and Bédard 2009). Zr/Y versus Th/Yb.



**Figure 24.** (A) Rock classification diagram (Lemaitre 1989) for the basalts studied. Data recalculated to 100% on anhydrous basis. Rock classification diagrams for the samples studied (Winchester and Floyd 1977, Pearce 1996, Stanley 2017); (B) Nb/Y versus  $Zr/TiO_2$ ; (C)  $Zr/TiO_2$  versus SiO<sub>2</sub>; and (D) Nb/Y versus Zr/Ti.



**Figure 25.** Comparison of the elements Nb, Hf, Ta, Ce, Sm, Y, Rb, Ba, Sr, TiO<sub>2</sub>, Th, and V versus Zr (Pearce 2014) to evaluate the mobility of these elements in PF and FIC.

most of the Carajás Basin and is composed of a volcano-sedimentary sequence represented stratigraphically by the FP, Carajás Formation, FIC, and Igarapé Boa Sorte Formation. Thus, it will not be possible to treat the Parauapebas and Igarapé Cigarra geological formations together, which is supported by the geochemical discrimination presented in this study. After all, the two units in question are associated with temporally distinct magmatic pulses.

Figure 26A shows a La/Nb versus La/Yb diagram. This diagram showed good discrimination between the two low-TiO<sub>2</sub> basaltic rock sets of the Grão Pará Group, separating them into different quadrants. In this diagram, the basalts of the FIC facies plot in a field with La/Yb (> 8 ppm) and La/Nb (> 4.35 ppm), while the basalts of the FP facies show comparatively lower values of these incompatible trace element ratios

**Table 3.** List of studied basalt samples discriminated in  $\text{low-TiO}_2$  suites according to the criteria by Bellieni *et al.* (1984) and Hergt *et al.* (1991).

Suite	Sample	TiO <sub>2</sub>	Ti	Y	Ti/Y
	SSD-FD00612-AM03	0.83	4,976	18	280
	SSD-FD00932-AM01	1.22	7,314	26	278
	SSD-FD01027-AM01	0.82	4,916	21	230
	SSD-FD00831-AM03	0.83	4,976	17	286
Paraupebas	SSD-FD00831-AM04	0.86	5,156	14	382
Formation	SSD-FD00612-AM04	0.81	4,856	19	260
	SSD-FD00612-AM06	0.85	5,096	21	244
	SSD-FD00612-AM07	0.8	4,796	25	192
	SSD-FD00931-AM02	0.8	4,796	22	223
	SSD-FD00931-AM03	0.74	4,436	20	217
	SSD-FD01009-AM01	0.46	2,758	13	217
	SSD-FD01009-AM02	0.48	2,878	13	218
	SSD-FD01009-AM03	0.48	2,878	14	213
Igarapé	SSD-FD01058-AM01	0.64	3,837	16	240
Cigarra Formation	SSD-FD01059-AM01	0.48	2,878	12	246
	SSD-FD01059-AM02	0.46	2,758	11	244
	SSD-FD01008-AM01	0.51	3,058	12	247
	SSD-FD01008-AM02	0.52	3,117	13	249

(La/Yb < 8 ppm and La/Nb < 4.35 ppm). In addition to this discriminant diagram, it was possible to discriminate these two varieties in the MgO versus La/Yb diagram as shown in Fig. 26B, because the FIC plots in one field (La/Yb > 8 ppm), while the FP plots (La/Yb < 8 ppm).

The samples are plotted in the fields of basalt, basaltic trachyandesite, and basaltic andesite on the TAS diagram (Fig. 24A). However, the classification of even slightly altered samples in the TAS is subject to criticism because alkalis and silica, to a lesser degree, are mobile elements. In contrast, the elements Zr, Nb, Ti, and Y are considered immobile (Pearce and Cann 1973). The Nb/Y versus  $Zr/TiO_2$  diagram (Winchester and Floyd 1977; Fig. 24B) was used in comparison with the TAS. This indicates that if there was mobilization of the oxides, the process did not substantially affect the chemical classification in the TAS. So, even if the values of LOI are outside acceptable parameters due to the rocks having active hydrothermal processes (Beisiegel *et al.* 1973, Beisiegel 1982), this change did not compromise the petrogenesis of the rocks studied in the present study.

In this study, the petrogenetic discussion will be based on the elements (oxides and trace elements) that presented the highest level of significance according to Tables 4 and 5 (Rollinson 1993).

#### Facies of Parauapebas Formation

The variation diagram of the low-TiO<sub>2</sub> facies (Fig. 27) shows significant linear and polynomial correlations (Table 4) and is also characterized by the absence of compositional gaps. Very close values of the significance levels for the linear curves compared to the polynomial ones were identified, and therefore the linear ones were used in the discussion of the evolutionary processes of the volcanic rocks (Table 4). Based on the characteristics described above, the FP rocks discussed here may have evolved by fractional crystallization or by assimilation concomitant to fractional crystallization (AFC) with no change in the fractional assemblage.

The discrimination related to the involvement of the evolutionary processes of fractional crystallization and AFC can be examined based on the variation of incompatible trace element ratios within the suite (Cox *et al.* 1979). In general, these ratios do not vary above 50% during the evolutionary process



**Figure 26.** (A) La/Nb versus La/Yb discriminant diagram of the low-TiO<sub>2</sub> varieties (PF and FIC) of the Grão Pará Group in immobile incompatible trace element ratios. (B) MgO (%wt) versus La/Yb discriminant diagram of the low-TiO<sub>2</sub> (PF and FIC) of the Grão Pará Group.

**Table 4.** Comparison of the  $R^2$  values of the linear and polynomial functions for the variation diagrams of the major oxides and trace elements. The degrees of significance (DS) of the polynomial  $R^2$  for n = 10 samples and the second-order linear polynomial equations are also presented (Rollinson 1993).

Facies	Element	R² (linear)	R² (polynomial)	Degrees of significance linear (DS) (%)	Degrees of significance polynomial (DS) (%)	Linear equations	Polynomial equations
	SiO <sub>2</sub>	0.345	0.503	< 80	80-90	y = -0.8358x + 56.593	$y = 1.6074x^2 - 22.607x + 128.61$
	TiO <sub>2</sub>	0.04	0.416	< 80	< 80	y = 0.0052x + 0.8227	$y = -0.0979x^2 + 1.3313x - 3.5637$
	Al <sub>2</sub> O <sub>3</sub>	0.564	0.757	90–95	95-99	y = 0.4094x + 11.188	$y = -0.6633x^2 + 9.3938x - 18.53$
	Fe <sub>2</sub> O <sub>3</sub>	0.438	0.566	< 80	90-95	y = 1.1198x + 7.2886	$y = 1.6661x^2 - 21.447x + 81.932$
	CaO	0.456	0.567	> 80	90-95	y = -1.4734x + 14.006	$y = -1.9756x^2 + 25.284x - 74.501$
	Na <sub>2</sub> O	0.697	0.743	95–99	95-99	y = -0.7052x + 6.634	$y = -0.4717x^2 + 5.6833x - 14.497$
ų	K <sub>2</sub> O	0.076	0.233	< 80	< 80	y = 0.0811x + 1.5355	$y = -0.422x^2 + 5.7974x - 17.372$
natio	P <sub>2</sub> O <sub>5</sub>	0.02	0.164	< 80	< 80	y = 0.0002x + 0.0905	$y = 0.003x^2 - 0.04x + 0.2236$
orn	Ba	0.02	0.434	< 80	< 80	y = -6.5382x + 532.82	$y = -208.43x^2 + 2816.5x - 8804.9$
ebas Fc	Rb	0.11	0.251	< 80	< 80	y = 4.1537x + 35.46	$y = -15.446x^2 + 213.36x - 656.52$
ıapebae	Sr	0.461	0.533	80–90	80-90	y = -26.237x + 254.44	$y = -27.663x^2 + 348.44x - 984.89$
ırau	Zr	0.171	0.461	< 80	80-90	y = 1.2867x + 89.56	$y = 5.8574x^2 - 78.048x + 351.98$
D.	Y	0.696	0.733	95–99	95-99	y = -2.5531x + 36.64	$y = -1.5225x^2 + 18.069x - 31.57$
	Nb	0.255	0.319	< 80	< 80	y = 0.0932x + 3.7033	$y = 0.128x^2 - 1.6407x + 9.4383$
	Ni	0.346	0.456	< 80	80-90	y = 2.1967x + 64.033	$y = -3.4146x^2 + 48.446x - 88.946$
	Cr	0.276	0.641	< 80	95-99	y = 13.817x + 24.513	$y = -52.539x^2 + 725.43x - 2329.3$
	La/Yb	0.505	0.511	80–90	80-90	y = -0.931x + 11.447	$y = 0.26x^2 - 4.4525x + 23.095$
	La/Nb	0.605	0.61	90–95	90–95	y = 1.6246x + 0.6763	$y = -0.4476x^2 + 4.0396x - 2.0955$
	La/Y	0.696	0.733	95–99	95-99	y = -2.5531x + 36.64	$y = -1.5225x^2 + 18.069x - 31.57$

**Table 5.** Comparison of the  $R^2$  values of the linear and polynomial functions for the variation diagrams of the major oxides and trace elements. The degrees of significance (DS) of the polynomial  $R^2$  for n = 8 samples and the second-order linear polynomial equations are also presented (Rollinson 1993).

Facies	Element	R² (linear)	R² (polynomial)	Degrees of significance linear (DS) (%)	Degrees of significance polynomial (DS) (%)	Linear equations	Polynomial equations
	SiO <sub>2</sub>	0.306	0.598	< 80	80-90	y = -0.8664x + 58.995	$y = 2.0307x^2 - 25.415x + 132.61$
	TiO <sub>2</sub>	0.607	0.864	80-90	99–99.9	y = -0.0647x + 0.8872	$y = 0.0915x^2 - 1.1711x + 4.2048$
	Al <sub>2</sub> O <sub>3</sub>	0.384	0.613	< 80	80-90	y = -0.1971x + 15.942	$y = -0.3425x^2 + 3.9437x + 3.5254$
	Fe <sub>2</sub> O <sub>3</sub>	0.098	0.459	< 80	< 80	y = 0.1534x + 9.1339	$y = 0.987x^2 - 11.778x + 44.914$
	CaO	0.134	0.1571	< 80	< 80	y = 0.34x + 4.822	$y = 0.2911x^2 - 3.1794x + 15.376$
	Na <sub>2</sub> O	0.62	0.678	80-90	90–95	y = 0.7437x - 1.5755	$y = 0.4551x^2 - 4.7574x + 14.921$
ion	K <sub>2</sub> O	0.264	0.597	< 80	80–90	y = -0.2769x + 3.7075	$y = -0.7848x^2 + 9.2101x - 24.742$
mat	P <sub>2</sub> O <sub>5</sub>	0.35	0.772	< 80	95–99	y = -0.0063x + 0.1159	$y = 0.0172x^2 - 0.214x + 0.7387$
For	Ba	0.16	0.754	< 80	95–99	y = -103.78x + 1,480.8	$y = -664.04x^2 + 7923.6x - 22591$
arra	Rb	0.516	0.7	80-90	90-95	y = -22.058x + 197.38	$y = -28.322x^2 + 320.32x - 829.32$
Cig	Sr	0.529	0.535	80-90	80-90	y = -33.17x + 379.24	$y = -7.0999x^2 + 52.658x + 121.86$
rape	Zr	0.595	0.858	80-90	99–99.9	y = -11.264x + 139.47	$y = 16.328x^2 - 208.65x + 731.39$
Igai	Y	0.456	0.967	< 80	99–99.9	y = -1.1856x + 19.936	$y = 3.094x^2 - 38.588x + 132.1$
	Nb	0.701	0.931	90–95	99–99.9	y = -0.5102x + 5.9472	$y = 0.6209x^2 - 8.0165x + 28.457$
	Ni	0.385	0.722	< 80	95–99	y = 8.8603x + 19.514	$y = -19.674x^2 + 246.69x - 693.69$
	Cr	0.405	0.493	< 80	< 80%	y = 32.906x - 117.43	$y = -31.862x^2 + 418.07x - 1272.4$
	La/Yb	0.573	0.947	80-90	> 99.9	y = 1.24x + 2.0316	$y = 2.2764x^2 - 26.279x + 84.554$
	La/Nb	0.774	0.985	95-99	> 99.9	y = 0.9321x - 0.7951	$y = 1.0218x^2 - 11.42x + 36.246$
	La/Y	0.456	0.967	< 80	> 99.9	y = -1.1856x + 19.936	$y = 3.094x^2 - 38.588x + 132.1$



**Figure 27.** Variation diagrams for MgO (%wt) for major discriminant elements of evolutionary processes for the low-TiO<sub>2</sub> facies of the studied area. The linear and polynomial curves, their respective equations, and squares of correlation coefficients (R2) are shown in the diagram.

of pure and simple fractional crystallization, unlike when the suite evolves by AFC.

Incompatible trace elements that showed significance levels greater than 90% (Table 6) were used to discriminate between the fractional crystallization and AFC processes in the generation of the basaltic magmatism related to the Parauapebas volcanic rocks. The analysis was done based on the variation of the ratios of these incompatible trace elements (Zr/Y, Zr/ Nb, Zr/Yb, and La/Yb) considering their concentrations in the parental magma (represented by the SSD-FD00612-AM03 sample, see Table 1) and in the most evolved sample of the formation (represented by the SSD-FD00612-AM07 sample). The results (Table 5) show that these elemental ratios varied by a maximum of 28.80%, suggesting pure and simple fractional crystallization up to this point as the most likely evolutionary process for the generation of the basaltic magmatism associated with the FP.

#### Facies of Igarapé Cigarra Formation

The variation diagram of the low-TiO<sub>2</sub> facies (Fig. 28) shows significant linear and polynomial correlations (Table 5), also

suggesting the absence of compositional gaps, which suggest that studied rocks evolved by fractional crystallization or AFC, very close values of the significance levels for the linear curves compared to the polynomial ones, were identified. This fact points out that there was no change in the fractional assemblage during the petrogenesis of the basaltic magmatism related to the FIC low-TiO<sub>2</sub> facies. Evolutionary processes of the facies are shown in Table 5.

The incompatible trace elements that showed significance levels greater than 90% (Table 5) were used to discriminate between the fractional crystallization and AFC processes as the evolutionary process that generates the mafic magmatism in the FIC low-TiO<sub>2</sub> facies. The analysis was done based on the variation of these incompatible trace element ratios (Zr/Y, Zr/Nb, Zr/Yb, and La/Yb) considering their concentrations in the parental magma (represented by the sample SSD-FD01009-AM03) and in the most evolved sample of the facies (represented by the sample SSD-FD1058-AM01). The results (Table 7) show that these ratios varied at most 18.61%, suggesting fractional crystallization as a possible evolutionary process for the facies. This will be further evaluated below. The criterion used to define

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Table 6. Variation of the immobile incompatible trace element ratio between the most evolved and parental sample of the low-TiO, PF facies.

Magnua Truna	Samulas		Re	asons	
Magina Type	Samples	Zr/Y	Zr/Nb	Zr/Yb	La/Yb
Parental magma	SDD-FD00612-AM03	5,56	22,50	42,86	5,80
More evolved magma	SDD-FD00612-AM07	3,96	22,50	38,67	7,42
Variation%		28,80%	0,00%	9,77%	-27,94%



**Figure 28.** Variation diagrams for MgO %wt for major discriminant elements of evolutionary processes for the low-TiO<sub>2</sub> facies of the studied area. The linear and polynomial curves, their respective equations and squares of correlation coefficients ( $R^2$ ) are shown in the diagram.

**Table 7.** Variation of the immobile incompatible trace element ratio between the most evolved and parental sample of the low- $TiO_2$  facies of FIC.

M	6		Reas	sons	
Magma Type	Samples	Zr/Y	Zr/Nb	Zr/Yb	La/Yb
Parental magma	SDD-FD01009-AM03	5,11	25,56	48,25	12,03
More evolved magma	SDD-FD01058-AM01	6,06	24,87	54,19	9,83
Variation%		-18,61%	2,68%	-12,31%	18,25%

the parental sample is related to the content (in %wt) of MgO in the samples since this oxide is a good index of differentiation in basaltic magmas (Valente 1997, Corval 2009).

## Modeling of possible evolutionary processes for the Parauapebas and Igarapé Cigarra Formations

Multi-elemental diagrams were used to test fractional crystallization, considering the PF and FIC. The results presented below are only a hypothesis to consider a possible evolutionary model.

The results of the evolutionary process hypothesis of fractional crystallization for the facies of the FP showed that the variations of the concentrations of Th, Nb, La, Ce, Nd, P, Sm, Ti, Tb, and Y in the facies of the FP can be explained by 20% involving an assembly of phenocrysts composed of 29% orthopyroxene, 22% clinopyroxene, 40% plagioclase, and 9% Fe-Ti oxides, from the parent magma, represented by sample SSD-FD00612-AM03, to the evolved magma, represented by sample SSD-FD00612-AM07 (Fig. 28A).

The results of the evolutionary process hypothesis of fractional crystallization for the facies of the FIC showed that the variations of the concentrations of Th, Nb, Ta, Ce, Nd, P, Zr, Hf, Ti, Y, Tm, and Yb in the FIC suite can be explained by 30% involving an assembly of phenocrysts composed of 29% orthopyroxene, 24% clinopyroxene, 43% plagioclase, and 3% Fe-Ti oxides, from the parent magma, represented by sample SSD-FD01009-AM03, to the evolved magma, represented by sample SSD-FD01058-AM01 (Figure 28B).

Figure 29 presents multielemental variation diagrams for the PF facies (Fig. 29a) and facies of the FIC (Fig. 29B). A potentially representative sample of the parent liquid from facies of the FP and facies of the FIC was represented in this diagram, along with results from model samples resulting from fractional crystallization modeling.

Nb showed a negative anomaly in both the parental and calculated liquid samples, which suggests crustal assimilation during this evolutionary process (Taylor and McLennan 1985). This fact leads to the conclusion that the evolutionary process was not pure and simple fractional crystallization only, thus having concomitant crustal assimilation (assimilation concomitant to fractional crystallization [AFC]).

## DISCUSSION

#### Paraupebas and Igarapé Cigarra formations: more than a low-TiO, facies

Discrimination diagrams based on immobile incompatible trace element ratios were used to analyze possible subgroups in both the FP and the FIC according to the criteria established by Bellieni *et al.* (1984), Hergt *et al.* (1991), and Peate (1997). It was observed that both PF and FIC separated into at least two low-TiO<sub>2</sub> facies each, namely, facies Violão, Amendoim, Jacaré, and Três Marias, respectively.

Figure 30A presents a Ti/Y versus Zr/Y diagram. This diagram showed satisfactory discrimination between the two low-TiO<sub>2</sub> facies of the FP basalts, separating them into different quadrants. In this diagram, the basalts of the Violão facies plot in a field with Ti/Y (> 300 ppm) and Zr/Y (> 5.5 ppm). In addition to this discriminant diagram, it was possible to separate these two sets in the Ti/Y versus Ti/Zr (Fig 30B; Ti/Y versus Ba/Y in Fig. 30C and Ti/Y versus Sr/Y in Fig. 30D).

Although the PF and FIC clearly have their subdivisions into two distinct sets, respectively, no modeling hypothesis was tested here due to these subdivided sets for each facies having few individuals in their population. This fact limits a more refined statistical study.

(B)

# Petrogenetic and geodynamic implications

In order to understand the petrogenetic processes and tectonic environment involved in the generation of the PF and FIC basalts, the geochemical affinities and chemical element contents of these units were compared. Considering that previous studies have been developed for the rocks of these two geological formations, different tectonic environments can be suggested, such as:

- The Itacaiúnas Supergroup units are volcanic and sedimentary rocks developed on continental crust adjacent to rift zones or intracratonic basins (Gibbs *et al.* 1986, Wirth *et al.* 1986, Docegeo 1988, Olszewski *et al.* 1989, Machado *et al.* 1991, Lindenmayer 1992, Pinheiro and Holdsworth 2000, Santos 2003, Tallarico *et al.* 2005, Grainger *et al.* 2007, Martins *et al.* 2017);
- Volcanosedimentary sequences are formed in arc environments and consequently involve the presence of a subduction zone (Meirelles and Dardenne 1991, Teixeira and Eggler 1994, Lobato *et al.* 2005, Rosière *et al.* 2006, Zucchetti *et al.* 2007).



## (A) Fractional Crystallization model for the Parauapebas Formation



Fractional Crystallization model for the Igarapé Cigarra Formation

**Figure 29.** (A) Normalized multi-element diagram for chondrite (Thompson *et al.* 1984, with K, P, and Rb values from Sun (1980) and Ba = 3.85 from Hawkesworth *et al.* 1984) for the PF facies containing the quantitative geochemical modeling results of the pure and simple fractional crystallization process. (B) Normalized multi-elemental diagram for chondrite (Thompson *et al.* 1984, with K, P, and Rb values from Sun (1980) and Ba = 3.85 from Hawkesworth *et al.* 1984) for the FIC facies containing the quantitative geochemical modeling results of the pure and simple fractional crystallization process. The numerical results of the original liquid and the calculated liquid are arranged next to each diagram for the respective suites.

Based on the above hypotheses, a sequence of discriminatory diagrams was chosen that makes it possible to distinguish the two environments more securely, besides allowing the recognition of the signatures of the sources involved. Finally, comparisons of these geological formations were made in a multi-elemental diagram with mid-oceanic ridge basalts (N-MORB), enriched mid-oceanic ridge basalts (E-MORB), oceanic island basalts (OIB) (Sun and McDonough 1989), and rocks from continental rift (Peate and Hawkesworth 1996) and island-arc (Chandrasekharam *et al.* 2009) environments.

According to the chemical data, it is observed that the basalts of PF and FIC present compositions equivalent to basalt, basaltic andesite, basaltic trachyandesite, and calcium-alkaline affinity trachyibasalt (Figs. 23 and 24A). Both units possess a distribution of most of the major and trace elements, which, in the face of the differentiation index values, is suggestive of evolution by fractional crystallization. However, both FP and



**Figure 30.** Bivariant diagram Ti/Y versus: (A) Zr/Y; (B) Ti/Zr; (C) Ba/Y; and (D) Sr/Y according to criteria established by Bellieni *et al.* (1984), Hergt *et al.* (1991), and Peate (1997) for discrimination facies on PF and FIC.



IAT: island-arc tholeiite; MORB: mid-ocean ridge basalt; CAB: calc-alkalibasalt.

**Figure 31.** Tectonic discrimination diagrams applied to PF and FIC rocks. (A) Zr versus Z/Y (Pearce and Norry 1979); (B) Ti versus Zr (Pearce and Cann 1973).

FIC show some similar geochemical features, such as signatures with negative anomalies of Nb and Ti and enrichment patterns of ETRL relative to ETRP (Figs. 31A and 31B). Negative Nb and Ti anomalies are characteristic of volcanic arc basalts, generated from the fractionation of these elements relative to Th and ETRL elements during dehydration and partial melting of the subducted crust, with Th and ETRL being transferred from this to the mantle wedge, whereas Nb and Ti are not transferred to the fluid phases, becoming insoluble and retained in the subducted plate (Wilson 1989, Pearce 1996, Condie 2001). However, negative Nb and Ti anomalies are also observed in continental basalts, termed arc-like continental basalts.

In determining the tectonic environment in which the PF and FIC basalts were generated, the geochemical data from the studied samples were initially plotted on the Zr versus Zr/Y diagram (Pearce and Norry 1979) (Fig. 31A). In this diagram, the rocks mainly occupy the intraplate basalt field, due to the high Zr and Zr/Y contents and ratios, respectively. Similarly, when plotted on the Zr versus Ti diagram (Pearce and Cann 1973) (Fig. 31B), due to the high Zr and Ti values, the samples mostly occupy the calc-alkalibasalt field.

In the ternary Th-Zr-Nb diagram (Wood 1980), the PF and FIC basalts occupy the VAB and CAB fields, respectively (Fig. 32A). This diagram shows great efficiency in separating intraplate environment basic rocks derived from more impoverished sources, similar to MORB, or enriched ones, similar to OIB, from those related to arc-type environments. The results observed in the diagram are compatible with the hypothesis of the generation of igneous magmas in an intraplate environment.



Figure 32. Tectonic discrimination diagrams applied to PF and FIC rocks. (A) Th-Zr-Nb (Wood 1980) and (B) La-Y-Nb (Humphris and Thompson 1989).



N-MORB: mid-oceanic ridge basalts; E-MORB: enriched mid-oceanic ridge basalts; OIB: oceanic island basalts; OCTZ: ocean-continent transition zone. **Figure 33.** Tectonic discrimination diagrams applied to the PF and FIC samples. (A) Nb/Yb versus Th/Yb (Pearce 2014); (B) Nb<sub>(N)</sub> versus Th<sub>(N)</sub> (Saccani 2015). Normalization to N-MORB (Sun and McDonough 1989). Backarc A indicates immature intra-oceanic or ensialic backarc basin basalts (BABBs), whereas Back-arc B indicates mature intra-oceanic BABBs. FP and FIC facies plotted in the continental arc field in both Figs. 33A and 33B.



**Figure 34.** Diagrams of geotectonic environments: (A) Wood (1980), (B) Meschede (1986), (C) Shervais (1982), (D) Pearce and Cann (1973). Basalts from PF and FIC plot in both graphs as a continental magmatic arc.

Humphris and Thompson (1989) proposed a ternary diagram based on La-Yb-Nb (Fig. 32B) to distinguish basalts from different tectonic environments. In this diagram, it is clearly observed that the studied PF and FIC samples form plots within the calc-alkalibasalt field.

In order to corroborate the tectonic environment where the magmas were generated, the Nb/Yb versus Th/Yb binary diagram by Pearce (2014) was used (Fig. 33A). In this diagram, the samples from PF and FIC are plotted in the continental arc field. The samples that plot in the continental arc environment are influenced by Th enrichment and are distributed in a trend similar to that indicated for crustal assimilation, concomitant with fractional crystallization (AFC).

Tectonic environment discrimination diagrams (Pearce and Cann 1973, Wood 1980, Shervais 1982, Meschede 1986) corroborate that continental arc and collisional environments as a possible geodynamic setting associated with this magmatism (Figs. 34a–34d), respectively.

Information on the possible mantle sources associated with the PF and FIC basalts could be extracted from the multi-elemental diagrams. The La/Yb<sub>(N)</sub> > 1 values found both for the low-TiO<sub>2</sub> (SSD-FD00612-AM03 La/Yb<sub>(N)</sub> = 4.96) facies of the PF basalts and for the low-TiO<sub>2</sub> (SSD-FD01009-AM03 La/Yb<sub>(N)</sub> = 6.57) facies of the FIC basalts are indicative of an enriched (lithospheric) or fertile (OIB or plume; Wilson 1989) mantle source.

All samples analyzed from the PF and FIC basalts showed La/Nb<sub>(N)</sub> ratios greater than unity. The only exception was a single sample that, despite having hydrothermal effects, maintained the original lithogeochemical characteristics and presented La/Nb<sub>(N)</sub> lower than the unit, namely sample SSD-FD00831-AM04 (La/NbN = 0.99, La/Yb<sub>(N)</sub> = 2.71). The characteristics of this sample suggest the generation of magma from a fertile, asthenospheric-type source.

With the tectonic environment classification data and the suggested mantle source qualification, we conclude that the basalts of the PF and FIC facies are continental magmatic arc tectonic environments. The generation of the basaltic magmatism studied in this study must have at least one contribution from the subcontinental lithospheric mantle since most of the basic magmas studied point to La/Yb and La/Nb ratios greater than unity. Isotopic data would need to be generated so that more robust petrological studies can be carried out to test the hypothesis of some asthenospheric participation in a



Source: adapted from Wyman (1996). Figure 35. Schematic diagram showing the proposed geological setting for the formation of basalts from the Grão Pará Group. FP and FIC.

possible mixture of mantle sources in the petrogenesis of the basaltic magmatism in PF and FIC. Figure 35 presents the geodynamic model for the studied area.

#### CONCLUSION

The petrographic data of the PF and FIC studied areas showed that the rocks are basalts with the following mineralogical compositions: plagioclase, clinopyroxene and orthopyroxene (essential minerals), calcite, quartz, and epidote (secondary minerals). The petrographic data also showed the presence of three samples of chloritite, whose mineral composition is chlorite, quartz, and calcite, as a possible product of hydrothermal process. The large quantities of elongated euhedral to subhedral plagioclase grains as well as the presence of intersertal texture indicated that these rocks were probably volcanic, in this case of basaltic composition. The occurrence of subhedral to anhedral pyroxene grains filling spaces of the well-formed plagioclase grains (intergranular texture) suggests that the latter crystallized early relative to the former. This fact is corroborated by the existence of ophitic and subophytic textures of plagioclase grains in pyroxene grains. In other words, the plagioclase grains present in the basaltic magmas studied are of primary crystallization and, therefore, of high temperature, which points to a more calcareous composition of the same (Bowen 1956).

It is important to note that the presence of opaque minerals included in the plagioclase grains in the basic rocks studied suggests early crystallization of iron-containing phases. The lithogeochemical data prove this assertion since they show that the basaltic facies of PF and FIC constitute a transitional facies of calcium-alkaline affinity. The calcium-alkaline affinity of the basalts of these geological formations is clearly defined in the AFM diagram. Calc-alkaline series are typically associated with convergent environments with subduction zones promoting volatile input and recycling of the lithospheric mantle. This scenario favors the development of an oxidizing environment and explains the early crystallization of oxides and sulfides. Furthermore, this interpretation supports the geodynamic context proposed in this study.

The lithogeochemical data classified the mafic rocks of PF and FIC, in general, as basalts, basaltic andesite, basaltic trachyandesite, and trachybasalt. The geochemical modeling developed in this scientific study was tested for fractional crystallization. But it was noted that fractional crystallisation alone would not generate basaltic magmatism associated with both the FP and the FIC, possibly having crustal assimilation along with crystallization (AFC). The ratio of immobile, incompatible trace elements between the parent compositions and more evolved basaltic magmatism of both formations initially suggested fractional crystallization.

Therefore, a more complete understanding of the evolutionary processes would require the application of petrogenetic modeling techniques to each of the four recognized low- $TiO_2$  facies in the studied area. However, this was not feasible due to the low number of samples distributed in each facies. But it is important to note that some anomalies observed in the behavior of some REE in multilementar diagrams in all PF and FIC basaltic magmas suggest possible crustal contamination processes in the petrogenetic context.

Least squares methods and regression curves were applied for the qualitative treatment of the geochemical data. Such curves, allied to diagrams of variation of incompatible immobile trace elements, evidenced in both the facies FP and the facies FIC, respectively: PF: Violão and Amendoim; and FIC: Três Marias and Jacaré. Finally, the values of La/Yb and La/Nb ratios of the basaltic parental magmas of the PF and FIC low-TiO<sub>2</sub> facies initially showed the participation of lithospheric components in the generation of the studied mafic magmatism. This is a plausible hypothesis if we consider the geodynamic context addressed in the present study where the lithospheric mantle was homogenized along the geological time by subduction mechanisms. After all, the tectonic environment of the rocks in the studied area is continental arc and collision. As previously mentioned, only a single sample (SSD-FD00831-AM04) showed La/Nb<sub>(N)</sub> less

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than unity, suggesting an asthenospheric source, a fact that needs further investigation and research.

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