The Western Amazonia Igneous Belt

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ABSTRACT

The Western Amazonia Igneous Belt (WAIB) occupies the northern part of South American continent, and a total area close to 125,000 km². The belt is composed dominantly by volcano-plutonic felsic rocks (Juruena super-suite, Teles Pires suite and Colíder group) and has dominant alkali-calcic, metaluminous to peraluminous, ferrous, geochemical characteristics, similar to A-type granites. The Silicic members are represented by granites and rhyolitic-rhyodacitic volcanic rocks, mafic members by gabbroic rocks and diabase dykes. Intermediate rocks are rare. Local magma mingling and hybridization are present in several areas. The assemblage of silicic and basic rocks of WAIB was formed between c. 1825 and 1757 Ma. The presence of inherited zircons, from 1875 to 2050 Ma, as well as some Archean ages in the granitic and volcanic rocks from the WAIB, are suggestive of derivation by melting of pre-existing crustal basement (Ventuari-Tapajós Province). This hypothesis is also corroborated by bimodal magmatism and by several model-ages of granites, felsic volcanic rocks and mafic plutonic rocks, with TDM ranging from 2.0 to 2.3 Ga, and εNd value, varying from −3.90 to +2.52.

The preferred model of formation of the WAIB envisages the emplacement of large volumes of hot mantle-derived melts into the lower crust. These processes resulted in partial melting of lower-crustal material, mixing with the mantle-derived melts and formation of granitic melts. The timing and spatial features and interpreted petrogenetic mechanisms of WAIB are suggestive of a continental rift setting. In addition, this volcano-plutonic province is similar to silicic igneous provinces (Silicic Large Igneous Province-SLIP) in areal extent, eruptive volume and petrogenetic characteristics.

1. Introduction

The Amazonian craton covers the largest Archean-Proterozoic continental area of the South American continent, and is divided into two exposed parts: Guiana shield in the north, and Central Brazil shield in the south (Fig. 1). Similarly, the Amazonian craton was subdivided into two Archean nuclei and five Proterozoic tectonic provinces, showing internally coherent structural and age patterns (Tassinari and Macambira, 1999) (Fig. 1). The craton was formed mainly by Paleoproterozoic orogenic collages of Archean cratonic nuclei during the Transamazonian Orogeny (2.2–2.0 Ga) in its eastern portion, while younger (Mesoproterozoic) accretionary events occurred in the western portion. Therefore, such fusion processes were essential in origin this immense tectonic block. On the other hand, global taphrogenesis took place on the Palesupercontinent, from the late Orosirian to the Statherian (e.g. Aral Rift; Botelho and Moura, 1998). In the initial phase of continental extension, dyke swarms were associated with fracturing, and magma injection led to melting of lower continental crust and further anorogenic magmatism. Voluminous volcanic and plutonic anorogenic activity was in several cases associated with mantle diapirism or mantle super swells under a Paleoproterozoic supercontinent (Storey et al., 2001; Turcotte and Schubert, 2002), generating large belts of igneous rocks by additions of magma to the continental crust both at the surface and at depth, similar to Large Igneous Provinces (LIPs).

In this context, we presently characterize and define the Western Amazonia Igneous Belt (WAIB), occupying the northern part of the South American continent, with a total area close to 125,000 km² (Fig. 2). Extensive igneous activity in the WAIB in Statherian time, and during the Calymmian occurred in the western corner of the belt. Massive quantities of high-K granitic magma were produced in this belt.

Despite lack of convincing evidence, these igneous rocks were interpreted as a continental arc (e.g., Santos et al., 2000; Souza et al., 2005; Scandolara et al., 2014, 2017; Duarte et al., 2012; Assis, 2015). In recent years, however, mafic dyke swarms and mafic intrusions associated with subvolcanic and shallow intrusive A-type granitoids, and...
coeval felsic volcanic rocks were found in the WAIB (Neder et al., 2002; Rizzotto et al., 2019).

Felsic volcanic and volcaniclastic rocks (rhyolite, trachyte, minor dacite, and ignimbrite) and A-types granite are the most common lithological assemblages in extensional tectonic settings, together with minor mafic dyke swarms and mafic intrusions (Bonin, 2007; Frost and Frost, 2008). Associated magmatism varies from alkaline to subalkaline, and bimodal suites are typical of most continental rift environments. In this way, rhyolitic volcanoes (volcanic domes) and A-type granitic batholiths are the major manifestations of silicic magmatism, and are important igneous building blocks of continents.

From a geodynamic perspective, intraplate bimodal magmatism was suggested to be related to thermal perturbations in the upper mantle with associated mafic underplating of plume-like character, or a result of crustal extension decompression and mantle upwelling (Aitken et al., 2013; Pirajno and Santosh, 2015). The model including magmatic underplating and crustal anatexis in an extensional tectonic environment was first applied to Finnish rapakivi granites by Haapala (1985), Haapala and Rämö (1999) and Nurmi and Haapala (1986). The associated mafic magmatism was directly mantle-derived, as assumed for intraplate bimodal magmatic suites (Dall’Agnol and Oliveira, 2007). In the same way, Paleoproterozoic A-type granites were described from many Precambrian shield areas, e.g., South America (Dall’Agnol et al., 1994, 2005), Fennoscandia (Haapala and Rämö, 1999; Ahl et al., 1997), North America (Anderson, 1983; Anderson and Bender, 1989; Emslie, 1991; Barnes et al., 1999). Typically, these granites are found as discordant multiple plutons, show bimodal (mafic-felsic) magmatic association, include rock types with rapakivi texture, and were intruded into an igneous and metamorphic crust that predated them by some hundred million years (e.g., Dall’Agnol et al., 2005; Rämö and Haapala, 1995). In Central Brazil shield, more specifically in the southern part of the Rio Negro-Juruena Province, a major period of felsic volcanism and granite emplacement with these same characteristics occurred between 1820 and 1760 Ma. In a similar geological context, voluminous intraplate mafic activity in the northern part of the Amazonian craton (Guiana Shield) is represented by Avanavero (1.79 Ga) LIP event of mafic dykes and sills (Reis et al., 2013). In this context, the Juruena supersuite, Teles Pires suite and Colíder group have similar ages to Avanavero LIP, and formed by breakup attempt of the continental lithosphere due to mantle convection reorganization below the already

![Schematic map of the Amazonian craton with the location of the studied area (Fig. 2) and division into geochronological provinces.](image-url)
stable Paleoproterozoic/(Archean) continental lithosphere.

The tectonic environment in which the rocks of the Rio Negro-Juruena Province were formed remains a major problem in Precambrian geology of Amazonian craton. For this reason, there are many contrasting suggestions of possible origin, such as: a) magmatism derived from the evolution of continental magmatic arc (e.g., Santos et al., 2000; Souza et al., 2005; Scandolara et al., 2014, 2017; Duarte et al., 2012; Assis, 2015), and b) bimodal magmatism generated in an intraplate extensional environment (Pinho et al., 2001; Neder et al., 2002; Rizzotto and Quadros, 2005; Leite et al., 2005; Barros et al., 2009; Rizzotto et al., 2016).

In light of this paradox in paleoenvironmental interpretations we reevaluate the origin of Statherian bimodal magmatism of the WAIB in the southern part of Rio Negro-Juruena Province (RNJP). We present new data from geological mapping, geophysical interpretation (magnetometry, gamma spectrometry, and gravity data), associated with petrographic, geochemical and geochronological studies. We suggest a new interpretation regarding the evolution of this expressive acid magmatism, and present a new geotectonic conception for the southwestern Amazonian craton.

2. Regional geological context

The WAIB consists of a set of massifs of granitic and volcanic rocks and associated mafic intrusions (1.82–1.76 Ga). This belt of magmatic rocks is 820 Km long and 150 Km wide, and borders a core of high-grade metamorphic rocks (Nova Monte Verde Complex, 1.80–1.76 Ga) (Fig. 2). A remnant core of older rocks to the east of this belt is named Peixoto de Azevedo Domain (2.80–1.87 Ga) and represents a remaining cratonic block of the Ventuari-Tapajós Province (VTP), that is the continuation of VTP to the south of Alto Tapajós Basin (Fig. 2).

The rocks that form the basement of this domain are inserted into the Cuiu-Cuiu Complex (2.05–1.99 Ga), which consists of tonalitic-granodioritic gneisses, commonly migmatized, with subordinate amphibolite. A set of granitoids and associated mafic plutonic rocks was intruded into the gneisses of the complex, and constitutes an expanded calc-alkaline magmatic series derived from the continental magmatic arc (Pé Quente suite, Guarantã suite; Assis, 2015). Another group of granitoids with similar genesis to the granitoids in the complex known as Novo Mundo, Aragão, Nhandu and Flor da Mata (Paes de Barros, 2007; Assis, 2015), was grouped into the Nhandu Intrusive suite. These granitoids have similar structural, textural, chemical and isotopic characteristics, in addition to zircon U-Pb ages between 1970 and 1955 Ma, correlated with Creporizão intrusive suite of Tapajós. Other group of younger granitoids is predominant in the southern part of the VTP, included in the Matupá intrusive suite (1890–1870 Ma) and has chemical characteristics compatible with formation in an intraplate extensional environment correlated to the Parauari and Maloquinha intrusive suite of Tapajós. This entire set of basement rocks and granitoids
is distributed in the Peixoto de Azevêdo Domain, and has $T_{DM}$ ages > 2.30 Ga and U-Pb crystallization ages ranging from 2.1 to 1.87 Ga, except for a few outcrops of gneiss-migmatitic rocks from the Gavião Gneiss Unit (Paes de Barros, 2007) dated at ~2.8 Ga (Archean). After 1.95 Ga, the Peixoto de Azevêdo Domain developed as a stable platform; deformational events and high-grade metamorphism were not observed.

On the other hand, the Western Amazonia Igneous Belt (WAIB) has granitoid rocks that show different degrees of deformation and metamorphism, ranging from multi-deformed rocks to rocks with incipient foliation or isotropic. In this context, the Nova Monte Verde Complex is represented by a strip of granulitic-migmatitic gneissic rocks. In previous studies, migmatite-gneiss domes were considered an old basement and were included in the Xingu Complex, with Archean/Paleoproterozoic age (Silva et al., 1974; Japan International Cooperation Agency, 2001). Associated with this "basement", the granitic masses were considered the product of remobilization of a migmatite-gneiss basement, and named Juruena Granite, which includes tonalite, granodiorite, quartz-monzodiorite, quartz-diorite and quartz-syenite. We presently name this stratigraphic unit as Juruena supersuite.

Granitic bodies included in the Juruena supersuite are batholiths and stocks, elongated along the EW structure, bordering this belt of migmatitic and granitic rocks, and are found both in the north and south of Nova Monte Verde Complex. These bodies have gneiss-gneiss texture, and farther from the metamorphic core deformation becomes weaker, showing rocks with incipient igneous flow fabric to isotropic. Isotropic rocks have transitional contacts with acid subvolcanic and volcanic predominantly explosive intrusions. In places, interdigitation between explosive volcanic and volcano-sedimentary rocks from the Colíder and Roosevelt groups is observed. These units have texture produced by low-grade metamorphism and are predominantly non-metamorphosed.

Souza et al. (2005) called the deformed to isotropic granitic and granodioritic rocks of "Juruena intrusive suite" and defined other units as Nhandú Granite, São Pedro Granite, São Romão Granite, Apiaças Granite and Nova Canãa suite. Among the units defined by Souza et al. (2005), the crystallization age of 1.96–1.97 Ga of the Nhandú Granite led to repositioning it stratigraphically (Barros et al., 2015). On the other hand, petrographic, geochemical and isotopic similarities, together with field characteristics of São Pedro, São Romão, Apiaças and Nova Canãa units, made possible to group them into one unit called “Juruena supersuite”. This significant plutonic felsic magmatism and associated acid volcanic rocks are widely distributed in an area of approximately 270,000 km² bordering the high-grade metamorphosed complex (Fig. 2). This acid magmatism occurs in the SW border of the VTP. The basement south of RNJP is constituted by fragments or "islands" of gneiss rocks, metavolcanic-sedimentary units and granitoids. Ages are older than WAIB, cropping out in a small and isolated dispersed nucleus, predominantly at the margins of the Alto Tapajós and Caiabís basins. Rocks of the basement are represented by the Jacaracanga group, São Marcelo-Cabeça group, Tabaporã Complex and several granitoids older than 1.8 Ga.

The Juruena supersuite granitoids have transitional contacts. Regarding their composition, no significant variations were observed among granites of Juruena supersuite, except for the Apiaças granite which is more peraluminous. However, the differences in texture of the granites of the supersuite are distinct, showing different intensities of metamorphism and deformation. Therefore, the Juruena supersuite is formed by granites that vary from isotropic to those with igneous flow foliation, weakly foliated, to metagranites with penetrative foliation, grading to augen gneisses. Among them, monzogranites predominate, with subordinate granodiorites. Mixing features of different magmas are also characteristic of these lithotypes, which show microgranular enclaves of composition ranging from basic to intermediate, and biotite cluster (melting restites), in addition to rapakivi texture. Fig. 2 shows the distribution of the Juruena supersuite and division into suites.

The acid volcanic rocks belong to the Colíder group, considered the volcanic equivalent of the Juruena supersuite and Teles Pires suite plutonism. This group is mainly formed by pyroclastic and effusive volcanic rocks, with predominantly rhyolitic-dacitic composition, with subordinate andesitic basalts and andesites. The effusive and subvolcanic intrusives of the Teles Pires suite, with textural and structural features of epizone, in addition to features of magma mixing, form together with the volcanic rocks of the Colíder group a co-magmatic set.

The mafic component of this extensive magmatism “Juruena-Teles Pires” is predominately represented by mafic rocks of the Vespore Mafic suite, mainly distributed in the interfluvues of Juruena and Roosevelt rivers. This lithostratigraphic unit consists of metagabbros, amphibolites, mafic granulites and metadiorites genetically associated in time and space with migmatites and granulites of the Nova Monte Verde Complex. Moreover, a swarm of diabase dykes and small gabbro bodies, either metamorphosed or not, included in the Guadalupe Intrusive suite, are probably coeval with mafic rocks of the Vespore suite, and crop out on the interfluence between Juruena and Teles Pires rivers.

2.1. Morphology, stratigraphy and petrography of main types of rocks

2.1.1. Juruena supersuite

Acid magmatism of Juruena supersuite is widespread along a continuous NW-ENE belt approximately 1200 × 300 km, in the centre-east of Rio Negro-Juruena Province and is represented by a series of granitic bodies and, to a lesser extent, by granodiorites, with crystallization ages ranging from 1810 to 1770 Ma (Rizzotto and Quadros, 2005). In general, granitic masses (batholiths and stocks) are aligned in the EW direction (Fig. 2), with the same trend of the metamorphic core complex (Nova Monte Verde Complex), with ellipsoidal bodies showing magmatic foliation and, more rarely, mylonitic structure with elongation of megacrysts of K-feldspar and quartz, and alignment of biotite clusters. Mylonites derived from granites are restricted to narrow transcurrent zones with EW direction, in many places associated with brecciation developed in shallower levels of the crust.

One of the granitic massifs peculiarities is their variable deformatonal style. Granites that are in contact, both in the north and south, with the migmatite-gneiss rocks of the Nova Monte Verde Complex, show magmatic foliation sub-concordant to the foliation developed during the subsolidus stage, often showing augen structure. Moving away from the contact zone with high-grade metamorphic rocks, granites show only an incipient foliation marked by the alignment of biotites and euhedral K-feldspar crystals, where only quartz is elongated. Moving away from the metamorphic core complex toward north, where the granites are in contact with volcanic rocks of Colíder group (Fig. 2), these intrusive are mainly isotropic, with rare features of magmatic flow, shown by the alignment of prismatic K-feldspar crystals and incipient mylonitic fabric in restricted and narrow zones, with predominance of brittle features (cataclasite, breccia, quartz vein in dilatation zone).

According to field characteristics, in addition to textural, compositional and structural characteristics, the Juruena supersuite is divided into the following suites: São Pedro, Paranaita and Nova Canãa (see description in Appendix A).

2.1.2. Colíder group

This unit consists predominantly of acid volcanic rocks (lava, lava dome, and pyroclastic rocks) and epiclastic rocks. The unit is distributed along an elongated, continuous belt, with EW to NW direction, and borders the southern part of Alto Tapajós Basin, inflecting to the NW on the interfluence between Aripuana and Sucundurí rivers. To the east, the unit partially overlies rocks of Peixoto de Azevêdo Domain (Fig. 2) and, to the south, forms a fringe surrounding the Caiabís graben, in continuation with the volcanic rocks of the Roosevelt group. Volcanic activity represented by the rocks of the Colíder group occurred
between 1810 and 1766 Ma (Duarte et al., 2012; Santos et al., 2019). A detailed description of the unit is in Appendix A.

### 2.1.3. Teles Pires suite

This unit consists of plutonic rocks and acid subvolcanic intrusions associated in time and space, and genetically with volcanic rocks of Colíder group. Several bodies form stocks and, more rarely, batholiths, and are predominantly elliptical with the major axis along EW and parallel to main regional lineaments. Their contacts with the effusive rocks of the Colíder group are intrusive to transitional, and they intrude into of the Peixoto de Azevêdo Domain rocks. According to literature, there is a wide range of crystallization ages, varying from the youngest age of 1757 Ma to the oldest age of 1782 Ma (Souza et al., 2005; Silva and Abram, 2008). In this study, an older crystallization age was obtained for a porphyry granite (1794 Ma—see section 3). Therefore, a plutonic activity of approximately 35 My, coinciding with the period of the Colíder volcanism (37 My), confirms that the acid volcanism and plutonism in the area are coeval. The peraluminous to slightly meta-

### 2.1.4. Teodózia and Zé do Torno suites

Granitoids of these units, with associated subvolcanic rocks, are distributed in the far northwest, bordering the Cachimbo basin, and in the southwest, bordering the Roosevelt basin (Fig. 2). Granitoids of both suites yielded crystallization ages between 1756 and 1758 Ma.

Granitoid outcrops of the Teodózia suite, in the form of slabs and boulders, are distributed in the interfluve of the Aripuanã, Guariba, Roosevelt, Paxiuba rivers and the upstream area of Buiçuçá river. A detailed description of the unit is in Appendix A.

### 2.1.5. Roosevelt group

The rocks of this group are widely distributed in the SW of the investigated area, on the interfluve of the Juruena and Roosevelt rivers, and to the north, extending to the town of Aripuanã-MT and, to the south, bordering the Paracés Basin. The group is represented by terrig-

### 3. Geochronology and isotope geochemistry

U-Pb isotopic data presented in this study were obtained from 73 samples analyzed in previous studies on the PRNJ, including samples of the Juruena supersuite (Paranáfa, São Pedro and Nova Canãá suites), Colíder group, Teles Pires suite, Roosevelt group, Vespor Mafic suite, Teodózia suite, Zé do Torno suite and Nova Monte Verde complex, and from 9 new samples analyzed in this study (Table 1—Appendix B). Data presented in Table 1 show that the significant magmatism, pre-

### 3.1. Sampling and analytical methods

Samples were collected during geological mapping. Our sampling covers most lithologies of granites and mafic rocks of the WAIB. These samples were crushed, milled, and split into fractions for determining the whole-rock isotopic compositions, and for dating zircon. Zircon grains were separated from nine samples, using heavy liquid and magnetic separation techniques. All rocks were examined in thin sec-

### 3.2. U-Pb zircon geochronology by LA-ICPMS and SHRIMP

#### 3.2.1. Juruena supersuite (Paranaíta suite)

Granitic rocks from this unit vary in texture from isotropic, coarse-
to very coarse-grained, to weakly foliated, medium-grained. Brittle deformation predominated, but narrow zones of ductile deformation are sometimes observed, usually along the margins of bodies oriented in EW direction. In a profile along the main body, from south to north, in the surroundings of Paranaíta town, a decrease in deformation intensity and biotite content was observed. The main population of zircons of sample API-455 (S 09°.5512; W 57°.4063) yielded a U-Pb isochron age of 1813 ± 9.8 Ma, which is interpreted as the crystallization age of sye-

### Appendix A

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#### 3.2.3. Zé do Torno suite

#### 3.2.4. Roosevelt group

#### 3.2.5. Vespor Mafic suite

Mafic rocks of the suite crop out as stocks of gabbros, diorites and the corresponding dyke swarms. In the neighborhood of Nova Monte Verde metamorphic core complex, mafic rocks show sigmoidal shapes and are bordered by an anastomosed network of shearing zones with EW direction, where amphibolites predominate. Features of magma mixing in acid rocks are frequent, therefore coeval with granites of the Juruena supersuite. Granite contacts are usually diffuse, with mafic enclaves within the granites and mafic microgranular enclaves con-

#### 3.3. Sample and analytical methods

#### 3.3.1. Juruena supersuite (Paranaíta suite)

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U-Pb isotopic data presented in this study were obtained from 73 samples analyzed in previous studies on the PRNJ, including samples of the Juruena supersuite (Paranaíta, São Pedro and Nova Canãá suites), Colíder group, Teles Pires suite, Roosevelt group, Vespor Mafic suite, Teodózia suite, Zé do Torno suite and Nova Monte Verde complex, and from 9 new samples analyzed in this study (Table 1—Appendix B). Data presented in Table 1 show that the significant magmatism, pre-

#### Appendix A

#### 3.4.1. Juruena supersuite

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narrow rims. Some crystals of zircons display U-rich (dark BSE) cores. Radial and cross-cutting fractures occur mostly in the dark gray core of the crystals. Fourteen analyses yield weighted mean 207Pb/206Pb age of 1827 ± 27 Ma (Fig. 3b) that records the age of crystallization of the granite. One xenocryst core indicates inheritance with 207Pb/206Pb age of 1903 Ma (Table 3 and Fig. 4a).

3.2.2. Juruena supersuite (São Pedro suite)

Rocks from this suite are predominantly monzogranite and rarely granodiorite. They show porphyritic texture (~40–70% of crystals of K-feldspar + plagioclase) in phaneritic matrix that consists of quartz, K-feldspar, plagioclase and biotite. Biotite defines a subtle foliation that surrounds K-feldspar phenocrysts. In general, phenocrysts show deformation in subsolidus conditions, and mafic microgranular enclaves

Fig. 3. U–Pb Concordia plots of zircon of granites from WAIB. (a) Paranaíta suite. The age of 1813 ± 10 Ma is the crystallization age. The other grains are inherited and yielded ages of Paleoproterozoic to Archean, and (b) The 1827 ± 27 Ma age is interpreted as crystallization age; (c) Monzogranite of the São Pedro suite. The age of 1805 ± 7 Ma is the crystallization age; (d, e and f) U–Pb Concordia plots of zircon of granites from Teles Pires suite.
Yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1794 ± 6 Ma, which is interpreted as the crystallization age.

### 3.2.3. Teles Pires suite

The analyzed samples represent different types of granites of the Teles Pires suite, which is divided into two facies: (a) Granitic Leucocratic facies: equigranular leucocratic alkali-feldspar granite and syenogranite, rich in globular quartz, with rapakivi texture; and quartz-K-feldspar porphyry; highly magnetic, and microporphyritic Subvolcanic facies: microsyenogranite, granophyre, quartz-porphyry

Eleven zircon crystals of porphyritic biotite syenogranite of granitic leucocratic facies (CT03 - S 9°.9230; W 54°.8383) were analyzed and yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1794 ± 6 Ma, which is interpreted as the crystallization age of the granitic magma (Fig. 3d).

Sample GR 04 (S 10°.5367; W 54°.5739) is an isotropic porphyritic syenogranite, produced by shallow crystallization (hypabyssal), and that has an intrusive contact with the volcaniclastic rocks of the Colíder group. This rock has prismatic and subrounded phenocrysts of K-feldspar, in places mantled by plagioclase, and pseudohexagonal to rounded phenocrysts of quartz, in a fine-grained reddish phaneritic matrix, consisting of K-feldspar + quartz + plagioclase and rare biotite. Zircons are euhedral to subhedral (about 150–500 μm long), occasionally translucent, and form a single population. Although some cores are present, most zircons show oscillatory magmatic zoning and, in the majority of cases, there is no discordance at the core-rim boundary. There is, moreover, no significant difference in age between cores and rims of zircons from the syenogranite. Seventeen analyses yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1794 ± 6 Ma (Fig. 3c) that records the crystallization age of the granite. In addition, two xenocryst populations are recognized: an older represented by one core with minimum $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1941 ± 18 Ma (Fig. 4b) and a younger (zr 07) with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1831 Ma (Table 3).

Another granite from this suite, sample RBE-2 (S 9°.8174; W 54°.9329) has two main populations of zircons, both magmatic, with Th/U ratios ranging from 0.60 to 1.56 (Table 2). The oldest population yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ (n = 6) age of 1809 ± 14 Ma, whereas the youngest population yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ (n = 6) age of 1763 ± 7 Ma (Fig. 3f). The youngest age is interpreted as the crystallization age of the granite, whereas the oldest age may represent xenocrysts within the alkali-feldspar granite that correspond to country rocks represented by the Paraná suite. Additionally, inherited grains (G2-1, G5-3) with ages of 1970 and 2135 Ma (Table 2) suggest inheritance from Nhandu granites and Cuiu-Cuiu basement gneisses, respectively.

### 3.2.4. Colíder group

Rhyolites, rhyodacites, ignimbrites and subordinate andesitic basalts from the Colíder group occur usually associated with the sub-volcanic granitic intrusive rocks of the Teles Pires suite, commonly showing textures and structures similar to those of the rhyolites and rhyodacites of the Colíder group. The contacts are transitional and diffuse, wherever visible. Sample CLD (S 10°.8285; W 55°.4141) is an amygdaloidal basaltic andesite, in the form of a long dyke trending EW, showing cavities filled with quartz and epidote and, sometimes, obsidian. Amygdules are ellipsoid to elongated, oriented along the igneous flow. In some places, andesitic basalts are over lain by thin layers of ash, with characteristics of surge deposits.

Isotopic analysis of four zircon crystals yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1785 ± 25 Ma, which is interpreted as the crystallization age of the andesitic basalt. There are also two inherited zircons with age of 1841 ± 16 Ma (Fig. 5a). This older age (inheritance) represents the granites that crop out at Zé Vermelho mine, to the north of Paranaíta town, and the granites of Acari river, to the SW of Amazonas state (Meloni et al., 2017), probably basement of the volcanic rocks.

Sample I-688 (S 10°.8351; W 57°.4477) is a dark gray andesite, which shows a significant structure of igneous flow with N25E orientation and a network of sub-parallel fractures filled with epidote, quartz and titanite. These rocks are over lain by ignimbrites and volcanogenic sandstones. They have fine-grained phaneritic to aphanitic matrix, consisting of few microphenocrysts of plagioclase and amphibole. Clusters of epidote and white mica developed into the core and microfractures of plagioclase microphenocrysts.

Isotopic analyses of six crystals of zircon yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1783 ± 15 Ma, which is interpreted as the crystallization age of the andesite. There are also four inherited zircons with age of 1827 ± 8 Ma (Fig. 5b). The crystallization ages of the two samples of volcanic rocks are identical thus, they have inherited older zircons from magmatic rocks with ages between 1840 and 1827 Ma, which are similar to ages obtained in sample CLD. Rock outcrops with this age occur in SE Amazonas (Acari river) (Meloni et al., 2017) and in Zé Vermelho deposit (Gomes, 2018).

### 3.2.5. 5- Vespor Mafic suite

Ages previously published for rocks of the Vespor Mafic suite include U-Pb (LA-ICPMS) 1773 and 1764 Ma (Ribeiro and Duarte, 2010). In this study, one sample was collected from a porphyritic gabbro, which has an intrusive contact with the volcaniclastic rocks of the Colíder group. Ages previously published for rocks of the Vespor Mafic suite include U-Pb (LA-ICPMS) 1773 and 1764 Ma (Ribeiro and Duarte, 2010). In this study, one sample was collected from a porphyritic gabbro, which has an intrusive contact with the volcaniclastic rocks of the Colíder group. In this study, one sample was collected from a porphyritic gabbro, which has an intrusive contact with the volcaniclastic rocks of the Colíder group.

Another granite from this suite, sample RBE-2 (S 9°.8174; W 54°.9329) has two main populations of zircons, both magmatic, with Th/U ratios ranging from 0.60 to 1.56 (Table 2). The oldest population yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ (n = 6) age of 1809 ± 14 Ma, whereas the youngest population yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ (n = 6) age of 1763 ± 7 Ma (Fig. 3f). The youngest age is interpreted as the crystallization age of the granite, whereas the oldest age may represent xenocrysts within the alkali-feldspar granite that correspond to country rocks represented by the Paraná suite. Additionally, inherited grains (G2-1, G5-3) with ages of 1970 and 2135 Ma (Table 2) suggest inheritance from Nhandu granites and Cuiu-Cuiu basement gneisses, respectively.
that some grains have irregular zoning pattern. The Th/U ratios vary between 0.75 and 1.70, suggestive of magmatic origin. The rock has one population of magmatic zircon and metamorphic rims or older cores not detected. Concordia age is 1779 ± 6 Ma (Fig. 6), which represents the age of crystallization of the gabbro.

### 3.3. Sm-Nd results

Data were gathered from 51 samples of previous studies on whole-rock Nd isotopes, and the results are shown in Table 4-Appendix B. $\varepsilon_{\text{Nd}(t)}$ was calculated based on crystallization ages from zircon U-Pb dating. For samples without U-Pb ages, $\varepsilon_{\text{Nd}(t)}$ was calculated based on the age obtained for the sample from the same outcrop or for a sample from the same suite. For undated samples, $\varepsilon_{\text{Nd}(t)}$ was calculated for crystallization age of 1.8 Ga, which, together with field data, indicates that plutonic and volcanic events are coeval. Model ages of depleted mantle (TDM) were calculated based on the De Paolo model (1981).

Although the studied samples show a wide range of $^{147}\text{Sm}/^{144}\text{Nd}$ ratios, from 0.08 to 0.13, which is expected due to SiO$_2$ ranging between 63 and 77 wt%, model ages and $\varepsilon_{\text{Nd}(t)}$ have small variations (Fig. 7 and tab. 4-Appendix B).

All samples collected from the granites of the Juruena supersuite, Teles Pires suite and from volcanic rocks of the Colider group have similar isotopic compositions and Nd concentration. Granites of the above-mentioned suites have $^{143}\text{Nd}/^{144}\text{Nd}$ initial ratio between 0.510149 and 0.510488, with $\varepsilon_{\text{Nd}(t)}$ ranging from −3.9 to +2.52, and TDM model ages ranging from 1.93 Ga to 2.36 Ga. Acid volcanic rocks of the Colider group have $^{143}\text{Nd}/^{144}\text{Nd}$ initial ratios similar to granites, ranging from 0.510144 to 0.510410, with close-to-zero to slightly negative $\varepsilon_{\text{Nd}(t)}$ values (−0.20 to −3.71), and only one sample has $\varepsilon_{\text{Nd}(t)}$ of +1.26. TDM model ages are similar to granites of Juruena supersuite and Teles Pires suite, ranging from 1.97 Ga to 2.34 Ga.

Samples of mafic rocks from the Vespor suite are characterized by slightly higher $^{143}\text{Nd}/^{144}\text{Nd}$ initial ratios, ranging from 0.510327 to 0.510426, with positive values of $\varepsilon_{\text{Nd}(t)}$ (+0.31 to +1.83), and TDM model ages between 1.93 Ga and 2.20 Ga, which indicate formation from mantle rocks with little participation of crustal material.

An alternative hypothesis for the evolution of the rocks of the western part of the WAIB was proposed by Duarte et al. (2012), who suggested two sources for the origin of the bimodal volcanic-plutonic magmatism. One older source, with TDM ages between 2.3 and 2.1 Ga, and negative values of $\varepsilon_{\text{Nd}}$ (~−1.5), and another younger source, with TDM ages between 2.0 and 1.9 Ga, and positive values of $\varepsilon_{\text{Nd}}$ (~+1.0).

### 4. Whole-rock geochemistry

In this section, granites of the Juruena supersuite, Teles Pires suite,
and volcanic rocks of the Colíder and Roosevelt groups are compared with the migmatitic rocks of the Nova Monte Verde complex. Chemical data from the Teodósea suite are not interpreted in this study, and the results are available in Costa et al. (2013). Analyzed samples (n = 586) are uniformly distributed over the WAIB, results shown in Tables 5, 6 and 7—Appendix C.

a) Juruena supersuite (Paranaíta, São Pedro, Nova Canaã and Zé do Torno suites)

All four suites consist essentially of granites (syenogranite to monzogranite with few alkali-feldspar granites). SiO₂ content ranges from 63 to 77 wt% in the granites, which vary from metaluminous to peraluminous with an increase in SiO₂. They show a sub-alkaline trend, which is different from the granites of calc-alkaline series. In contrast, granites plot in the ferrous granite field, and most samples plot in the A-type granite field (Frost et al., 2001). More chemical data, tables and figures are in Appendix C.

b) Teles Pires suite

In general, granites from the Teles Pires suite have a chemical composition similar to granites of the Juruena supersuite (tab. 5—Appendix C). Granites have SiO₂ contents from 63 to 78 wt% and vary from metaluminous to peraluminous as SiO₂ content increases. However, in those granites less evolved and with mafic microgranular enclaves, SiO₂ contents are lower (63–69 wt%). They show a sub-alkaline trend, which is different from granites of calc-alkaline series. More chemical data, tables and figures are in Appendix C.

c) Colíder and Roosevelt groups

Intermediate and acid volcanic rocks from these groups are discussed together because they show similar chemical and mineralogical characteristics (tab. 5). Chemical characteristics of this volcanic set are similar to granites of the Teles Pires suite and Juruena supersuite. Volcanic rocks are predominantly acid, with SiO₂ content ranging from 63 to 77 wt%. Rhyolite and rhyodacite predominate, with subordinate dacites and quartz-latitites. Rocks are metaluminous to peraluminous and show a strong sub-alkaline trend. More chemical data, tables and figures are in Appendix C.

d) Nova Monte Verde complex

A genetic link between migmatites and granites has been the subject of discussion and petrological studies by several authors in the world (for example, Sawyer, 1996; Johannes et al., 2003; Johnson et al., 2003). Migmatites, in general, are considered partially melted source rocks of granites (Sawyer, 1998). Moreover, studies have indicated that a considerable part of rocks from the continental crust are the source for the production of significant volumes of granite magma (Patíño Douce and Johnston, 1991; Clemens and Vielzeuf, 1987). In this context, migmatites from the Nova Monte Verde complex are considered possible sources of the granitoids and volcanic rocks of the Juruena supersuite and Colíder and Roosevelt groups.

Samples from the Nova Monte Verde complex are mostly ortho-derived metatexites, with a high proportion of granitic leucosome. Diatexites are subordinate. Chemical analysis of migmatitic gneisses shows a set of rocks that range from tonalite to granite, in addition to rare quartz monzonite. SiO₂ contents are variable, ranging from 62 to 74 wt% and the rocks vary from metaluminous to peraluminous. Chemical data, tables and figures are in Appendix C.

e) Vespor Mafic suite

Data on major and trace elements of rocks from the Vespor Mafic suite are shown in table 7. In general, mafic rocks have low content of SiO₂ (46.30–50.40 wt%), high contents of Fe₂O₃ (9.37–15.10 wt%) and MgO (5.51–12.88 wt%), low to intermediate content of TiO₂ (0.62–1.52 wt%), and mg# values that range from 0.45 to 0.72. Mafic rocks of the suite are chemically gabbros and show a trend of progressive enrichment in iron with differentiation, which is a diagnostic characteristic of magmas from the tholeiitic series. Complementary chemical data are in Appendix C.

5. Petrogenesis and tectonic setting

Mafic rocks from the Vespor suite have low SiO₂ contents, and high TiO₂, Fe₂O₃(t) and MgO contents. They are gabbros in the (K₂O + Na₂O) vs. silica (SiO₂) diagram and show in the AFM diagram a FeO enrichment trend that is characteristic of tholeiites. These geochemical features indicate that mafic rocks were formed from mantle-derived magma, similar to modern P-MORBs and continental tholeiites. The slight enrichment in LREE, positive anomalies of Th, U, Ba, Nb and Sr, and the slight negative anomaly of Nb are features suggestive of crustal assimilation during magmatic processes (Wilson, 1989). Moreover, trace elements of Vespor mafic rocks are similar to continental tholeiites, particularly enrichment in LREE and negative anomalies of Nb, Zr and Ti (Weaver and Tarney, 1983; Thompson et al., 1984). The negative Nb anomaly may represent not only the removal of Ti oxides, but also magma contamination by crustal material. These anomalies can also occur in continental tholeiites (for example, Thompson et al., 1984; Dupuy and Dostal, 1984; Cox and Hakesworth, 1985; Campbell and Griffiths, 1990). Therefore, negative Nb anomalies are not exclusive of magmas related to subduction. Moreover, a negative HFSE anomaly is not a definitive geochemical characteristic of a subduction zone. In addition, strong enrichment in Th and ETRL is a distinctive feature of continental crust (for examples, Taylor and McLennan, 1985). Therefore, crustal contamination is a mechanism for the development of negative Nb anomalies in basaltic rocks, not related to a subduction environment.

Isotopic data of mafic rocks indicate close-to-zero values of εNd, which is a common characteristic of modern continental basalts. Therefore, Statherian mafic rocks of the WAIB may have formed by partial melting of a depleted asthenospheric mantle associated with slight assimilation of continental crust in a continental rift environment.

On the other hand, granitic rocks of the Juruena supersuite and Teles Pires suite, and the correlated felsic volcanic rocks of Colíder group are characterized by high SiO₂ and K₂O + Na₂O contents and low TiO₂, Fe₂O₃(t) and MgO contents; most of them classified as granite/ryholite in geochemical diagrams. They are oxidized ferrous rocks, ranging from alkali-calcic to calc-alkaline. These and other chemical characteristics are similar to A-type granites.

The Vespor suite and Juruena supersuite do not have intermediate petrographic types and, therefore, constitute bimodal magmatism, where the mafic rocks from the Vespor suite and the granites from the Juruena supersuite and Teles Pires suite are two groups with different chemical compositions (Fig. 8).

Intrusive and felsic volcanic rocks can be generated by fractional crystallization of a basaltic magma or by partial melting of old continental crust. The Statherian granitic rocks of the Juruena supersuite and Teles Pires suite and the volcanic rocks of the Colíder group are characterized by close-to-zero values of εNd(t) (negative and positive) in whole-rock samples, and by model ages (1.97–2.34 Ga) older than crystallization ages (1.81–1.76 Ga). Mafic rocks, in turn, are characterized by slightly positive values of εNd(t) in whole-rock samples and model ages similar to those of granites (1.93–2.20 Ga). Therefore, Nd isotopic compositions of granites and acid volcanic rocks are similar. This, together with the values of εNd, indicates a mixed source for the Statherian acid magmatism of WAIB. Thus, Statherian plutonic and volcanic felsic rocks may have formed by partial melting of old
continental crust (Ventuari-Tapajós). Anatexis of old crust in the PRNJ was probably induced by ascent of hot asthenospheric mantle during rifting.

Numerical thermal modeling suggests that large-scale crustal melting requires unusually high heat flow (e.g. Pettford and Gallagher, 2001; Annen and Sparks, 2002; Dufek and Bergantz, 2005). This applies even in dehydration melting, and the production of relatively dry magmas such as the Juruena supersuite, resulted in the enormous volume of felsic melt required to produce this regionally dominant lithological feature. The suggestion that voluminous mantle-derived magmatism contributed both heat and source material to the petrogenesis of the Juruena supersuite is consistent with recent models for the generation of large-volume felsic magmas in all tectonic environments (e.g. Annen et al., 2006; Bachmann and Bergantz, 2008). Bachmann and Bergantz (2008) argued that evolved felsic magmas form within, and are extracted from, long-lived crystallizing mush zones periodically fed by mantle-derived magmas. Partial melting of crust is considerably less important, but is coupled to emplacement of mush zones, and allows for the transfer of crustal compositional attributes to the interstitial mush magmas. Such models are heavily based on the MASH (melting, assimilation, storage, homogenization; Hildreth and Moorbath, 1988) hypothesis, which attributes large-scale homogeneity in the lower crustal source regions of granites to the formation of MASH domains. These are produced when mantle-derived mafic underplated and intraplated magmas mix with, and assimilate, local crustal components (typically as melts of country rock), producing crystal-rich mush chambers that undergo dynamic homogenization as well as periodic magma recharge (e.g. Hildreth and Moorbath, 1988; Riley et al., 2001; Hildreth and Wilson, 2007).

During this process, magmatism was predominantly bimodal, and mantle rocks interacted with old continental crust (Ventuari-Tapajós crust), resulting in a mixture of mafic-felsic magmas (mush zone; Fig. 9).

In this context, field evidence, together with textures/structures of granites of the studied suites, and an abundance of experimental data from several countries show that microgranular enclaves within granitic plutons and corresponding volcanic rocks were the result of the dynamic interaction between two different types of magmas (Blake et al., 1965; Didier, 1964). This finding, which is widely accepted by most researchers in the field of granites, implies that mafic microgranular enclaves correspond to hot mafic liquids of basic to intermediate composition (45–55% of SiO₂), which were injected into colder acid felsic magmas (65–75% of SiO₂) (Bonin, 2004). Moreover, abovementioned geochemical data suggest that basaltic and granitic magmas are not commagmatic.

Therefore, the evolutionary history of WAIB in SW Amazonian proto-craton initially consisted of extensional tectonics associated with decompression of upper crust, induced by mantle melting and basaltic magma generation. In this context, the dyke swarm and mafic bodies of Vespor mafic suite were formed. This magma was trapped in the lower crust in the form of subcrustal magmatic layers, providing enough heat for the partial melting and generation of granitic magma (Fig. 9).

At the end of Orosirian and beginning of Statherian, landmasses went through a long process of taphrogenesis, forming bimodal magmatism and sedimentary basins (Brito Neves et al., 1995; Goodwin, 1991; Bossi et al., 1993). Similarly, felsic and mafic magmas ascended to the upper crust through reactivated deep structures, forming mafic bodies and dyke swarms associated with alkali-calcic A-type plutons (gabbros and diabases of the Vespor mafic suite and plutonic/volcanic rocks of the Juruena supersuite and Teles Pires suite, and volcanic rocks of the Colíder group), in addition to fissured acidic volcanic rocks. However, during magma rising, mixing took place and the initial composition was changed, generating magmas with intermediate composition and hybrid rocks (for example, anidesites and granodiorites).

Therefore, the old continental crust that went through the extensional process consists predominantly of Paleoproterozoic rocks with ages between 2.05 and 1.87 Ga, with high K calc-alkaline composition. This old crust is part of the Peixoto de Azevedo Domain of the Ventuari-Tapajós Province. Archean rocks were identified within this domain and are an inlier of old migmatic rocks. Moreover, further east of the Peixoto de Azevêdo Domain, Archean rocks are more widely distributed (Central Amazonia Province). The Ventuari-Tapajós old crust with Archean fragments was melted by heat-related to basic magma underplating, resulting in significant felsic magmatism, which was widely distributed in the southern part of the Rio Negro-Juruena Province during the beginning of Statherian. Alkali-calcic to calc-alkaline high-K composition characteristic of Paleoproterozoic rocks of the Juruena-Teles Pires-Colíder was inherited from their source – Paleoproterozoic (Archean) rocks of the Ventuari-Tapajós Province (see geochemistry data). Along this hypothesis, model ages of the PRNJ rocks indicate a Paleoproterozoic source (2.0–2.3 Ga), as well as the Orosirian-Archean inherited zircons from the Statherian plutonic-volcanic rocks.

Analysis of the data suggests important and significant participation of crustal sources (Paleoproterozoic/Archean?) in the generation of the predominant acid plutonic volcanism in PRNJ, which took place between 1820 and 1760 Ma and was not related to a subduction environment (Fig. 9).

A model that considers melting of a depleted mantle in an Andean-type arc system to produce long-term felsic magmatism was discussed by Duarte et al. (2012) and Scandolara et al. (2014). However, there is no evidence of tectonic segmentation of an Andean-type arc in the PRNJ during the formation of the WAIB. Geological and geochemical data indicate intra-plate segmentation. According to this reasoning, an ensialic extensional tectonic setting is documented in the PRNJ because of the close association, in time and space, of (Fig. 9): a) granites and felsic volcanic rocks derived from the Ventuari-Tapajós continental crust melting; b) formation of migmatites and granulites coeval to granites/acid volcanic rocks by underplating of basic magma; c) mafic tholeiitic rocks formed by partial melting of the upper mantle, similar to P-MORBs or continental tholeiites; d) mixing of contrasting mafic-felsic magmas. Therefore, we propose that the PRNJ records a continental stretching episode, not related to coeval subduction. In addition, evidence of arc-derived magmatism was not found.

6. Conclusions

The interpretation of an intraplate setting for Western Amazonia Igueo Belt is based on several lines of evidence, including: 1) lack of evidence for prolonged regional scale compressional deformation; 2) felsic rocks have dominant alkali-calcic, metaluminous to
bridization, and fractional crystallization. The observed mantle have a mantle component, and evolved through assimilation, hy-
sociation in the PRNJ. Felsic rocks are essentially crust derived, but crust is the most plausible mechanism for the bimodal magmatic as-
underplating with voluminous dehydration partial melting of deep
of the whole spectrum of granitic rocks present in WAIB. Magmatic

crystallization caused extensive melting of ambient crust and formation
Emplacement of tholeiitic melts into the middle crust and partial
mixing with mantle-derived melts and formation of granitic melts.
These processes resulted in partial melting of lower-crustal material,
overlapping those of associated granites.

Associated mafic rocks of all regions have Nd isotope signatures largely
input of juvenile Nd from coeval mantle-derived tholeiite melts.

Appendix A. Supplementary data
Supplementary data to this article can be found online at https://

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