Geochemistry and petrogenesis of the Mesoarchean granites from the Canaã dos Carajás area, Carajás Province, Brazil: Implications for the origin of Archean granites

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A B S T R A C T

Four Mesoarchean (2.93 to 2.83 Ga) granite units, which encompass the Canaã dos Carajás, Bom Jesus, Cruzadão and Serra Dourada granites, were recognized in the Canaã dos Carajás area of the Archean Carajás Province. The Mesoarchean units are composed dominantly of biotite leucomonzogranites. They are compared with the Neoarchean Pluton suite (2.73 Ga) which encompasses biotite–hornblende monzogranites to syenogranites. The Canaã dos Carajás, Bom Jesus and the variety of the Cruzadão granite with higher (La/Yb)N are geochronologically more akin to the calc–alkaline granites, whereas the other varieties of the Cruzadão granite are transitional between calc–alkaline and alkaline granites. The Serra Dourada granite has an ambiguous geochemical character with some features similar to those of calc–alkaline granites and other peraluminous granites. The Pluton granites have ferroan character, are similar geochronologically to reduced A-type granites and show a strong geochemical contrast with the Mesoarchean studied granites. The Mesoarchean granites described in the Canaã dos Carajás area are geochemically distinct to those of the Rio Maria domain of the Carajás Province. The Canaã dos Carajás and Bom Jesus granites are similar to the high-Ca granites, whereas the Cruzadão and Serra Dourada are more akin to the low-CaO granites of the Yilgarn craton. The geochemical characteristics of the Mesoarchean studied granites approach those of the biotite granite group of Dharwar but the latter are enriched in HFSE and HREE compared to the Canaã dos Carajás granites. The Neoarchean Pluton suite granite has no counterpart in the Mesoarchean Rio Maria domain of the Carajás Province, neither in the Yilgarn and Dharwar cratons. Geochemical modeling suggests that partial melting of a source similar in composition to an Archean basaltic andesite of the Carajás Province could give origin to the Bom Jesus and Cruzadão granites. In the case of the Bom Jesus granite the residue of melting contained, in similar proportions, plagioclase, clinopyroxene, amphibole, and garnet, with subordinate ilmenite. The variations in (La/Yb)N and Sr/Y of the Cruzadão granite are controlled by changes in the residual melting phases. Garnet and amphibole are abundant in the residue of the variety with higher (La/Yb)N, whereas in the rocks with moderate to lower (La/Yb)N garnet is absent, magnetite appears in the residue and amphibole initially increases but is replaced by orthopyroxene in the rocks with the lowest (La/Yb)N. In the Canaã dos Carajás and Serra Dourada granites garnet was probably an absent phase in the residue of melting and the influence of amphibole was also apparently limited. A crustal environment and a variable pressure between 10 to 7 kbar are estimated for the generation of the granite magmas. The Bom Jesus and Cruzadão granites are similar to the high-Ca granites, whereas the Serra Dourada and Bom Jesus are more akin to the low-CaO granites of the Yilgarn craton. The geochemical characteristics of the Mesoarchean studied granites approach those of the biotite granite group of Dharwar but the latter are enriched in HFSE and HREE compared to the Canaã dos Carajás granites. The Neoarchean Pluton suite granite has no counterpart in the Mesoarchean Rio Maria domain of the Carajás Province, neither in the Yilgarn and Dharwar cratons. Geochemical modeling suggests that partial melting of a source similar in composition to an Archean basaltic andesite of the Carajás Province could give origin to the Bom Jesus and Cruzadão granites. In the case of the Bom Jesus granite the residue of melting contained, in similar proportions, plagioclase, clinopyroxene, amphibole, and garnet, with subordinate ilmenite. The variations in (La/Yb)N and Sr/Y of the Cruzadão granite are controlled by changes in the residual melting phases. Garnet and amphibole are abundant in the residue of the variety with higher (La/Yb)N, whereas in the rocks with moderate to lower (La/Yb)N garnet is absent, magnetite appears in the residue and amphibole initially increases but is replaced by orthopyroxene in the rocks with the lowest (La/Yb)N. In the Canaã dos Carajás and Serra Dourada granites garnet was probably an absent phase in the residue of melting and the influence of amphibole was also apparently limited. A crustal environment and a variable pressure from 10 to 7–8 kbar are estimated for the generation of the granite magmas. The Bom Jesus and Cruzadão granites of Carajás derived from basaltic andesite sources and not of TTG and their geochemical contrasts can be explained by variation in the pressure of melting. The sources of Archean granite magmas are more diversified and could be more mafic than generally admitted.

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1. Introduction

Archean cratons are composed dominantly of tonalitic–trondhjemitic–granodioritic series (TTG) associated with greenstone belts (Condie, 1993; Goodwin, 1991; Martin, 1994; Moyen, 2011). However, other kinds of granitoid rocks which include sanukitoid series (Halla, 2005; Heilimo et al., 2011; Lobach-Zhuchenko et al., 2005; Moyen et al., 2003; Oliveira et al., 2009; Smithies and Champion, 2000; Stern and Hanson, 1991) and different varieties of potassic granites (Almeida, 2010; Champion and Sheraton, 1997; Champion and Smithies, 2007; Davis et al., 1994; Frost et al., 1998; Ishihara et al., 2002; Jeyaraj et al., 2006; Käpyaho et al., 2006; Moyen, 2011b; Moyen et al., 2003; Sylvester, 1994; Whalen et al., 2004), are now recognized as important components of Archean cratons.

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Fig. 1. (a) Location of the Carajás Province in the Amazonian craton; (b) Geological map of the Carajás Province, showing the location of the Canaã dos Carajás area and the approximate limits between the Rio Maria and Carajás domains (dashed line), and the Carajás basin and 'Transitional' sub-domain (continuous lines); (c) Geological map of the Canaã dos Carajás area.
Sylvester (1994) stated that the Archean granites were more voluminous than previously admitted and there is increasing evidence in the literature of a large geochemical diversity of Archean granites (Almeida, 2010; Almeida et al., 2010; Champion and Sheraton, 1997; Champion and Smithies, 2007; Jayananda et al., 2006; Kápyaño et al., 2006; Many et al., 2007; Moyen et al., 2003). On the other hand, potassic granites are generally related to the late stages of tectonic stabilization of Archean cratons (Davis et al., 1994; Goodwin, 1991; Kröner et al., 1991; Nisbet, 1987). Thus, it is relevant for a clear understanding of the late Archean evolution, a better geochemical characterization and the definition of the petrogenetic processes involved in the origin of different granites formed at that period.

We present in this paper a detailed geochemical characterization of four different Mesoarchean varieties of granites distinguished in the Canaã dos Carajás area of the Carajás Archean province of the eastern Amazonian craton (Fig. 1a). These granites show distinct Sr/Y and La/Yb ratios and are compared with the Neoarchean Planalto suite of the same province and with the Archean granites found in the adjacent Rio Maria domain and in the Yilgarn and Dharwar cratons in order to contribute to clarify the nature and possible origin of the Archean potassic granites. The meaning of whole rock Sr/Y and La/Yb ratios (Almeida et al., 2010; Halla et al., 2009; He et al., 2011; Martin, 1999; Moyen, 2009) for definition of sources and processes involved in magma origin is emphasized. We have tested by geochemical modeling the sources of the studied granites. Possible explanations for their geochemical contrasts and the implications for the origin of Archean granite magmas are discussed.

2. Geological and tectonic setting

The Carajás Province is the largest and best preserved Archean segment of the Amazonian craton (Fig. 1a). It is located in the southeastern part of the Amazonian craton (Fig. 1a; Dall’Agnol et al., 2006; Machado et al., 1991; Santos et al., 2000; Tassinari and Macambira, 2004) and two distinct domains separated by approximately E–W shear zones were distinguished on it (Fig. 1b; Vasquez et al., 2008). To the south, it exposed the Mesoarchean Rio Maria domain (RMGGT; 3.0 to 2.86Ga; Almeida et al., 2011; Althoff et al., 2000; Macambira and Lafon, 1995; Souza et al., 2001) and, to the north, the Carajás domain (3.0 to 2.55Ga; Dall’Agnol et al., 2006; Gibbs et al., 1986; Machado et al., 1991; Vasquez et al., 2008).

The Mesoarchean Rio Maria domain is composed of greenstone belts (3.0–2.90Ga; Macambira and Lafon, 1995; Souza et al., 2001 and references therein) and several granitoid series: (1) An older TTG series (2.98–2.93Ga; Almeida et al., 2011; Althoff et al., 2000; Leite et al., 2004; Macambira and Lancelot, 1996); (2) The sanukitoid Rio Maria suite (~2.87Ga; Macambira, 1992; Oliveira et al., 2009, 2010 and references therein); (3) A younger TTG series (~2.87–2.86Ga; Almeida et al., 2011; Leite et al., 2004); (4) High Ba–Sr leucogranodiorite–granite suite (~2.87Ga; Almeida et al., 2010); and (5) Potassic leucogranites of calc-alkaline affinity (~2.87–2.86Ga; Almeida, 2010; Leite et al., 1999, 2004). Despite their diversity, the magmatic units of that terrane were generated in a relatively short period of ~120Ma.

The Carajás domain comprises a southern ‘Transition’ sub-domain, formed by strongly deformed Mesoarchean to Neoarchean units, and a northern sub-domain which corresponds essentially to the Neoarchean Carajás basin. Most of the Archean granitoid and gneissic rocks of the ‘Transition’ sub-domain were generally grouped in the Xingu Complex (Fig. 1b). The border between the RMGGT and the Carajás domain is located to the North of the Sapucaia belt (Fig. 1b), where there is geophysical evidence of a major tectonic discontinuity which separates the strongly deformed ‘Transition’ sub-domain of the RMGGT.

The Neoarchean Carajás basin (Fig. 1b) is formed dominantly by banded iron formations and basalts with subordinate felsic volcanic rocks metamorphosed in greenschist facies conditions (Itacaiunas Supergroup; 2.76–2.74Ga; Machado et al., 1991; Tallarico et al., 2005; Trendall et al., 1998). These sequences are partially covered by the fluvial to marine siliciclastic deposits of the Águas Claras formation (Nogueira et al., 1995). Neoarchean (~2.76–2.57Ga) subalkaline granite plutons (Barros et al., 2004, 2009; Feio et al., 2012a; Sardinha et al., 2004, 2006) and mafic-ultramafic stratified bodies (Vasquez et al., 2008 and references therein) are intrusive in the Mesoarchean units and in the Itacaiunas supergroup (Fig. 1b). These rocks are cross-cut by small stocks, sills, and dykes of Neoarchean hydrothermally altered gabbros.

Differently of the RMGGT, a large part of the evolution of the Carajás domain occurred during the Neoarchean when the Carajás basin and a widespread plutonic magmatism were formed. This implies that the tectonic stabilization of the RMGGT preceded that of the Carajás domain (Dall’Agnol et al., 2006). In this context, the ‘Transition’ sub-domain was interpreted as a probable Mesoarchean substratum, similar to the RMGGT, that was intensely affected by the magmatic and tectonic Neoarchean events recorded in the Carajás domain (Dall’Agnol et al., 2006 and references therein; Domingos, 2009). However, recent geological, geochemical and geochronological data obtained in the Canaã dos Carajás area (Feio et al., 2012b), in the northern part of the ‘Transition’ sub-domain, indicate that its evolution was distinct to that of the RMGGT. It is not possible to extrapolate this conclusion to all the ‘Transition’ sub-domain, but it suggests that...
the evolution of the two Archean domains of the Carajás Province could be more distinct than previously admitted.

3. Geology and geochronology of the Canaã dos Carajás area

The Canaã dos Carajás area is located in the border between the Carajás basin and the ‘Transition’ sub-domain. A more detailed discussion about the geology, geochronology and crustal evolution of that area was presented by Feio et al. (2012b) and additional geochronological data on the Planalto granite suite is given by Feio et al. (2012a). The geological map of the Canaã dos Carajás area is shown in Fig. 1c. The available geochronological information (Fig. 2, Table 2) demonstrates that the main evolution of the Canaã dos Carajás crust was concentrated in the Mesoarchean and Neoarchean. The oldest units (ca. 3.0 to 2.93 Ga) are small remnants of greenstone belts, the Pium granulitic complex, the Canaã dos Carajás granite and local
The tonalitic formations of the Itacaiúnas supergroup, the Vermelho ma-
2.70Ga) are represented by the metavolcanics and banded iron for-
2.37 to 2.83Ga) include the Campina Verde
suite granites, charnockitic rocks associated with the Plum complex,
and a little younger (ca. 2.65Ga) small stocks, dikes and sills of
granites, charnockitic rocks associated with the Pium complex,
the main part of the Rio Verde trondhjemitic, the Bom Jesus, Cruzadão, and Serra Dourada granites.

The Neorican units (mostly formed between 2.76 and 2.70Ga) are represented by the metavolcanics and banded iron formations of the Itacaínas supergroup, the Vermelho maﬁc-ultramafic stock, the tonalite–trondhjemitic Pedra Branca suite, the Planalto
trondhjemitic occurrences (part of the Rio Verde trondhjemitic). Other Mesoarchean units (ca. 2.87 to 2.83Ga) include the Campina Verde tonalitic complex, the major part of the Rio Verde trondhjemitic, the Bom Jesus, Cruzadão, and Serra Dourada granites.

Five distinct granite units (Fig. 2, Table 2) with variable ages (2.93 to 2.73Ga) were selected for the present study. They include (1) the Canaã dos Carajás granite, exposed in the southeastern part of the
Table 2
Summary of granites intrusions of the Canaã dos Carajás area, Carajás Province.

| Granite (geochronology) | Varieties and mafic contents (M’) | Geochemistry | Trace elements | REE | Sylvester classification | Modeling-fractionated phases. (in decreasing abundance order) |
|-------------------------|----------------------------------|--------------|----------------|-----|-------------------------|------------------------------------------------|---|
| Canaã dos Carajás (2.93–2.95Ga) | Granodiorite to monzogranite (M’=0–10%) | ACNK= 1.03–1.12 | Ba = 684–961 ppm | (La/Yb)N = 7–21 | Calc-alkaline | CA1 – calc-alkaline 1 Undefined |
|                         |                                  | SiO₂ = 70.56–72.93 wt.% | Sr = 202–282 ppm | Eu/Eu* = 0.7–1.1 |
|                         |                                  | Al₂O₃ = 14.28–14.84 wt.% | Y = 6–15 ppm |
|                         |                                  | FeO₂t = 1.55–1.03 wt.% | Nb = 5–7 ppm |
|                         |                                  | CaO = 1.50–1.60 wt.% | Zr = 89–126 ppm |
|                         |                                  | K₂O/Na₂O = 0.67–1.05 | |
|                         |                                  | ACNK= 1.02–1.08 | Sr/Y = 14–43 |
|                         |                                  | SiO₂ = 71.83–74.87 wt.% | |
|                         |                                  | Al₂O₃ = 13.24–14.84 wt.% | |
|                         |                                  | FeO₂t = 1.03–1.80 wt.% | |
|                         |                                  | CaO = 1.24–1.60 wt.% | |
|                         |                                  | K₂O/Na₂O = 0.98–1.60 | |
|                         |                                  | ACNK = 0.99–1.05 | |
|                         |                                  | Ba = 365–1531 ppm | |
|                         |                                  | Sr = 89–343 ppm | |
|                         |                                  | Y = 6–47 ppm | |
|                         |                                  | Nb = 4–39 ppm | |
|                         |                                  | Zr = 146–345 ppm | |
|                         |                                  | Sr/Y = 2–53 | |
| Bom Jesus (2.83–2.85Ga) | Monzogranite to syenogranite (M’=2–7%) | 1– High (La/Yb)N = 78–120 | Eu/Eu* = 0.3–0.5 |
|                         |                                  | Sr/Y = 61–376 | |
|                         |                                  | Sr = 20–42 ppm | |
|                         |                                  | Y = 14–43 ppm | |
|                         |                                  | Nb = 1–7 ppm | |
|                         |                                  | Zr = 111–267 ppm | |
| Cruzadão (2.85–2.86Ga) | Monzogranite to syenogranite (M’=0–10%) | 1– High (La/Yb)N = 78–120 | Eu/Eu* = 0.3–0.5 |
|                         |                                  | SiO₂ = 70.63–74.34 wt.% | |
|                         |                                  | Al₂O₃ = 13.35–14.36 wt.% | |
|                         |                                  | FeO₂t = 1.13–2.55 wt.% | |
|                         |                                  | CaO = 0.54–1.62 wt.% | |
|                         |                                  | K₂O/Na₂O = 1.13–1.97 | |
|                         |                                  | Ba = 365–1531 ppm | |
|                         |                                  | Sr = 89–343 ppm | |
|                         |                                  | Y = 6–47 ppm | |
|                         |                                  | Nb = 4–39 ppm | |
|                         |                                  | Zr = 146–345 ppm | |
|                         |                                  | Sr/Y = 2–53 | |
| Serra Dourada (2.83Ga) | Monzogranite (M’=0–6%) | 1– High (La/Yb)N = 78–120 | Eu/Eu* = 0.3–0.5 |
|                         |                                  | SiO₂ = 72.32–75.40 wt.% | |
|                         |                                  | Al₂O₃ = 13.50–14.42 wt.% | |
|                         |                                  | FeO₂t = 0.69–2.12 wt.% | |
|                         |                                  | CaO = 0.26–1.94 wt.% | |
|                         |                                  | K₂O/Na₂O = 0.84–1.94 | |
|                         |                                  | ACNK = 1.06–1.16 | |
|                         |                                  | Ba = 561–1299 ppm | |
|                         |                                  | Sr = 60–194 ppm | |
|                         |                                  | Y = 9–16 ppm | |
|                         |                                  | Nb = 8–20 ppm | |
|                         |                                  | Zr = 54–235 ppm | |
|                         |                                  | Sr/Y = 4–18 | |
| Planalto* (2.73Ga) | Monzogranite to syenogranite (M’=3–20%) | 1– High (La/Yb)N = 78–120 | Eu/Eu* = 0.3–0.5 |
|                         |                                  | SiO₂ = 70.39–75.62 wt.% | |
|                         |                                  | Al₂O₃ = 11.13–13.44 wt.% | |
|                         |                                  | FeO₂t = 2.18–4.88 wt.% | |
|                         |                                  | CaO = 0.48–2.18 wt.% | |
|                         |                                  | K₂O/Na₂O = 1.18–2.39 | |
|                         |                                  | Ba = 489–1814 ppm | |
|                         |                                  | Sr = 85–204 ppm | |
|                         |                                  | Y = 16–96 ppm | |
|                         |                                  | Nb = 8–20 ppm | |
|                         |                                  | Zr = 283–506 ppm | |
|                         |                                  | Sr/Y = 1–6 | |

* Compiled from Feio et al. (2012a).
area; (2) the Bom Jesus granite in its central part; (3) the Cruzadão granite, with two different areas of occurrence, in the western and center-southern parts of the area; (4) the Serra Dourada granite, a stock located in the northern part of the area; and (5) the Planalto suite, represented by several stocks distributed along most of the area.

4. Geological and petrographic aspects of the Canaã dos Carajás granites

The studied granites are deformed and generally show penetrative foliation which follows the dominant NW–SE to W–E regional main trend (Fig. 1c). They were affected by important shear zones that locally define the limit of the granite bodies. The Serra Dourada is comparatively less deformed than the other granite units.

The modal compositions of representative samples of the five granite units (Table A in the supplemental data, and Fig. 3) demonstrate that the analyzed rocks are dominantly monzogranites, with subordinate granodiorite (Canaã dos Carajás) or syenogranite (Planalto suite, Bom Jesus and Cruzadão granites). Alkali feldspar granites are rare and limited to the Planalto suite. Except for some samples of the Planalto suite which can have hornblende as the main mafic mineral and have M’ (total modal mafic content minus muscovite, apatite, and primary carbonates; Le Maitre et al., 2002) generally between 5% and 20%, the remaining granite units are commonly composed of hololeucocratic rocks (M’<5%) with biotite as the main mafic phase.

4.1. Canaã dos Carajás granite

This granite forms a relatively large intrusion exposed in the southeastern part of the study area in the proximities of the Canaã dos Carajás town (Fig. 1c). Its western contact is limited by an important NE–SW lineament that is bordered by the southernmost extension of the Itacaiúnas supergroup (Fig. 1c). The granitic body was affected by large approximately E–W shear zones and was intruded by the Pedra Branca and Planalto suite stocks. The contact relationships were not observed in the field but geochronological data are conclusive about the younger age of the latter units compared to the granite. Locally, the latter includes metric enclaves of amphibolite.

The granite shows a penetrative, vertical NW–SE to E–W foliation which was locally crosscut by dextral and subordinate sinistral NE–SW oriented shear zones (Fig. 1c). A lineation dipping 60° to 70° to S or SE was also observed. The dominant foliation was folded and affected by faults oriented E–W dipping at high angle to S.

The granite is a strongly deformed and mylonitized, hololeucocratic rock (M’<5%). It displays gray color and medium- to fine-grained seriate texture. It is a biotite monzogranite to granodiorite, with zircon, magnetite, titanite ± apatite ± allanite as primary accessory minerals and muscovite, tourmaline, and chlorite as secondary ones. At the microscope, the texture is characterized by the presence of augen shaped plagioclase and alkali feldspar crystals enveloped by fine-grained recrystallized aggregates (core and mantle structures; Vernon, 2004). Quartz is strongly recrystallized and occurs as polygonal fine or elongated aggregates of grains. The biotite is oriented along the dominant foliation and contours the feldspar. Bulbous myrmekite (Phillips, 1980) is common in the border of the larger alkali feldspar crystals.

4.2. Bom Jesus granite

The Bom Jesus granite is exposed in the central-eastern part of the mapped area (Fig. 1c). It consists essentially of banded and foliated granite oriented along NE–SW to EW with vertical or steep SE- to S-dips. Sinistral mylonitic shear zones crosscut the granite and, locally, isoclinal folds with SE-dipping axes were registered. The granite was submitted to an intense ductile deformation responsible for its gneisic aspect. In the center of the Canaã dos Carajás area, this granite is intimately associated with the Rio Verde trondhjemite and both rocks show similar structures and occur in the field as intercalated bands or strips. The granite contains enclaves of amphibolites but field relationships between it and the other granite units were not observed.

It shows pink to gray color and fine- to medium- to coarse-grained seriated to porphyroclastic texture. It has monzogranite to syenogranite composition with biotite as the mafic mineral. The accessory minerals are allanite, titanite, zircon, magnetite ± ilmenite, and apatite. The secondary mineralogy is chlorite, rutile, hematite, epidote, carbonates, scapolite, and muscovite. In thin section, the foliation observed in the granite is defined by the oriented micas, the oval shaped feldspar porphyroclasts and the elongated recrystallized quartz aggregates. K-feldspar and plagioclase form the porphyroclasts which are set in a fine-grained recrystallized matrix. Plagioclase grains generally display deformed curved twin lamellae and myrmekite intergrowths occur in the borders of K-feldspar grains.

Fig. 3. QAP and Q-(A+P)-M’ diagrams (fields of Le Maitre et al., 2002) for the Archean granites of the Canaã dos Carajás area.
4.3. Cruzadão granite

The Cruzadão granite shows dominant NW–SE- to EW-striking foliation and was affected by shear zones and mylonitized. In its occurrence of the western of the area, it is locally associated with hornblende tonalites which were tentatively correlated with the Campina Verde tonalite complex (Feio et al., 2012b). In that area, both rocks define folded banded structures with intercalated bands of granitic and tonalitic compositions which indicate that these rocks were submitted to similar ductile deformational processes. In the occurrence of the center-southern of the area, this granite defines a NE–SW-oriented strip (Fig. 1c) and is intruded by the Vermelho mafic body, a pluton of the Planalto suite and a small stock of the Pedra Branca suite. The field relationships between different units were not observed in the field and the local stratigraphy was defined with support of geochronological data.

The granite displays pink to gray color and coarse- to medium- to fine-grained seriated texture. It is a hololeucocratic (M’<7%), biotite monzogranite to syenogranite, with zircon, allanite, apatite, magnetite± epidote± titanite as common accessory minerals. Chlorite, epidote, muscovite± carbonates are the secondary minerals. This granite is quite similar to the Bom Jesus granite in mineralogy and broad textural aspects. However, these two granites differ significantly in their geochemical signature and for this reason were distinguished in the present work.

4.4. Serra Dourada granite

The Serra Dourada granite is a sub-circular stock, located near the homonymous village in the northern part of the Canaã dos Carajás area (Fig. 1c). The major part of the stock is formed by little deformed rocks which shows a not pervasive EW-striking vertical foliation and is only locally affected by shear zones. This granite is intrusive in the Campina Verde tonalitic complex, includes remnants of greenstone belts, and is intruded by a small body of the Planalto suite. It shows also a close spatial association with abundant Neoarchean dikes and sills of mafic rocks.

This granite displays pink color and medium- to coarse-grained or subordinate fine-grained texture. It has monzogranite composition and biotite, with accessory allanite, zircon ± magnetite and ilmenite as mafic minerals. Secondary phases, mostly related to hydrothermal alteration, are common, including albite, muscovite, biotite, chlorite, epidote, opaque, titanite, quartz, scapolite, and tourmaline. Pegmatite and aplitic veins cut the granite.

The plagioclase (calcic oligoclase – An30-20) and alkali feldspar form subhedral crystals. The latter is perthitic and shows myrmekite quarts–plagioclase intergrowths along the borders of its crystals. Quartz consists of locally fractured and partially recrystallized anhedral grains; biotite is interstitial to the feldspars and quartz.

4.5. Planalto suite granite

The Planalto suite consists of several lenticular granite stocks with less than 10km in the largest dimension, located in the areas of stronger deformation and oriented concordantly to the dominant EW-trending regional structures or, eventually to NE–SW or NS (Fig. 1c). This Neoarchean suite is intrusive in the Mesoarchean granitoid units, in the mafic Pium complex, in the Neoarchean supracrustal Itacaúnas supergroup (Fig. 1c) and is associated spatially with the Pium complex and the Pedra Branca suite. It was described in more detail by Feio et al. (2012a).

These granites show penetrative EW- to NNW-subvertical foliation locally accompanied by a high angle stretching mineral lineation and C-type shear bands. Mylonites are found along sinistral or subordinate dextral shear zones. The less deformed rocks preserve magmatic textures. The suite is composed of biotite–hornblende monzogranite to syenogranite, with subordinate alkali feldspar granite. Relics of clinopyroxene with coronae of amphibole are present in some samples. The primary accessory minerals are zircon, apatite, allanite, ilmenite± fluorite.

Most rocks display porphyroclasts of quartz, perthitic alkali-feldspar, and plagioclase, which show core-and-mantle microstructures. The quartz occurs also as ribbons and recrystallized aggregates. The plagioclase shows curved twin plans and recrystallization to fine-grained polygonal aggregates of largely untextured grains. Bulbous myrmekite intergrowths are found along the borders of alkali-feldspar grains. The amphibole occurs as medium-grained oval porphyroclasts or forms oriented aggregates together with biotite and other mafic minerals. In the mylonites, the foliation is deflected around alkali-feldspar porphyroclasts and strain shadows are formed by the fine-grained recrystallized aggregates.

5. Geochemistry of the granites of Canaã dos Carajás

28 samples of the different Mesoarchean granite units of the Canaã dos Carajás area were selected for chemical analyses, including 3 samples from the Canaã dos Carajás, 8 samples from the Bom Jesus, 11 samples from the Cruzadão, and 6 samples from the Serra Dourada (Table 1). The geochemistry of the Neoarchean Planalto suite was discussed in detail by Feio et al. (2012a) and the available chemical analyses are presented in Table B (supplemental electronic data). The geochemistry of the Mesoarchean studied granites will be compared with that of the Neoarchean Planalto suite along this section.

Whole-rock chemical analyses were performed at AcmeLabs in Canada. Major elements (SiO2, TiO2, Al2O3, Fe2O3, MnO, MgO, CaO, Na2O, K2O, P2O5) were analyzed by Inductively Coupled Plasma Emission Spectrometry (ICP-ES) and Ba, Rb, Ga, Hf, Nb, Y, Sr, Ta, Th, U, Zr, and REE by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Major and minor elements have a detection limit of 0.01%, whereas trace elements have a detection limit between 0.01 and 1 ppm. Major and trace element abundance were determined on 0.2g samples following a lithium metaphosphate/tetraborate fusion and dilute nitric acid digestion. Loss on ignition (LOI) is by weight difference after ignition at 1000°C.

5.1. Major and trace elements

Harker diagrams for selected major and trace elements (Figs. 4, 5) demonstrate that all analyzed samples of Mesoarchean granite units and also those of the Planalto granite exhibit high silica contents with a restrict variation (70–76 wt.%). All Mesoarchean granites have relatively high Al2O3 contents (>13 wt.% to ca. 15 wt.%). Table 1, Fig. 4a) and contrast in this respect with the low-Al2O3 (11–13 wt.%) Planalto granite. The Mesoarchean granites are enriched in MgO (Fig. 4d), Na2O (Fig. 4f), Rb, and Sr (Fig. 5b, c) and impoverished in FeO (Fig. 4c), Ba, Zr, Y, and Nb, compared to the Planalto granites. Among the Mesoarchean granites, the Canaã dos Carajás granite has relatively higher contents of Al2O3, CaO, and Na2O (Fig. 4a, b, f) and lower contents of K2O (Fig. 4e), Ba, Rb, Zr, Nb, and Y (Fig. 5a, b, d, e, f), compared to the other high-Al2O3 granites. The Serra Dourada granite has also relatively high Al2O3 and Na2O contents, but a little lower than in the Canaã dos Carajás granite, and is enriched in Nb, and Y (Fig. 5e, f), and impoverished in Sr (Fig. 5c) compared with the Bom Jesus and Canaã dos Carajás granites. Finally, the Bom Jesus and Cruzadão granites, that show similar field aspects and ages (Figs. 1c, 2), can be distinguished by their significant geochemical contrasts. CaO, K2O, Ba, and Sr, are higher, and Rb, Nb, and Y contents are lower in the Bom Jesus granite compared to the Cruzadão. There is also significant geochemical variation in the samples of the Cruzadão granite. Some rocks, as exemplified by samples ARC-141A, GRB-58A, and ARC-58B, have lower silica and are clearly more enriched in Zr, Nb, and Y compared to the dominant rocks of that unit (Fig. 5d,
e, f). Apparently the registered chemical contrasts in the Cruzadão granite are not related with the provenance of the samples, in the sense that samples with different geochemical signatures occur in both the western and center-southern plutons (Fig. 1c).

The Rare Earth Element (REE) patterns (Fig. 6) of the Mesoarchean granites show clear contrasts in the extent of Heavy-REE (HREE) fractionation and in the nature of the europium anomaly. The Canaã dos Carajás granite (Fig. 6a) has the lowest $\Sigma$REE contents (Table 1), shows low to moderate fractionation of the HREE [(La/Yb)$_N$=7 to 21] and europium anomalies slightly positive or negative (Eu/Eu* = 1.1 to 0.7). The Bom Jesus granite samples are relatively enriched in Light-REE (LREE), show a strong fractionation of HREE [(La/Yb)$_N$=79 to 330], and europium anomalies generally also slightly positive or negative (Eu/Eu* = 1.2 to 0.7 with two anomalous values of 1.8 and 0.5; Table 1) and a concave shape of the HREE branch (Fig. 6b) which suggests fractionation of amphibole during the granite magma evolution. The Cruzadão granite shows the higher $\Sigma$REE contents (Table 1) of the Mesoarchean granites, and two different REE patterns (Fig. 6c, d) were identified: (1) The first group shows accentuated HREE fractionation [(La/Yb)$_N$=78 to 120], but lower than...
that observed in the Bom Jesus granite, strongly negative europium anomalies (Eu/Eu* = 0.5 to 0.3; Table 1), and concave-shaped HREE patterns (Fig. 6c). (2) The second group has a moderate degree of HREE fractionation [(La/Yb)N = 11 to 56], and prominent negative europium anomalies (Eu/Eu* = 0.5 to 0.2; Table 1, Fig. 6d). The samples ARC-141A, GRD-58A, and ARC-58B, which are relatively enriched in HREE and show flat HREE branch patterns are those enriched in High-Field Strength Elements (HFSE; Table 1). The Serra Dourada granite displays low to moderate fractionation of REE [(La/Yb)N = 9 to 63] and discrete to accentuate negative europium anomalies (Eu/Eu* = 0.8 to 0.4; Table 1, Fig. 6e). In comparison with the Mesoarchean granites, the Planalto suite (Feio et al., 2012a) has
higher $\Sigma$REE, is enriched in LREE but shows a low degree of REE fractionation $[(La/Yb)_N=6\,\text{to}\,17$, Table 1], and generally accentuates negative europium anomalies $(Eu/Eu^*=0.7\,\text{to}\,0.3$; Table 1, Fig. 6f).

5.2. Magmatic series and classification of the Archean Canaã dos Carajás granites

The PQ diagram (Fig. 7a) shows that almost all analyzed samples are monzogranites or syenogranites with rare granodiorites. Except for two samples, the Mesoarchean granites are weakly peraluminous, whereas the Planalto granites are metaluminous to mildly peraluminous $(cf.\,\text{ACNK values in Table 1})$. In the $100\times(MgO+FeO_t+TiO_2)/SiO_2$ vs. $(Al_2O_3+CaO)/(FeO_t+Na_2O+K_2O)$ diagram (Sylvester, 1989), the Mesoarchean granites plot in the calc–alkaline and strongly peraluminous or strongly fractionated fields, except for the Cruzadão granite that plots in the border between the calc–alkaline and alkaline fields (Fig. 7b). In the $Al_2O_3$ vs. $FeO_t/(FeO_t+MgO)$ diagram (Dall’Agnol and Oliveira, 2007), the Mesoarchean granites plot in the area of superposition of the oxidized-A-type and calc–alkaline fields (Fig. 7c). In contrast, the Planalto granites are alkali and reduced-A-type granites $(Fig. 7d, c)$. In the Na$_2$O vs. K$_2$O diagram it could be seen that almost all analyzed samples have K$_2$O/Na$_2$O $<1$ $(Fig. 7d, Table 1)$ and could be considered potassic granites, except for the Canaã dos Carajás granite that shows K$_2$O/Na$_2$O $>1$ and has a more sodic character. In the Yb vs. Sr/Y plot $(Fig. 7e)$, there is also a good discrimination between the Mesoarchean granites. The Bom Jesus granite has the highest Sr/Y ratios and the lowest Yb contents. The samples of the Canaã dos Carajás and Serra Dourada granites and part of those of the Cruzadão granite display similar distribution in this diagram due to their moderate Yb and Sr/Y values $(Fig. 7e)$. The remaining samples of the Cruzadão granite (HFSE-enriched varieties) have the highest Yb contents and show systematically low Sr/Y. Similar aspects can be observed in the $(La/Yb)_N$ vs. Sr/Y diagram $(Fig. 7f)$. Compared to the Mesoarchean granites, the Planalto granites show the highest Yb contents and the lowest Sr/Y and $(La/Yb)_N$ ratios.

A comparison between the REE patterns and spidergrams (Fig. 8) of the analyzed rocks with the different types of Archean granites distinguished by Sylvester (1994) shows that: (1) The Canaã dos Carajás granite is akin geochemically to the calc–alkaline granites of type 1 $(CA1,\,Figs. 6a, 8a)$ of Sylvester (1994); (2) The Bom Jesus granite is more similar to the calc–alkaline granites of type 2 $(CA2$ of Sylvester (1994) but its REE patterns are generally devoid of negative europium anomalies and show a more accentuated fractionation of HREE and Y compared to the average composition of CA2 $(Figs. 6b, 8b)$; (3) The comparison with the Cruzadão granite is a little more complex due to the chemical variations observed in this granite. The variety of this granite with stronger fractionation of HREE $(Fig. 6c)$ has more
geochemical affinity with the CA2 granites but it differs from them by the presence of positive anomalies of Th and U and negative anomaly of Sr (Fig. 8c). The HREE-enriched variety of the Cruzadão granites (Fig. 6d) is similar to the alkaline granite types (ALK 3 or 4) of Sylvester (1994), as evidenced by the behavior of most incompatible elements (Fig. 8d), but the Cruzadão granites have comparatively higher Al₂O₃ contents.

(4) The Serra Dourada granite REE pattern (Fig. 6e) and spidergram (Fig. 8e) suggest geochemical similarities with the strongly peraluminous granites of the type 3 of Sylvester (SP3). The Planalto suite granites have clear geochemical affinities with the alkaline granites of the ALK3 subtype (Sylvester, 1994), as indicated by the REE patterns (Fig. 6f) and multi-element diagram (Fig. 8f) and differ significantly to the Mesoarchean granites of Canaã dos Carajás.

The whole geochemical data obtained on the Mesoarchean granites demonstrate that the Canaã dos Carajás, Bom Jesus and part of the Cruzadão granites display geochemical signatures more akin to the calc-alkaline granites of CA1 (Canaã) or CA2 types (Bom Jesus and part of the Cruzadão). The second variety of the Cruzadão granite is clearly transitional between the calc-alkaline and alkaline granites and the alkaline character is reinforced in the samples enriched in

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**Fig. 7.** Geochemical plots showing the distribution of the Archean granites of the Canaã dos Carajás area. (a) P–Q diagram (Debon and Le Fort, 1988); (b) 100*(MgO+FeOt+TiO₂)/SiO₂ vs. (Al₂O₃+CaO)/(FeOt+K₂O+Na₂O) diagram (Sylvester, 1989); (c) FeOt/(FeOt+MgO) vs. Al₂O₃ diagram (fields of calc-alkaline and reduced and oxidized A-type granites of Dall’Agnol and Oliveira, 2007); (d) Na₂O vs. K₂O diagram; (e) Yb vs. Sr/Y diagram; (f) (La/Yb)ₚ vs. Sr/Y diagram. The fields of leucogranodiorite to leucogranite of the Guarantã suite (Almeida et al., 2010) and potassic leucogranites (Almeida, 2010) of the Rio Maria domain, and the Neoarchean Dharwar granites (Jayananda et al., 2006) are plotted for comparison.
HFSE and HREE. The Serra Dourada granite differs in some aspects of the calc-alkaline granites and the behavior of incompatible elements approaches that registered in the strongly peraluminous granites of SP3 subtype. However, the Nb and Y contents of the Serra Dourada are significantly higher than those observed in the SP3 granites and their ACNK ratios (<1.16 and generally <1.1; Table 1) are significantly lower than the average of the SP3 granites (1.44; Sylvester, 1994). Other relevant aspects are: the modal mineralogy of the Serra Dourada granite does not show any evidence of a strong peraluminous character; the lack of inherited zircon in the dated sample of this unit (Feio et al., 2012b); and the positive εNd values yielded by the two analyzed samples of this granite. Thus, despite some geochemical evidence in favor of metasedimentary sources for the Serra Dourada granite, there are also indications of its derivation from more juvenile, possibly igneous sources.

Feio et al. (2012a) proposed to classify the biotite–hornblende granites of the Planalto suite as hydrated granites of the charnockitic rock series based on their close association with rocks of the charnockitic series and emplacement in a syntectonic setting. Independent of their origin, the Planalto granites have ferroan character, are similar geochemically to reduced A-type granites, and exhibit a strong geochemical contrast with the Mesoarchean granites of Canã dos Carajás.

6. Discussions

6.1. Comparison with other Archean granites

The granites of different Archean cratons have received increasing attention in the last years. At present, there is more information about
their geochemistry and some broad classifications have also been proposed (Almeida, 2010; Almeida et al., 2010; Champion and Sheraton, 1997; Champion and Smithies, 2003; Davis et al., 1994; Evans and Hanson, 1997; Frost et al., 1998; Jayananda et al., 2006; Moyen, 2011b; Moyen et al., 2003; Sylvester, 1994) but the need for refinement of the geochemical characterization of these rocks is still evident.

The geochemical comparison between the granites of Canaã dos Carajás area and those of other Archean cratons or domains will be limited in this paper to the Rio Maria domain, and the Yilgarn and Dharwar cratons which were chosen because their Archean granites are relatively better discriminated and there is a good data set in the literature about them. The geochemistry and petrogenesis of the Archean granites of the Rio Maria domain were summarized by Almeida (2010) which distinguished essentially: (1) a leucogranodiorite–leucogranite group (Guaranã suite and related rocks) similar to the transitional TTG or high-Ca granites of the Yilgarn craton (Champion and Sheraton, 1997; Champion and Smithies, 2003); (2) potassic leucogranites (Xinguara and Mata Surrão plutons and related rocks) akin to the low-CaO granites or biotite granites of Yilgarn and Dharwar cratons, respectively. The comparison between the compositional variation of representative samples of these two groups of granites of Rio Maria and those of Canaã dos Carajás indicates that there is not a good equivalence between the mentioned granites. The PQ and Na2O vs. K2O plots (Fig. 7a, d) show that, except for the Canaã dos Carajás granite which has Na2O/K2O ratios > 1, the studied granites are distinct of the leucogranodiorite–leucogranite group of Rio Maria. This is shown in the PQ plot (Fig. 7a) by the total dominance of monzogranites in the analyzed Canaã dos Carajás granites. These contrasts can also be seen in some selected Harker diagrams (Figs. 4b, e; 5a, b, c, d). Except for the Planalto suite granite which is clearly distinct because it has a more accentuated alkaline and reduced character (Figs. 5d, 7b, c, e), and has no counterpart in Rio Maria (Feio et al., 2012a), in general, the remaining studied granites are more akin chemically to the potassic granites of Rio Maria. However, there are also relevant differences between the Canaã dos Carajás granites and the potassic granites of Rio Maria. The Bom Jesus granite has CaO, Ba, Sr, and Sr/Y ratios (Figs. 4b, 5a, c, 7e) that are higher than those shown by the Rio Maria potassic leucogranites and its (La/Yb)N ratios are higher than those registered in both groups of Rio Maria (Fig. 7f).

Compared to the Yilgarn granites, the Canaã dos Carajás and Bom Jesus granites are similar to the high-Ca granites, whereas the Cruzadão and Serra Dourada are more akin to the low-CaO granites. The Planalto suite granites have no described equivalents in the Yilgarn craton (Champion and Sheraton, 1997; Champion and Smithies, 2003).

In general, the geochemical characteristics of the studied granites approach those of the biotite granite group of Dharwar (Moyen et al., 2003). Granites equivalent to the two-mica and peralkaline granites were not identified in Canaã dos Carajás so far. Compared to the granites of Canaã dos Carajás and Rio Maria, the Neoarchean granites of the Dharwar craton (Jayananda et al., 2006) differ in geochemical signature of the leucogranodiorite–leucogranite group (Almeida et al., 2010) and are more akin to the potassic granites of Rio Maria and to the various granites of Canaã dos Carajás (Figs. 5a, b, c, d, 7a, b, c, d). However, the Dharwar granites (Jayananda et al., 2006; their Table 2) show lower (La/Yb)N ratios (ca. 10) and Eu/Eu* (0.65 to 0.23) and are commonly enriched in CaO, and Zr, and impoverished in K2O and Ba compared to the Canaã dos Carajás granites. The Dharwar granites are also characterized by low values of the Sr/Y ratio. Thus, they show a quite distinct distribution in the (La/Yb)N vs. Sr/Y plot compared to the Mesoarchean granites of Canaã dos Carajás and approach in this diagram the field defined by the Planalto suite granites (cf. Yb vs. Sr/Y plot, Fig. 7e). This indicates that the Neoarchean granites of Dharwar (Jayananda et al., 2006), despite their similarity with the CA1 and CA2 granites of Sylvester (1994), are relatively enriched in HFSE and HREE compared to the Mesoarchean granites of Canaã dos Carajás, except for the variety of the Cruzadão granite that is also enriched in the mentioned elements. On the other hand, the Planalto granites are enriched in Zr and Ba compared to the Dharwar granites, and differ also of the latter because they have a clear alkaline character (Fig. 7b) and are reduced granites (Fig. 7c).

6.2. Significance of the Sr/Y and (La/Yb)N ratios in the Archean Canaã dos Carajás granites

The relevance of the Sr/Y and (La/Yb)N ratios for petrogenetic interpretation of the origin of granitoid magmas was far recognized (Drummond and Defant, 1990; Martin, 1999) and has been recently emphasized (Almeida et al., 2010; He et al., 2011; Moyen, 2009; Zhang et al., 2009). The high Kd of Sr in plagioclase and the strong geochemical affinity of Yb and Y with garnet implies that the presence of garnet or plagioclase as dominant fractionating phase could exert a strong influence in the geochemical signature of granitoid magmas generated during the Archean and the presence or absence of these minerals in the melting residue or fractionate was attributed to variations of pressure (cf. Almeida et al., 2010; Rapp and Watson, 1995; Rapp et al., 1991). However, there is increasing evidence that other parameters than pressure and also different processes are able to explain the variations in the Sr/Y and (La/Yb)N ratios (He et al., 2011; Moyen, 2009, and references therein). Moyen (2009) argued that compositional variations in the source can be as relevant as pressure to determine the values of the mentioned ratios in granitoid magmas and emphasize that melting of normal crustal sources at pressures of 5–10 kbar could be able to generate magmas with high Sr/Y ratios.

The (Dy/Yb)N ratio and the behavior of Middle REE (MREE) give also indications about the influence of amphibole during the magma origin or fractionation. The decrease of that ratio and the presence of concave REE patterns for the HREE branch are strong indications of prominent amphibole fractionation (He et al., 2011; Moyen, 2009). The variations of Er contents face up to those of Sr and Ba can also give indications of the role of garnet or plagioclase during the fractionation and allow a preliminary estimate of the possible influence of enriched-mantle sources in the origin of the granitoid magmas (Heilimo et al., 2010).

The (La/Yb)N vs. Sr/Y diagram (Fig. 7f) indicates that the Bom Jesus granite, despite its somewhat higher (La/Yb)N, approaches the High-Sr/Y granites (HSG), whereas the other studied granites are akin to the Normal granites (NG), as defined by He et al. (2011). However, one of the varieties of the Cruzadão granite shows also significantly higher (La/Yb)N. The (La/Yb)N vs. (Dy/Yb)N diagram (Fig. 9a) suggests that both garnet and amphibole were fractionated during the evolution of the Bom Jesus granite. In the triangular (Ba + Sr)/100 – 1/Er – Er plot (Fig. 9b), the Canaã dos Carajás Archean granites show a distinct distribution due essentially to strong variations in the Er contents which should reflect the varying influences of residual garnet. The Bom Jesus granite and the high-(La/Yb)N Cruzadão granite variety have lower contents of Er and contrast with the low-(La/Yb)N varieties of the Cruzadão granite and the Planalto granite that are relatively enriched in that element. A similar geochemical behavior can be observed in the triangular Eu/Eu* – [(Al2O3 + CaO)/(Na2O + K2O)]/Y plot (Fig. 9c) where the studied granites can be distinguished by their simultaneous variations of Eu/Eu* and [(Al2O3 + CaO)/(Na2O + K2O)] vs. Y contents. The Bom Jesus and Canaã dos Carajás granites have the highest Eu/Eu* and [(Al2O3 + CaO)/(Na2O + K2O)]/Y contents and the reverse is observed in the variations of the Cruzadão granite enriched in HREE and Y and in the Planalto granite.

The geochemical behavior of the Bom Jesus and Cruzadão granites suggests that the evolution of their magmas was controlled by plagioclase ± amphibole ± garnet, among other phases. A remarkable influence of amphibole and garnet was restricted to the Bom Jesus granite and to the variety of the Cruzadão granite with the
in the lower crust of mafic mantle magmas. This process occurred in a high heat flow domain possibly located near the borders of distinct Archean tectonic blocks that are not yet clearly distinguished in Carajás.

7. Conclusions

1. The Mesoarchean granites of the Canaã dos Carajás area of the Carajás Province are dominantly holohlocratic biotite monzogranite, with subordinate granodiorite (Canaã dos Carajás) or syenogranite (Bom Jesus and Cruzadão granites). The Neoarchean Planoalto biotite-hornblende monzogranite to syenogranite have generally mafic content between 5% and 20%.

2. The Bom Jesus and the variety of the Cruzadão granite with high (La/Yb)N are geochemically more akin to the calc–alkaline granites of CA2 type and the Canaã dos Carajás granite with the CA1 type. The moderate and low (La/Yb)N varieties of the Cruzadão granite are transitional between calc–alkaline and alkaline granites. The Serra Dourada granite has an ambiguous geochemical character (calc–alkaline or peraluminous granites of SP3 subtype?). The Planoalto granites are ferroan granites, similar to reduced A-type granites and contrast with the Mesoarchean granites.

3. There is no a good equivalence between the Mesoarchean granites of the Canaã dos Carajás area and Rio Maria domain of the Carajás Province. The Canaã dos Carajás granites differ to the leucogranodiorite–leucogranite group and are more akin geochemically to the potassic granites of Rio Maria and to the biotite granite group of Dharwar. Compared to the granites of the Yilgarn craton, the Canaã dos Carajás and Bom Jesus granites of Canaã dos Carajás are similar to the high–Ga granites, whereas the Cruzadão and Serra Dourada are more akin to the low–Ga granites. The Planoalto suite granites have no equivalent in Rio Maria, and apparently also not in Yilgarn and Dharwar.

4. The studied granites show accentuated variation of the Sr/Y and (La/Yb)N ratios. Our results indicate that TTGs are not suitable sources and an intermediate mafic source (54.6 wt.% silica) was assumed for the dominant granite varieties. It is concluded that the changes of these ratios are essentially due to contrast in the pressure of magma generation, which controlled the residual phases of melting. A pressure of ca. 10 kbar was estimated for the Bom Jesus and high (La/Yb)N Cruzadão granite which had garnet and amphibole as abundant residual phases and 7–8 kbar pressure for the moderate to low Cruzadão granite without garnet and containing more plagioclase and magnetite±orthopyroxene in the residue.

5. The Archean leucogranite magmas can have variable crustal sources and, for similar crustal sources, changes in the pressure of melting exert strong influence in the geochemical signature of the resulting magma and can explain variations in (La/Yb)N and Sr/Y, as well as also transition from calc–alkaline to alkaline magmas.

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References


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Acknowledgments

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Itacaiúnas supergroup of the Serra dos Carajás; sample N4F32-231 from a drill hole in the N4 iron deposit; Teixeira and Eggler, 1994) and changing the residual phases of melting (Table 3).

In the cases of the Bom Jesus granite and the variety of the Cruzadão with high (La/Yb)N ratios, the adjustment for major elements was very good (r²=0.049 and 0.003; degree of melting of 22 and 23%, respectively) and that for trace elements was good except for Nb and, for the Bom Jesus granite, also Sr (Table 3; Fig. 10d, e, f). The residue was composed of similar proportions of plagioclase (An17), clinopyroxene, hornblende, garnet, with subordinate ilmenite. In the varieties of the Cruzadão granite with moderate to low (La/Yb)N, the residual phases of melting show important changes: garnet is absent, magnetite is always present and the proportions of plagioclase are more elevated; compared to the granites with high (La/Yb)N, amphibole increases in the variety with moderate (La/Yb)N, but is replaced by orthopyroxene in the rocks with the lowest (La/Yb)N. It resulted in a good adjustment for major (La/Yb)N0, the residual phases of melting show important changes: garnet is absent, magnetite is always present and the proportions of plagioclase are more elevated; compared to the granites with high (La/Yb)N0, amphibole increases in the variety with moderate (La/Yb)N0, but is replaced by orthopyroxene in the rocks with the lowest (La/Yb)N0.

In the case of the Serra Dourada, partial melting modeling (Feio et al., 2012a) of a granulitic mafic source (50.9 to 54.9 wt.% silica) left in the residue similar phases than those observed in the low (La/Yb)N Cruzadão granites and a pressure of 8±1 kbar could also be estimated for it. The relatively low pressures of melting for the studied granites could also explain their K2O/Na2O ratios (>1) and their geochemical similarities with the ‘Normal granites’ (He et al., 2011).

Geochemical evidence suggests that the varieties of the Cruzadão granite are not comagmatic and that despite their similarities they could also be possibly not cogenetic. However, it is not possible at this stage to distinguish different domains for each variety of the Cruzadão granite and this justifies keeping it as a single unit. In the case of the Canaã dos Carajás and Serra Dourada granites, the
magma and can explain variations in (La/Yb)N and Sr/Y and also tran-

granite magmas (Almeida et al., 2011; Martin, 1999; Moyen, 2009).

variations as

strong in

for similar crustal sources, changes in the pressure of melting exert

they indicate that the latter can have variable crustal sources and,

sions could not be generalized to all Archean granite magmas but

considerations made above on the basis of the geochemical data.

6.4. Implication for the origin of Archean granites

TTGs are generally admitted as the more common source for

Archean granite magmas (Champion and Sheraton, 1997; Moyen

et al., 2003; Sylvester, 1994). However, mafic to intermediate or
depleted granulite sources were also considered (Champion and

Sheraton, 1997; Jayananda et al., 2006). On the other hand, there is

relevant geochemical aspect is the significance of (La/Yb)N and Sr/Y

variations as fingers of sources and magmatic evolution of Archean

granite magmas (Almeida et al., 2011; Oliveira et al., 2009). Considering that

geochemical data showing that the Canaã dos Carajás granites are potas-

cic better than sodic and should not be related to the initial stages of

Archean cratonization.

On the other hand, the Mesoarchean granites of the Canaã dos

alkaline or A-type like (Feio et al., 2012a). This prob-
iclusion is reinforced in some degree by our geo-

craterian through time in the Canaã dos

6.5. Tectonic setting of the Canaã dos Carajás area Archean granites

The Mesoarchean granites cover a large area and are more abun-
dant than TTGs in the Canaã dos Carajás area. In this respect, the

Canaã dos Carajás area contrasts with the nearby Rio Maria domain

where the dominant Mesoarchean granitoids are TTG and sanukitoid

series (Almeida et al., 2011; Oliveira et al., 2009). Considering that

granites are markers of the cratonization of Archean terranes (Davis

et al., 1994; Jayananda et al., 2006; Kröner et al., 1991; Nisbet, 1987;

Sylvester, 1994), this was interpreted as evidence that the Canaã

dos Carajás area stabilized before the Rio Maria domain (Feio et al.,

2012b). That conclusion is reinforced in some degree by our geo-

craterian through time in the Canaã dos

Our results indicate that TTGs are not suitable sources for the studied

potassic granites which are more probably derived from intermediate

discernible than TTGs in the Canaã dos Carajás area. In this respect, the

Table 3

Geochemical modeling data for the granites of the Canaã dos Carajás area.

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Sources</th>
<th>Bom Jesus granite</th>
<th>TTG*</th>
<th>N4F32-231**</th>
<th>AER-65C</th>
<th>ERF-123</th>
<th>GRD-58</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>69.79</td>
<td>54.56</td>
<td>74.87</td>
<td>71.83</td>
<td>70.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO2</td>
<td>0.34</td>
<td>0.78</td>
<td>0.21</td>
<td>0.18</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al2O3</td>
<td>15.56</td>
<td>14.79</td>
<td>13.24</td>
<td>14.47</td>
<td>14.2</td>
<td></td>
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</tr>
<tr>
<td>Fe2O3</td>
<td>3.17</td>
<td>11.46</td>
<td>1.45</td>
<td>1.56</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>1.18</td>
<td>5.35</td>
<td>0.25</td>
<td>0.41</td>
<td>0.6</td>
<td></td>
<td></td>
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<tr>
<td>CaO</td>
<td>3.19</td>
<td>8.68</td>
<td>1.29</td>
<td>1.59</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na2O</td>
<td>4.88</td>
<td>3.28</td>
<td>3.28</td>
<td>3.83</td>
<td>3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K2O</td>
<td>1.76</td>
<td>1.34</td>
<td>4.70</td>
<td>4.51</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>690</td>
<td>584</td>
<td>1379</td>
<td>1658</td>
<td>885</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td>55</td>
<td>44</td>
<td>161</td>
<td>140</td>
<td>232</td>
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<td></td>
</tr>
<tr>
<td>Sr</td>
<td>454</td>
<td>141</td>
<td>261</td>
<td>463</td>
<td>234</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>152</td>
<td>86</td>
<td>210</td>
<td>167</td>
<td>302</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>8</td>
<td>20</td>
<td>2</td>
<td>3</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>La</td>
<td>32.0</td>
<td>12.5</td>
<td>45.1</td>
<td>51.3</td>
<td>88.1</td>
<td></td>
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</tr>
<tr>
<td>Ce</td>
<td>56.0</td>
<td>26.0</td>
<td>89.6</td>
<td>87.8</td>
<td>187.6</td>
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<td></td>
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<tr>
<td>Nd</td>
<td>21.4</td>
<td>15.9</td>
<td>25.7</td>
<td>20.9</td>
<td>66.6</td>
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<tr>
<td>Sm</td>
<td>3.3</td>
<td>4.2</td>
<td>3.1</td>
<td>2.0</td>
<td>10.8</td>
<td></td>
<td></td>
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<tr>
<td>Eu</td>
<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tb</td>
<td>0.3</td>
<td>0.8</td>
<td>0.1</td>
<td>0.1</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yb</td>
<td>0.6</td>
<td>1.9</td>
<td>0.2</td>
<td>0.2</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lu</td>
<td>0.1</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F (%)</td>
<td>68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Partial melting formula</td>
<td>Hornblende</td>
<td>Plagioclase (An17)</td>
<td>Plagioclase (An30)</td>
<td>Plagioclase (An41)</td>
<td>Garnet</td>
<td>Clinopyroxene</td>
<td>Orthopyroxene</td>
</tr>
<tr>
<td>Cl/Co=1/(F+D–FD)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>7.59</td>
</tr>
<tr>
<td>D–distribution coefficient</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15.11</td>
</tr>
<tr>
<td>Co–original solid concentration</td>
<td>–</td>
<td>16.83</td>
<td>–</td>
<td>–</td>
<td>16.83</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Geochemical modeling

Residual phase/r2

F (%) 68 22 23

Partial melting

Hornblende

Plagioclase (An17)

Plagioclase (An30)

Plagioclase (An41)

Garnet

Clinopyroxene

Orthopyroxene

Magnetite

Ilmenite

0.74

**Teixeira and Eggler (1994)

Teixeira and Eggler (1994) Ilmenite

Condie (1993) Magnetite 4.43

Sheraton, 1997; Jayananda et al., 2006). On the other hand, there is

experimental evidence that TTGs could not be suitable sources for

potassic stricto sensu granite magmas (Watkins et al., 2007). Another

relevant geochemical aspect is the significance of (La/Yb)N and Sr/Y

variations as fingers of sources and magmatic evolution of Archean

granite magmas (Almeida et al., 2011; Martin, 1999; Moyen, 2009).

Our results indicate that TTGs are not suitable sources for the studied

potassic granites which are more probably derived from intermediate

mafic sources. Besides, the strong variations of (La/Yb)N and Sr/Y

ratios observed in the Bom Jesus and Crazuddão granites are better

explained by variations of pressure than for contrasts in the com-

position of the sources of their magmas. We believe that these conclu-
sions could not be generalized to all Archean granite magmas but

they indicate that the latter can have variable crustal sources and,

for similar crustal sources, changes in the pressure of melting exert

strong influence in the geochemical signature of the resulting

gmaga and can explain variations in (La/Yb)N and Sr/Y and also trans-

transition from calc-alkaline to alkaline magmas.
in the lower crust of mafic mantle magmas. This process occurred in a high heat flux domain possibly located near the borders of distinct Archean tectonic blocks that are not yet clearly distinguished in Carajás.

7. Conclusions

1. The Mesoarchean granites of the Canaã dos Carajás area of the Carajás Province are dominantly hololeucocratic biotite monzogranite, with subordinate granodiorite (Canaã dos Carajás) or syenogranite (Bom Jesus and Cruzadão granites). The Neoarchean Planalto biotite-hornblende monzogranite to syenogranite have generally mafic content between 5% and 20%.

2. The Bom Jesus and the variety of the Cruzadão granite with high \((\text{La}/\text{Yb})_\text{N}\) are geochemically more akin to the calc–alkaline granites of CA2 type and the Canaã dos Carajás granite with the CA1 type. The moderate and low \((\text{La}/\text{Yb})_\text{N}\) varieties of the Cruzadão granite are transitional between calc–alkaline and alkali granite. The Serra Dourada granite has an ambiguous geochemical character (calc–alkaline or peraluminous granites of SP3 subtype?). The Planalto granites are feroan granites, similar to reduced A-type granites and contrast with the Mesoarchean granites.

3. There is no a good equivalence between the Mesoarchean granites of the Canaã dos Carajás area and Rio Maria domain of the Carajás Province are dominantly hololeucocratic biotite monzogranite, with Neoarchean Planalto biotite hornblende monzogranite to syenogranite have generally ma tent between 5% and 20%.

4. The studied granites show accentuated variation of the \(\text{Sr}/\text{Y}\) and \((\text{La}/\text{Yb})_\text{N}\) ratios. Our results indicate that TTGs are not suitable sources and an intermediate mafic source (54.6 wt.% silica) was assumed for the dominant granite varieties. It is concluded that the changes of these ratios are essentially due to contrast in the pressure of magma generation, which controlled the residual phases of melting. A pressure of ca. 10 kbar was estimated for the Bom Jesus and high \((\text{La}/\text{Yb})_\text{N}\) Cruzadão granite which had garnet and amphibole as abundant residual phases and 7–8 kbar pressure for the moderate to low Cruzadão granite without garnet and containing more plagioclase and magnetite±orthopyroxene in the residue.

5. The Archean leucogranite magmas can have variable crustal sources and, for similar crustal sources, changes in the pressure of melting exert strong influence in the geochemical signature of the resulting magma and can explain variations in \((\text{La}/\text{Yb})_\text{N}\) and \(\text{Sr}/\text{Y}\), as well as also transition from calc–alkaline to alkaline magmas.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2012.06.022.

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References


