Precambrian Research 119 (2002) 257–275

Precambrian Research

www.elsevier.com/locate/precamres

Archean crustal sources for Paleoproterozoic tin-mineralized granites in the Carajás Province, SSE Pará, Brazil: Pb–Pb geochronology and Nd isotope geochemistry

Nilson P. Teixeira [a,*], Jorge S. Bettencourt [b], Candido A.V. Moura [a], Roberto Dall'Agnol [a], Edésio M.B. Macambira [c]

[a] *Centro de Geociências da Universidade Federal do Pará, Caixa Postal 1611, 66075-900, Belem, Pará, Brazil*
[b] *Instituto de Geociências da Universidade de São Paulo, Caixa Postal 11348, 05422-970, Sao Paulo, Brazil*
[c] *Companhia de Pesquisa de Recursos Minerais/Geological Survey of Brazil, Belem, Pará, Brazil*

Received 18 April 2001; received in revised form 5 October 2001; accepted 14 May 2002

Abstract

Whole-rock and K-feldspar Pb, single zircon Pb-evaporation, and Nd whole-rock isotopic data are presented for granites of the Velho Guilherme intrusive suite and the volcanic rocks of the Uatumã Group in the Carajás Mineral Province, southern Pará, Brazil. Pb–Pb zircon ages of 1867 $\pm$ 4 Ma, 1862 $\pm$ 16 Ma, and 1866 $\pm$ 3 Ma for the Antonio Vicente, Mocambo, and Rio Xingu granite massifs, respectively, show that the granites were emplaced at $\sim$ 1870 Ma. Pb–Pb whole-rock reference age of the Uatumã volcanic rocks, 1875 $\pm$ 158 Ma, is comparable within the limits of the error. 1870 Ma thus represents the time of an important magmatic event in the eastern part of the Amazonian craton. Nd model ages of the granites (3.0–3.2 Ga) and volcanic rocks (2.9–3.1 Ga) and their strongly negative initial ε_{Nd} values indicate that the magmas were derived from Mesoarchean rocks with a long crustal residence time. A mantle contribution cannot be completely ruled out, however.

Keywords: Tin-granites; Uatumãm volcanism; Geochronology; Nd isotopes; Amazonian craton; Paleoproterozoic

1. Introduction

Proterozoic anorogenic magmatism of the Amazonian craton was voluminous and comprises granitoids with associated subordinate mafic plutonic and intermediate to felsic volcanic rocks (Bettencourt and Dall'Agnol, 1987; Issler and Lima, 1987; Teixeira et al., 1998; Dall'Agnol et al., 1999a). This magmatism is similar in age, geochemical characteristics, and magmatic evolution with comparable suites in the North American Proterozoic Provinces and in the Fenoscandian Shield of northern Europe (Anderson and Bender, 1989; Haapala and Rämö, 1990; Emslie, 1991; Rämö and Haapala, 1995). The Paleoproterozoic granites of the Amazonian craton (Dall'Agnol,

* Corresponding author. Tel.: +55-91-211-1429; fax: +55-91-211-1609
E-mail address: noslin@ufpa.br (N.P. Teixeira).

0301-9268/02/$ - see front matter
PII: S0301-9268(02)00125-0

1980; Bettencourt and Dall'Agnol, 1987; Horbe et al., 1991; Dall'Agnol et al., 1993; Teixeira et al., 1998; Dall'Agnol et al., 1999a) include large volumes of subalkaline and alkaline granitoids showing similarities with A-type granites (Loiselle and Wones, 1979; Collins et al., 1982; Eby, 1992). These Amazonian granitoids are interpreted as belonging to the rapakivi series (Dall'Agnol et al., 1999a) and they host tin and other rare metal mineralization (Bettencourt and Dall'Agnol, 1987; Horbe et al., 1991; Dall'Agnol et al., 1993; Bettencourt et al., 1995; Dall'Agnol et al., 1999a).

In the south–southeastern part of the state of Pará, Carajás Mineral Province (Fig. 1), granitic massifs with associated greisen-type tin mineralization have been grouped in the Velho Guilherme intrusive suite (CPRM/DNPM, 1997; Teixeira et al., 1998). The Velho Guilherme, Antonio Vicente, Mocambo, and Rio Xingu (Dall'Agnol et al., 1993, 1999a; Teixeira et al., 1998) granitic massifs have been identified (Fig. 1b). The chronology of these plutons is inadequately known; for example, a Rb–Sr whole-rock isochron age of 1653 ± 28 Ma was obtained for the Velho Guilherme massif (Lafon et al., 1991) but a Pb–Pb whole-rock isochron age of 1874 ± 30 Ma for this massif led Lafon et al. (1995) to re-interpret the Rb–Sr age as being reset. The voluminous volcanic rocks of the Uatumã Group are spatially associated with the Velho Guilherme intrusive suite. The geology of this group is barely known mainly because of poor accessibility. Until the end of the 1980's, the available geochronology for the Uatumã volcanic rocks was restricted to whole-rock Rb–Sr and K–Ar data. A compilation of recent geochronological data for volcanic and granitic rocks from the Amazonian craton is presented in Table 1.

In order to contribute to the understanding of the geology, age, and origin of Velho Guilherme plutonism and Uatumã volcanism, new geologic, zircon Pb–Pb geochronologic, and whole-rock Nd isotopic data obtained for the doctoral thesis of the senior author (Teixeira, 1999) are presented and discussed. The new data lead to a better understanding of the stratigraphic relationships in the Xingu region of eastern Amazonian craton. The relationship between the Velho Guilherme intrusive suite and Paleoproterozoic granitic massifs farther to the east in the Carajás Mineral Province (e.g., Carajás, Jamon, Musa, Redenção, Cigano) and the relationships between the intrusive suite and the volcanic rocks of the Uatumã Group will be discussed. The new geochronologic and isotopic data also form the basis for a petrogenetic model of the Velho Guilherme intrusive suite, the type and age of the crustal reservoir from which these granites were derived in particular.

2. Geologic setting and petrography

2.1. Regional setting

The granitic massifs of the Velho Guilherme intrusive suite and the volcanic rocks of the Uatumã Group are found in the Amazonian craton in the south–southeastern part of the state of Pará. Syntheses about the evolution of the Amazonian craton (Almeida et al., 1981; Dall'Agnol et al., 1999a; Tassinari and Macambira, 1999; Santos et al., 2000) can be divided into two groups. One (e.g., Almeida et al., 1981) considers the Amazonian craton as a collage of Archean mobile belts and platform sequences with the main fold belts having developed during the 2.1 ± 0.1 Ga Transamazonian event. The other (e.g., Brito Neves and Cordani, 1991; Tassinari and Macambira, 1999) divides the Amazonian craton into six geochronologic provinces related to continental accretion events. According to the latter, the massifs of the Velho Guilherme intrusive suite and the volcanic rocks of the Uatumã Group belong to the Central Amazonian Province (Fig. 1a). The Archean rocks of the study area are exposed in the South Pará granite-greenstone terrane and the Itacaiúnas shear belt (Araújo et al., 1988). The oldest Paleoproterozoic sequences of this region are represented by the mafic-ultramafic Cateté intrusive suite and the Parauari granite (cf. Fig. 1b). The Uatumã Group is generally considered as part of the volcano-sedimentary sequence of the Middle Rio Xingu basin (CPRM/DNPM, 1997). The granitic massifs of the Velho Guilherme intrusive suite are intrusive into (1) the metavolcano-sedimentary greenstone se-

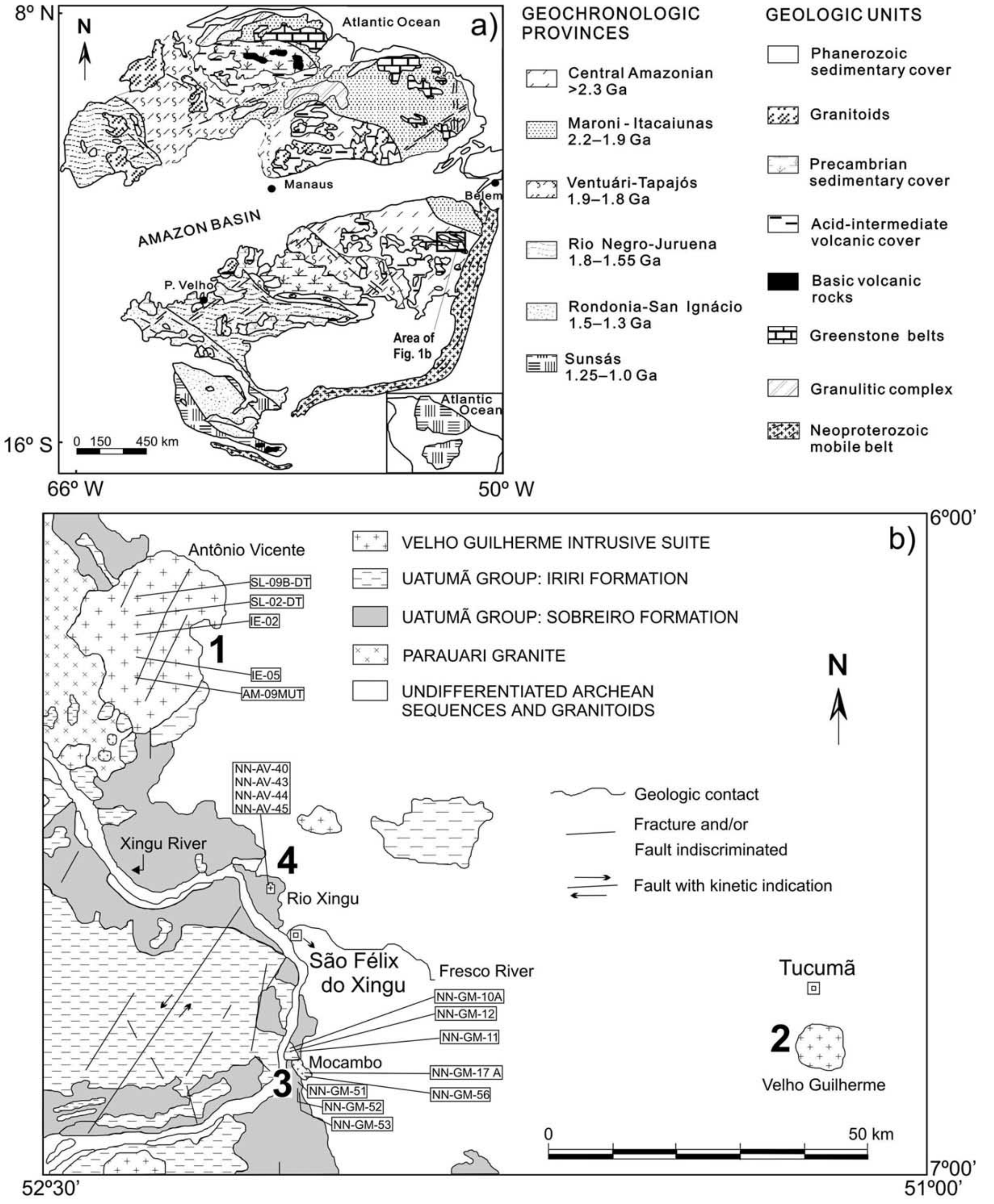
8º N
16º S
66º W
50º W
a)
N
Atlantic Ocean
Manaus
Belem
AMAZON BASIN
P. Velho
Area of Fig. 1b
0 150 450 km
Atlantic Ocean
GEOCHRONOLOGIC PROVINCES
Central Amazonian >2.3 Ga
Maroni - Itacaiunas 2.2–1.9 Ga
Ventuári-Tapajós 1.9–1.8 Ga
Rio Negro-Juruena 1.8–1.55 Ga
Rondonia-San Ignácio 1.5–1.3 Ga
Sunsás 1.25–1.0 Ga
GEOLOGIC UNITS
Phanerozoic sedimentary cover
Granitoids
Precambrian sedimentary cover
Acid-intermediate volcanic cover
Basic volcanic rocks
Greenstone belts
Granulitic complex
Neoproterozoic mobile belt
b)
6º00'
7º00'
52º30'
51º00'
Antônio Vicente
SL-09B-DT
SL-02-DT
IE-02
1
IE-05
AM-09MUT
VELHO GUILHERME INTRUSIVE SUITE
UATUMÃ GROUP: IRIRI FORMATION
UATUMÃ GROUP: SOBREIRO FORMATION
PARAUARI GRANITE
UNDIFFERENTIATED ARCHEAN SEQUENCES AND GRANITOIDS
N
NN-AV-40
NN-AV-43
NN-AV-44
NN-AV-45
Xingu River
4
Rio Xingu
Geologic contact
Fracture and/or Fault indiscriminated
Fault with kinetic indication
São Félix do Xingu
Fresco River
Tucumã
NN-GM-10A
NN-GM-12
NN-GM-11
Mocambo
NN-GM-17 A
NN-GM-56
3
NN-GM-51
NN-GM-52
NN-GM-53
2
Velho Guilherme
0
50 km

Fig. 1

quence of the Tucumã Group (Araújo et al., 1988) and the Rio Maria granodiorite (Medeiros et al., 1987), both part of the South Pará granite-greenstone terrane; (2) Itacaiúnas shear belt (Araújo et al., 1988); and (3) Parauari granite (CPRM/DNPM, 1997). The rocks of the Uatumã Group represent an extensive volcanic event that postdates the Paleoproterozoic Parauari granite and the basement units of the Itacaiúnas shear belt.

2.2. Studied granitic massifs and volcanic rocks

The granitic massifs of the Velho Guilherme intrusive suite are tin-mineralized. At present, the deposits are not exploited; however, in the 1980s, placer deposits associated with the Antonio Vicente and Mocambo massifs were in production. The granitic facies are intensively affected by late-to postmagmatic alteration (in the sense of Taylor and Pollard, 1988). Greisenized zones and sheet like greisen bodies associated with both massifs host small primary concentrations of cassiterite (Teixeira, 1999). Different facies have been recognized in these granitic plutons but the temporal relationships of them cannot be deduced due to the lack of outcrops (Teixeira, 1999).

The absence of deformational structures in the interior of the massifs, the discordant character of the plutons, contact aureola grading outward from hornblende hornfels to albite–epidote hornfels facies (Dall'Agnol, 1980; Teixeira, 1999), and the presence of micrographic intergrowths suggest a high level of emplacement (Teixeira, 1999). These features have been described in other anorogenic and post-tectonic granites of the Amazonian region (e.g., Dall'Agnol, 1980; Dall'Agnol et al., 1987; Teixeira, 1999) and they indicate that the crystal–liquid ratio was not very high during emplacement (Pitcher, 1979).

The granites of the four massifs of the Velho Guilherme intrusive suite are hololeucocratic to leucocratic syeno- to monzo-granites; minor alkali feldspar granites are also found (Fig. 2). Geochemical data confirm the subalkaline nature and the metaluminous to peraluminous character of the granites, as well as their within-plate signature and A-type character, as observed in the other anorogenic granites of the Carajás Mineral Province (Teixeira, 1999). Petrographic, mineral chemistry, and geochemical data (Teixeira, 1999) suggest that this granitic suite evolved at relatively reducing conditions. In the late- and post-magmatic alteration stages, more oxidizing conditions prevailed. The studied granites were emplaced at high crustal levels, with temperatures and pressures between 890 and 690 °C and 4.0 and 0.8 kbar, respectively (Teixeira, 1999).

2.2.1. Antônio Vicente massif

This massif occupies ~ 600 km^2 (Fig. 1b) and has four petrographic domains (Teixeira, 1999): (1) biotite-amphibole syenogranite with minor amphibole monzogranite, both only little affected by late- to postmagmatic alteration; (2) amphibole-biotite syenogranite, associated with biotite-amphibole alkali feldspar granite, biotite syenogranite with chlorite and alkali feldspar granite; (3) biotite syenogranite with minor biotite monzogranite, variously affected by late- to postmagmatic alteration; and (4) biotite monzogranite (without intense pervasive alteration) and minor biotite syenogranite. Locally, micromonzogranite and granophyric syeno-monzogranite are observed. Three different types of greisens are associated with the biotite syenogranite: muscovite-quartz, chlorite-quartz, and chlorite-siderophyllite-quartz.

The different facies show usually hypidiomorphic granular textures although porphyritic, equigranular, and heterogranular textures are also present. The rocks are usually grayish with some pink varieties. Reddish or grayish shades are found in the granites more intensely affected by

Fig. 1. (a) Map outlining the geochronologic provinces of the Amazonian craton after Tassinari and Macambira (1999). Inset shows Amazonian craton relative to northern South America. (b) Regional geological map of the São Félix do Xingu region showing the location of the samples from the granitic rocks of the Velho Guilherme intrusive suite and Uatumã Group analyzed for Pb and Sm–Nd isotopes. 1—Antônio Vicente massif; 2—Velho Guilherme massif; 3—Mocambo massif; 4—Rio Xingu massif. Simplified from CPRM/DNPM (1997).

Table 1
Geochronologic data of some volcanic and granitic rocks of the Amazonian craton

Stratigraphic unit (rock type)	Region	Age	Method	Reference
Volcanic rocks related to the uatumã group				
Iriri Group (R)	Tapajós	1888 ± 2 Ma	Pb–Pb Zrn[a]	Vasquez et al. (1999)[b]
Vila Riozinho Trachyte	Tapajós	2001 ± 6 Ma	Pb–Pb Zrn[a]	Lamarão et al. (1999)
Moraes Almeida Ignimbrite	Tapajós	1877 ± 6 Ma	Pb–Pb Zrn[a]	Lamarão et al. (1999)
Iriri Group (R)	Tapajós	1888 ± 6 Ma	Pb–Pb Zrn[a]	Moura et al. (1999)[b]
Iriri Group (R)	Tapajós	1888 ± 2 Ma	Pb–Pb Zrn[a]	Dall'Agnol et al. (1999c)
Iricoumé Group (Rd)	Pitinga	1962 + 42/ − 33 Ma	U–Pb Zrn	Schobbenhaus et al. (1994)[b]
Iricoumé Group (Rd)	Pitinga	1888 ± 3 Ma	Pb–Pb Zrn	Costi et al. (2000)
Surumu Group (And)	N. Roraima	1966 ± 9 Ma	U–Pb Zrn	Schobbenhaus et al. (1994)[b]
Surumu Group (And)	N. Roraima	2006 ± 4 Ma	Pb–Pb Zrn[a]	Costa (1999)[b]
Uatumã Group (And + R)	Xingu	1875 ± 158 Ma	Pb–Pb wrn	This work
Tin-barren Rapakivi Granites				
Musa Granite	Rio Maria	1883 + 5/ − 2 Ma	U–Pb Zrn, Tit	Machado et al. (1991)
Seringa Granite	Xinguara-Tucumã	1892 ± 30 Ma	Pb–Pb Zrn[c]	Avelar et al. (1994)
Jamon Granite	Rio Maria	1885 ± 32 Ma	Pb–Pb Zrn[a]	Dall'Agnol et al. (1999b)
Cigano Granite	Carajás	1883 ± 3 Ma	U–Pb Zrn	Machado et al. (1991)
Carajás Granite	Carajás	1880 ± 2 Ma	U–Pb Zrn	Machado et al. (1991)
Redenção Granite	Redenção	1870 ± 68 Ma	Pb–Pb wr	Macambira and Lafon (1995)
Marajoara Granite	Rio Maria	1724 ± 50 Ma	Rb–Sr wr	Macambira (1992)
Tin-bearing and related Rapakivi Granites				
Mocambo[t(VGIS)]	Xingu	1862 ± 32 Ma	Pb–Pb Zr[a]	This work
Rio Xingu [(VGIS)]	Xingu	1866 ± 3 Ma	Pb–Pb Zrn[a]	This work
Antônio Vicente[t(VGIS)]	Xingu	1867 ± 4 Ma	Pb–Pb Zrn[a]	This work
Velho Guilherme Granite[t] [(VGIS)]	Tucumã	1874 ± 30 Ma	Pb–Pb wr	Lafon et al. (1995)
Madeira Granite[t]	Pitinga	1817 ± 2 Ma to 1834 ± 6 Ma	U–Pb Zrn	Costi et al. (2000) Fuck et al. (1993)[b]
Europa Granite	Pitinga	1829 ± 1 Ma	Pb–Pb Zrn[a]	Costi et al. (2000)
Moderna Granite	S. Roraima	1814 ± 27 Ma	Pb–Pb Zrn[c]	Santos et al. (1997)
Água Boa Granite[t]	Pitinga	1798 ± 10 Ma to 1815 ± 10 Ma	U–Pb Zrn[d]	Lenharo (1998)[b]
Serra do Acari Granite	Mapuera	1750 ± 30 Ma	Rb–Sr (wr)	Jorge João et al. (1985)[b]
Surucucu Suite[t]	W. Roraima	1551 ± 5 Ma	U–Pb Zrn[e]	Santos et al. (1999)[b]
Parguaza Granite	S. Venezuela	1545 ± 20 Ma	U–Pb Zrn	Gaudette et al. (1978)
Serra da Providência Granite	Rondônia	1566 ± 3 Ma to 1606 ± 24 Ma	U–Pb Zrn	Bettencourt et al. (1999)
Mucajaí Granite	C. Roraima	1544 ± 42 Ma	U–Pb Zrn	Gaudette et al. (1996)
Caripunas felsic volcanics	Rondônia	1312 ± 3 Ma	U–Pb Zrn	Bettencourt et al. (1999)
São Lourenço Granite[t]	Rondônia	1309 ± 24 Ma	U–Pb Zrn	Bettencourt et al. (1999)
Oriente Novo Granite[t]	Rondônia	1080 ± 27 Ma	U–Pb Zrn	Bettencourt et al. (1999)
Pedra Branca Granite[t]	Rondônia	998 ± 5 Ma	U–Pb Zrn	Bettencourt et al. (1999)

Key to abbreviations: VGIS—Velho Guilherme intrusive suite; R—rhyolite; Rd—rhyodacite; And—andesite; [t]—tin-mineralized granite; Tit—titanite; Zrn—zircon; wr—whole-rock.

[a] $^{207}Pb/^{206}Pb$ double filament evaporation method.

[b] As referred to in Costi et al. (2000).

[c] $^{207}Pb/^{206}Pb$ single filament evaporation method.

[d] SHRIMP II $^{207}Pb/^{206}Pb$.

[e] SHRIMP II U–Pb.

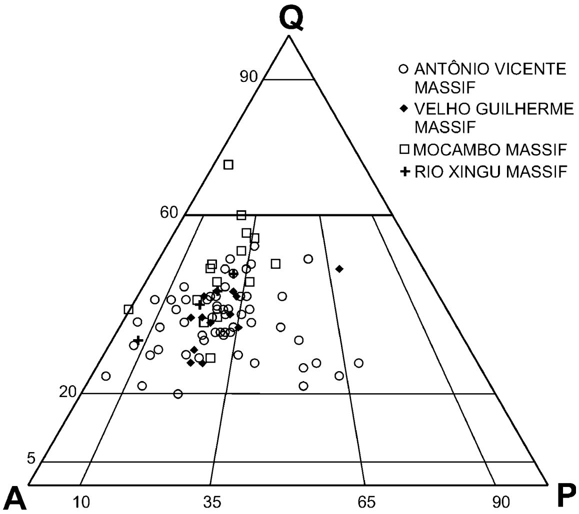

Fig. 2. QAP diagram showing the modal compositions of the four granitic massifs of the Velho Guilherme intrusive suite. Antônio Vicente data from Teixeira and Dall'Agnol (1991).

late- and post-magmatic alteration. Quartz, perthitic alkali feldspar, and sodic plagioclase (albite-oligoclase) are the most abundant felsic minerals. Albite-oligoclase crystals are subhedral and corroded. Abundant granophyric and rare myrmekitic intergrowths also occur. Annite-rich biotite is the main primary mafic mineral and hastingsitic to edenitic amphibole is also found in the less evolved granitic rocks. Accessory minerals include zircon, ilmenite, fluorite, and commonly, topaz and monazite. The secondary mineral assemblage of the altered granites includes sericite, muscovite, chlorite, fluorite, epidote, topaz, microcline, albite, allanite, monazite, and clay minerals. Cassiterite is associated with the most intensely altered granite types and mica-quartz greisens.

2.2.2. *Velho Guilherme massif*

This massif is roughly rounded and covers ~80 km^2 (Fig. 1b; Dall'Agnol, 1980; Teixeira, 1999). Three main facies are found: (1) medium-grained equigranular biotite syenogranite; (2) seriated syenogranite; and (3) microsyenogranite (Teixeira, 1999). The granitic types are affected by variable late- and post-magmatic alteration. The rocks are essentially holo-leucocratic subsolvus syenogranites and are very similar to the biotite syenogranite facies of the Antonio Vicente massif. Quartz, plagioclase (An_{6-12}), and perthitic microcline are the main felsic phases, biotite is the main mafic mineral. Zircon and opaque minerals (ilmenite ± titano–magnetite ± magnetite) are the primary accessory phases, whereas sericite, muscovite, chlorite, fluorite, topaz, microcline, albite, sphalerite, allanite, epidote, carbonate, clay-minerals, and thorite are secondary, late- to postmagmatic phases.

2.2.3. *Mocambo massif*

This massif consist of a main granitic pluton and three small satellitic stocks ~20 km south of São Félix do Xingu (Fig. 1b). The main pluton is elongated in the NW–SE direction and forms a dome intensely affected by pervasive late- and post-magmatic alteration. Three granitic facies have been identified (Teixeira, 1999): (1) dominant porphyritic syeno- to monzogranite; (2) muscovite syenogranite; and (3) aplitic alkali-feldspar granite. A siderophyllite-chlorite-muscovite-quartz greisen is also present.

The dominant syeno- to monzogranitic facies is characterized by phenocrysts of quartz and plagioclase in a medium to fine-grained heterogranular hypidiomorphic matrix. The syenogranite with muscovite is medium-grained and heterogranular to equigranular and occupies a small area of the main pluton. Iron-rich biotite or aluminous siderophyllite is present in the porphyritic syeno- to monzogranite and syenogranite with muscovite. Late- to postmagmatic phases associated with the alteration of biotite and plagioclase are sericite ± muscovite ± clorite ± fluorite ± epidote ± topaz ± carbonate and K-feldspar. Albite and clay minerals are related to the alteration of primary K-feldspar. Cassiterite is related to oxidation of the iron-micas and is associated with muscovite and chlorite (Teixeira, 1999). Allanite, monazite, fluocerite, and yttrocerite are also found. Siderophyllite-chlorite-muscovite-quartz greisen has been observed only in the contact zone between the syenogranite with muscovite facies and the country rocks. Zircon, hematite and magnetite are the common accessory phases; albite, fluorite, and cassiterite are subordinate.

2.2.4. *Rio Xingu massif*

The Rio Xingu massif is a homogeneous, circular small (~ 1 km^2) stock, located 3 km north of São Félix do Xingu (Fig. 1b; Teixeira, 1999). It consists of a porphyritic alkali feldspar granite with medium to coarse K-feldspar, quartz, and plagioclase phenocrysts. The K-feldspar and plagioclase phenocrysts are generally tabular (the former occasionally ovoid) and quartz phenocrysts are rounded and sometimes show a blue shade. The matrix is heterogranular and made up of granophyric K-feldspar-quartz intergrowths and individual crystals of quartz, K-feldspar, and plagioclase. Zircon, opaque minerals, and apatite also occur in this matrix as primary phases. Late- and post-magmatic phases are sericite, muscovite, chlorite, carbonate, epidote, fluorite, sphalerite, and opaque minerals. Carbonates, muscovite, opaque minerals, sphalerite, and epidote fill cavities in this rock.

2.2.5. *Uatumã Group*

In the São Félix do Xingu region, the volcanic rocks of the Uatumã Group show a close spatial relationship with the Rio Xingu, Mocambo, and Antonio Vicente massifs (Fig. 1b; Teixeira, 1999) and are divided two formations (CPRM/DNPM, 1997). The Sobreiro Formation is composed of mesocratic to melanocratic andesites with an aphanitic to microporphyritic texture with augite, plagioclase, and basaltic hornblende phenocrysts and a pilotaxitic matrix (CPRM/DNPM, 1997). Chlorite, calcite, epidote, and quartz are secondary phases, related to local hydrothermal alteration. The Iriri Formation consists of felsic volcanic rocks associated with pyroclastic material. These show a dominant porphyritic texture characterized by quartz, K-feldspar, and plagioclase phenocrysts in a felsitic matrix. Spherulitic features and micrographic intergrowths are locally observed. The pyroclastic tuffs usually show a vitroclastic texture with crystals, vitric, and lithic fragments in a glassy to microcrystaline felsitic matrix (CPRM/DNPM, 1997).

3. Geochronology and Nd isotopes

3.1. *Analytical procedures*

Radiogenic isotope investigations were carried out on the Antonio Vicente, Mocambo, and Rio Xingu massifs of the Velho Guilherme intrusive suite and on andesites and rhyolites of the Uatumã Group. These involved Pb isotope analyses of whole-rock and K-feldspar fractions, single zircon Pb-evaporation analysis, and Nd whole-rock analysis. The Pb isotope data were obtained at the Laboratory of Isotopic Geology of the Federal University of the Pará (Pará-Iso). About 500 mg of whole-rock and 200 mg of feldspar fractions were dissolved in HF using teflon capsules. The feldspar fractions were leached with 1N HF before dissolution. After evaporation, the samples were dissolved in HBr. Pb exchange chromatography was performed in teflon microcolumns using 0.1 ml of AG1X8 resin. Pb retention in the column was obtained by adding 0.5N HBr and Pb was eluted with 6N HCl. Pb was loaded with silica gel and H_3PO_4 on Re filaments and analyzed on a single-collector VG 54E thermal ionization mass spectrometer (TIMS). The data were corrected for instrumental mass fractionation of 0.12% based on multiple runs of the NBS SRM 981 Pb isotope standard. The analytical errors are quoted at 2σ. The total chemical process Pb blank was significantly lower than 1 ng.

The single zircon Pb-evaporation analyses (Krober, 1987) were performed on a Finnigan MAT 262 TIMS following the routine procedure established at the Pará-Iso (Costi et al., 2000; Noce et al., 2000). Each sample was collected from a single outcrop and processed by conventional methods of heavy mineral separation. Zircon crystals were handpicked from the least magnetic fractions and loaded on a canoe-shaped Re filament. The filament was heated to evaporate the Pb in the zircon and precipitate it on a cold ionization filament. Three evaporation steps of 5 minutes each were performed, usually at 1450, 1500, and 1550 °C. After each step, the temperature of the ionization filament was slowly raised until Pb emission was detected (~ 1050–1150 °C) and then the Pb isotopic composition was measured using the ion counting collector. Pb signal was collected by peak hopping in the order 206-207-208-206-207-204 using ten mass scans, which led to one block of data with 18 $^{207}Pb/^{206}Pb$ ratios. Blocks yielding a mean $^{204}Pb/^{206}Pb$ ratio above 0.0004 were eliminated in order to avoid significant errors caused by inaccurate common Pb correction. Common Pb correction was performed using the model of Stacey and Kramer (1975). Blocks of data that scattered more than two standard deviations from the average $^{207}Pb/^{206}Pb$ ratios were also eliminated. The calculated $^{207}Pb/^{206}Pb$ age for one zircon grain is the weighted mean and standard error of the accepted blocks of data. Similar calculation was applied to the selected zircon grains of a rock sample in order to define its apparent average $^{207}Pb/^{206}Pb$ age. Uncertainties are given at the 2σ level.

The Nd isotopic analyses were carried out at the Centro de Pesquisas Geocronológicas (CPGeo) of the Instituto de Geociencias at the University of São Paulo (for overall laboratory procedures, see Sato et al., 1995). About 50 mg of sample, mixed with a ^{150}Nd-^{149}Sm spike, was dissolved overnight using HF–HNO_3 (2:1) in teflon capsules. The sample was then attacked with 6.2N HCl to dissolve still remaining residue (if residue remained still after this, a PARR bomb dissolution was performed). Sm and Nd were purified in two steps, first by standard cation exchange in quartz column; then, Sm and Nd were extracted using teflon powder (Richard et al., 1976). The isotope analyses were performed dynamically using a VG 354 multi-collector mass spectrometer. Total procedural Nd blank was less than 300 pg. Repeated analysis of the La Jolla Nd standard gave $^{143}Nd/^{144}Nd$ of 0.511847 ± 0.000044 (mean and external error 2σ error of fourteen measurements). The Nd isotopic ratios were normalized to $^{146}Nd/^{144}Nd$ ratio of 0.7219. The ε_{Nd} values were calculated using chondritic ratios of $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd =$ 0.1967. Nd model ages were calculated based on the depleted mantle model of DePaolo (1981).

3.2. Pb–Pb geochronology

3.2.1. Velho Guilherme intrusive suite

For the Antonio Vicente massif, four whole-rock samples and two K-feldspar fractions were analyzed for Pb isotopes (Table 2). In the $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram (Fig. 3a), they define a regression line corresponding to an age of 1896 ± 18 Ma (MSWD = 4.47; $\mu_1 = 9.2 \pm 0.06$; $\mu_2 = 12.5 \pm 0.16$). Single zircon Pb-evaporation analyses were performed on ten crystals from the Antonio Vicente massif. However, only two gave a suitable Pb signal for isotopic analysis (Table 3; Fig. 3b). These yielded an average $^{207}Pb/^{206}Pb$ apparent age of 1867 ± 4 Ma, which is comparable to that achieved by the Pb–Pb whole-rock and K-feldspar data.

For the Rio Xingu massif, four whole-rock samples were analyzed for Pb isotopes (Table 2). These define an isochron (Fig. 4a) with an age of 1906 ± 58 Ma (MSWD = 0.06; $\mu_1 = 9.3 \pm 0.11$; $\mu_2 = 12.6 \pm 0.32$). Pb evaporation analyses were performed on six zircon crystals. Their $^{207}Pb/^{206}Pb$ apparent age ranges between 1860 ± 7 Ma and 1870 ± 3 Ma (Table 3), with an average at 1866 ± 3 Ma (Fig. 4b). This overlaps, within error, the Pb–Pb whole-rock age.

For the Mocambo massif, four metamict zircon crystals gave apparent $^{207}Pb/^{206}Pb$ ages ranging from 1421 to 1921 Ma, with an average age of 1862 ± 16 Ma (Table 3; Fig. 5). The average age is comparable to the Pb–Pb whole-rock age of 1864 ± 30 Ma obtained by Lafon et al. (1995) for the Velho Guilherme massif. One crystal yielded an age of 1865 ± 2 Ma, which is quite similar to the $^{207}Pb/^{206}Pb$ zircon ages obtained for the Antonio Vicente and Rio Xingu massifs.

3.2.2. Uatumã Group

For the Uatumã Group, four andesites from the Sobreiro Formation and two rhyolites of the Iriri Formation were analyzed for Pb isotopes (Table 2). These volcanic rocks are considered part of the same magmatic event in the São Félix do Xingu region. The data yield an errorchron correspond-

Table 2
Whole-rock and K-feldspar Pb isotopic data for the granites of the Velho Guilherme intrusive suite and volcanic rocks of the Uatumã Group

Sample	$^{206}Pb/^{204}Pb^{a}$	$^{207}Pb/^{204}Pb^{a}$	$^{208}Pb/^{204}Pb^{a}$
Antônio Vicente massif (1896 ± 18 Ma)			
SL-2C-DT (wr)	53.507(66)	20.208(36)	56.246(134)
SL-09-DT (wr)	64.662(80)	21.460(38)	81.947(198)
IE-05 (wr)	29.779(36)	17.394(32)	51.408(124)
AM-03MUT (wr)	62.623(78)	21.191(38)	62.445(150)
IE-02 (Kfs)	17.111(20)	15.935(28)	37.267(90)
IE-05 (Kfs)	17.273(20)	15.981(100)	37.503(90)
Rio Xingu massif (1906 ± 58 Ma)			
NN-AV-40 (wr)	20.972(26)	16.402(30)	45.843(110)
NN-AV-43 (wr)	23.471(28)	16.699(30)	50.644(122)
NN-AV-44 (wr)	17.7601(22)	16.038(30)	39.058(106)
NN-AV-45 (wr)	27.773(34)	17.213(32)	59.637(152)
UatumÃ Group (1875 ± 158 Ma)			
NN-GM-11 (wr,And)	19.262(24)	16.079(30)	39.738(96)
NN-GM-51 (wr, And)	21.073(24)	16.308(30)	41.093(104)
NN-GM-52 (wr, And)	17.804(22)	15.933(28)	38.054(92)
NN-GM-53 (wr, And)	18.589(22)	16.057(30)	39.255(96)
NN-GM-10A (wr, R)	25.906(32)	16.882(32)	47.182(118)
NN-GM-12 (wr, R)	22.024(26)	16.369(30)	43.175(104)

Key to abbreviations: Kfs—K-feldspar; And—andesite; R –rhyolite; wr—whole-rock.
[a] Analytical erros in parentheses quoted at 2σ.

ing to an age of 1875 ± 158 Ma (MSWD = 5.95; $\mu_1 = 9.0 \pm 0.27$; $\mu_2 = 12.0 \pm 0.81$; Fig. 6). In spite of the high MSWD and uncertainty, this data set is considered to represent a reference age for this volcanic event in the Uatumã Group. Pb–Pb zircon age of 1.88 Ga is generally considered as the most representative of the Uatumã volcanism (see Table 1 and references therein). However, this volcanic event is certainly more complex than originally thought. In the Tapajós region farther to the west, two different sequences (~ 2.0 and 1.88 Ga) have been dated (Lamarão et al., 1999). Obviously, more detailed research is necessary on the Uatumã volcanism in the Xingu region.

3.3. Nd isotopes

The Nd isotopic data for the granitic rocks of the Antonio Vicente, Mocambo, and Rio Xingu massifs, an andesite from the Sobreiro Formation, and rhyolites from the Iriri Formation of the Uatumã Group were obtained to get information about the ages of the protoliths of these rocks, and to assess their relationship to the surrounding Archean bedrock (cf. Teixeira, 1999; Dall'Agnol et al., 1999b). These data are listed in Table 4 and they are shown in an ε_{Nd} versus age diagram in Fig. 7. Because field evidence suggests contemporaneity of the volcanic and plutonic events (Teixeira, 1999), the ε_{Nd} values were all calculated at 1.87 Ga—this represents the average of the ages obtained for the Velho Guilherme intrusive suite granites and the presumable age of the volcanic rocks of the Uatumã Group (Table 1). The ε_{Nd} (at 1875 Ma) value varies from −7.9 to −12.2 for the granitic rocks and is −10.1 for the andesite and between −9.7 and −11.6 for the rhyolites. Both the granites and the volcanic rocks thus show strongly unradiogenic initial Nd isotopic compositions indicating a long period of crustal residence time for the sources of these rocks. The Nd model ages fall in the 3.2–3.0 Ga range for the granitic rocks and are between 3.1 and 2.9 Ga for the volcanic rocks (Table 4).

The Archean rocks considered here are the nearby Arco Verde tonalite, Rio Maria granodior-

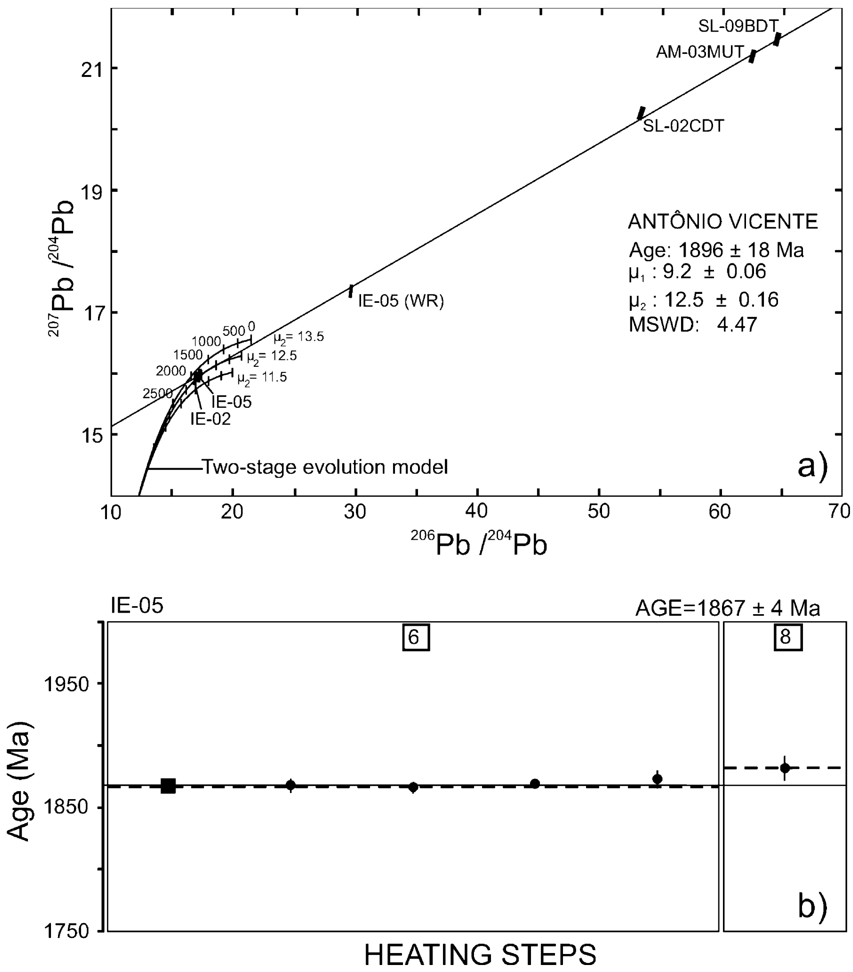

Fig. 3. (a) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram (whole-rock and K-feldspar data) for the granitic rocks of Antônio Vicente massif. μ_1 refers to the single-stage Holmes-Holtermans model, μ_2 to the two-stage evolution of Stacey and Kramer (1975). Three Stacey and Kramer (1975) second-stage growth curves are also shown. (b) Diagram showing heating steps for the $^{207}Pb/^{206}Pb$ single zircon Pb evaporation analysis of the Antônio Vicente massif. Numbers in square boxes refer to the two analyzed zircon grains (Table 3).

ite, and a metavolcanic mafic rock of the Tucumã Group (Dall'Agnol et al., 1999b; Avelar et al., 1999). The Nd model ages of the Rio Maria granodiorite and Tucumã Group rocks in the São Félix do Xingu region (3.15 and 3.17 Ga, respectively) are comparable to those of the Arco Verde tonalite (2.95 Ga) and Rio Maria granodiorite (3.0 Ga) in the Rio Maria region (Table 4). These data indicate an important period of crust formation in the Amazonian craton at ~3.0 Ga. The ε_{Nd} values for these rocks are strongly negative at 1.87 Ga and, on average, only slightly lower than those of the Velho Guilherme intrusive suite granites and Uatumã Group volcanic rocks (Table 4). In addition, the Nd model ages of the Velho Guilherme intrusive suite granites (3.2–3.0 Ga) and Uatumã Group volcanic rocks (3.1–2.9 Ga) are similar to those of these Archean rocks. It is thus likely that the Velho Guilherme intrusive suite granites and Uatumã Group volcanic rocks

Table 3
Pb–Pb zircon evaporation ages for granitic rocks of the Velho Guilherme intrusive suite

Grain	Evaporation temperature (°C)	n^{a}	^{206}Pb/^{b204}Pb	^{207}Pb/^{b206}Pb	^{207}Pb/^{c206}Pb*	Age (Ma)
IE-05—Antônio Vicente biotite-amphibole syeno—to monzogranite—1867 ± 4 Ma						
Zircon 6	1500	88	> 15000	0.1148(2)	0.1142(2)	1867 ± 2
Zircon 8	1550	18	> 15000	0.1152(14)	0.1151(14)	1882 ± 22
Average	–	–	–	–	–	1867 ± 4
NN-AV-43—Rio Xingu porphyritic syeno—to alkali feldspar granite—1866 ± 3 Ma						
Zircon 1	1450	18	> 15000	0.1143(2)	0.1138(4)	1861 ± 4
	1500	34	> 15000	0.1150(10)	0.1143(6)	1869 ± 8
Age	–	–	–	–	–	1863 ± 7
Zircon 2	1450[d]	86	5747	0.1150(4)	0.1126(2)	1842 ± 4
	1480	54	9434	0.1154(2)	0.1140(2)	1864 ± 4
	1550	88	> 15000	0.1141(2)	0.1135(2)	1857 ± 4
Age	–	–	–	–	–	1860 ± 7
Zircon 3	1480	36	> 15000	0.1144(4)	0.1138(6)	1868 ± 8
	1500	36	> 15000	0.1146(6)	0.1140(2)	1861 ± 4
Age	–	–	–	–	–	1866 ± 7
Zircon 4	1450	88	> 15000	0.1144(2)	0.1140(2)	1864 ± 2
	1480	86	> 15000	0.1144(2)	0.1143(2)	1870 ± 4
	1550	88	> 15000	0.1149(2)	0.1146(2)	1874 ± 4
Age	–	–	–	–	–	1869 ± 6
Zircon 5	1450	34	4831	0.1172(2)	0.1143(4)	1869 ± 6
	1480	78	> 15000	0.1151(2)	0.1143(4)	1870 ± 4
	1550	54	10989	0.1156(6)	0.1143(4)	1870 ± 8
Age	–	–	–	–	–	1870 ± 3
Zircon 6	1450	90	9901	0.1156(4)	0.1143(4)	1869 ± 5
Average	–	–	–	–	–	1866 ± 3
NN-GM-56—Mocambo porphyritic syeno—to monzogranite—1862 ± 16 Ma						
Zircon 1	1450	72	5025	0.1190(4)	0.1164(4)	1902 ± 6
	1550	82	5405	0.1202(2)	0.1177(2)	1921 ± 4
Zircon 2	1480	82	12346	0.1152(2)	0.1140(2)	1865 ± 2
Zircon 3	1450[e]	64	2151	0.1151(2)	0.1088(2)	1780 ± 2
	1480[e]	88	2358	0.1179(2)	0.1120(2)	1832 ± 4
	1550	88	2857	0.1170(2)	0.1124(4)	1839 ± 4
Zircon 5	1450[e]	36	1269	0.1009(6)	0.0898(6)	1421 ± 12
	1480[e]	86	2132	0.1075(6)	0.1011(10)	1644 ± 10
	1550	84	7463	0.1137(2)	0.1120(2)	1832 ± 2
Average	–	–	–	–	-	1862 ± 16

Uncertainties are quoted at the 2σ level.
[a] Number of ^{207}Pb/^{206}Pb ratios used for age calculation.
[b] Measured ratios.
[c] ^{207}Pb/^{206}Pb ratio corrected for common Pb.
[d] Lower temperature step discarded because the age does not overlap with those determined at higher temperatures.
[e] Step discarded because ^{206}Pb/^{204}Pb lower than 2500.

were derived from a Mesoarchean source and that open-system processes did not much affect the Nd isotopic composition of these rocks.

4. Discussion

4.1. Temporal evolution

The average zircon Pb-evaporation age of 1867±4 Ma of the Antonio Vicente massif is somewhat younger, yet comparable to the Pb–Pb whole-rock-K-feldspar age of 1896±18 Ma. This indicates a reasonable agreement between these geochronological systems. Considering that the Pb-evaporation age is more robust to post-magmatic process and that the Pb–Pb whole-rock-K-feldspar age shows considerable scatter (Fig. 3a), the 1867±4 Ma age is regarded as the best available estimate of the emplacement of the granite massif. The average Pb–Pb zircon age of the Rio Xingu massif, 1866±3 Ma, is quite consistent as it is defined by six zircon crystals with ages varying from 1870±3 Ma to 1860±7 Ma and is interpreted as the age of emplacement of the pluton. The Pb–Pb whole-rock age of 1906±58 Ma is compatible within error. The average Pb–Pb zircon age of 1862±16 Ma obtained for the Mocambo granite is interpreted as a fair estimate of the age of crystalization of the Mocambo massif.

The Pb–Pb obtained zircon ages overlap, within error, with the 1874±30 Ma (MSWD = 1.53) Pb–Pb whole-rock age of the Velho Guilherme massif (Lafon et al., 1995). Considering this similarity, and the good agreement among the zircon ages from three granitic massifs of the Velho Guilherme intrusive suite, we suggest that these granites represent one magmatic event at ~1.87 Ga. Compared to the other Paleoproterozoic anorogenic granites farther to the east in the Carajás Mineral Province (e.g., the 1883+5/−2 Ma Musa, 1885±32 Ma Jamon, 1880±2 Ma Carajás, and 1883±3 Ma Cigano; Table 1), the Velho Guilherme intrusive suite granites are somewhat younger and thus the anorogenic Paleoproterozoic magmatism may get younger westward in the Central Amazonian Province.

The 1875±158 Ma Pb–Pb whole-rock reference age of the volcanic rocks of the Uatumã Group of is comparable, within error, to the Pb–Pb zircon age of the granites of the Velho Guilherme intrusive suite. As both the granites and volcanic rocks are probably anorogenic and spatially associated, it is possible that these events were contemporaneous. More accurate geochronological data for the volcanic rocks are, however, needed to confirm this hypothesis.

4.2. Magma sources

The μ values for the granitic and volcanic rocks are in the same range (Figs. 3, 4 and 6) suggesting that they derived from sources with similar overall $^{238}U/^{204}Pb$. The μ_1 values of 9.2 and 9.3 obtained for the rocks Antonio Vicente and Rio Xingu massifs are similar to the value of 8.9 obtained by Lafon et al. (1995) for the Velho Guilherme massif. This suggests an important crustal contribution for the generation of these granitic rocks, as the μ_1 values of average mantle is lower, between 7.5 and 8.0 (Dupré and Arndt, 1990). This interpretation is corroborated by the high content of LILE (Rb, K and Th), LREE and HFSE (Zr, Nb and Y) in the granites of the Velho Guilherme intrusive suite (Teixeira, 1999).

The Nd model ages of the granites and volcanic rocks indicate that the magmas that generated these rocks evolved from ancient Archean rocks with a long crustal residence time (Fig. 7). The protoliths probably formed a Mesoarchean magmatic arc that was partially consumed to generate the granites and the volcanic rocks at ~1.87 Ga. The $f_{Sm/Nd}$ values are between −0.49 and −0.35 (Table 4) and suggest that significant fractionation did not occur in the Sm–Nd system during the process of formation of the magmas from which the granitic and volcanic rocks were crystallized.

The strongly negative ε_{Nd} (at 1870 Ma) values, varying from −7.9 to −12.2 for the granitic rocks and −9.7 to −11.6 for the volcanic rocks, indicate that these rocks could have formed by partial melting of Archean crust or by mixing of a mantle derived magma and an anatectic melt from an Archean crust. The relatively high ε_{Nd} (at 1870 Ma) value, −7.9, and young model age, 2976 Ma,

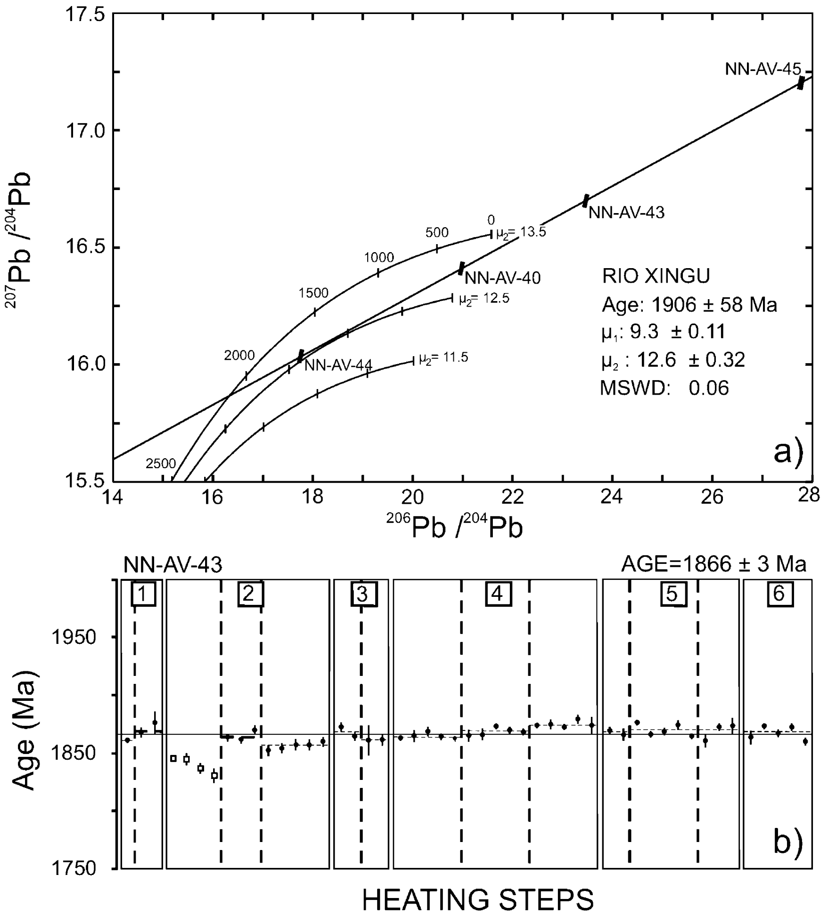

Fig. 4. (a) $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram (whole-rock data) for the granitic rocks of the Rio Xingu massif. μ_1 and μ_2 as in Fig. 3, three Stacey and Kramer (1975) second-stage growth curves are shown. (b) Diagram showing heating steps for the $^{207}Pb/^{206}Pb$ single zircon Pb evaporation analysis of the Rio Xingu massif. Numbers in square boxes refer to the six analyzed zircon grains (Table 3).

of the Mocambo massif may suggest involvement of a relatively juvenile source (Fig. 7). It is also possible to argue for variable mixing of mantle-derived and crust-derived melts to account for the different compositions of the different granitic massifs. There is, however, no direct evidence of magma mixing or mingling process in the studied granites.

The Nd isotope data suggest a two-stage evolution for the generation of the Velho Guilherme intrusive suite and Uatumã Group rocks. First, Mesoarchean 'juvenile' crust was formed by mantle-crust differentiation at ~3.0 Ga. This Mesoarchean crust was subsequently melted to give rise to felsic magmas at ~1.87 Ga. The oldest rocks recognized in the VISG region are the mafic and felsic granulites of the Pium complex (Araújo et al., 1988). These granulitic domains alternate with undifferentiated granitoid and gneissic rocks of Archean age and have been interpreted to represent slices of lower crust that were tectonically transported to the upper crust through oblique shearing (Costa et al., 1995). A U–Pb SHIRIMP age of 3002±12 Ma has been interpreted as the age of the igneous protolith of these granulites (Pidgeon et al., 2000). This age is within the model age range of the presumable sources of the granites of the Velho Guilherme intrusive suite

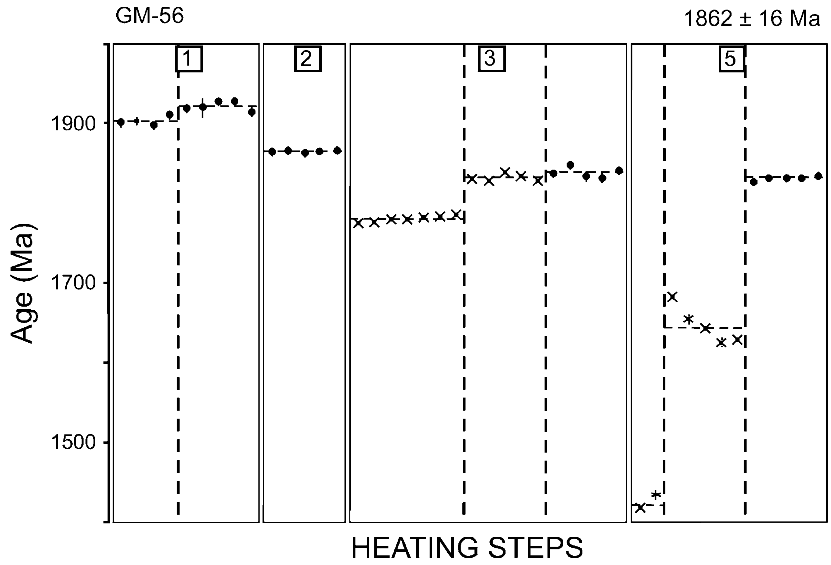

Fig. 5. Diagram showing heating steps for the $^{207}Pb/^{206}Pb$ single zircon Pb evaporation analysis of the Mocambo massif. Numbers in square boxes refer to the four analyzed zircon grains (Table 3).

and the volcanic rocks of the Uatumã group. Hence, a granulitic and/or granitoid geochemically similar to the Archean country rocks of the studied granites may well have been the source of these Paleoproterozoic magmas.

4.3. Relation to orogenic events

The absence of obvious effects of the 2.1 ± 0.1 Ga Transamazonian event in the Carajás Mineral Province and the relatively young ages of the

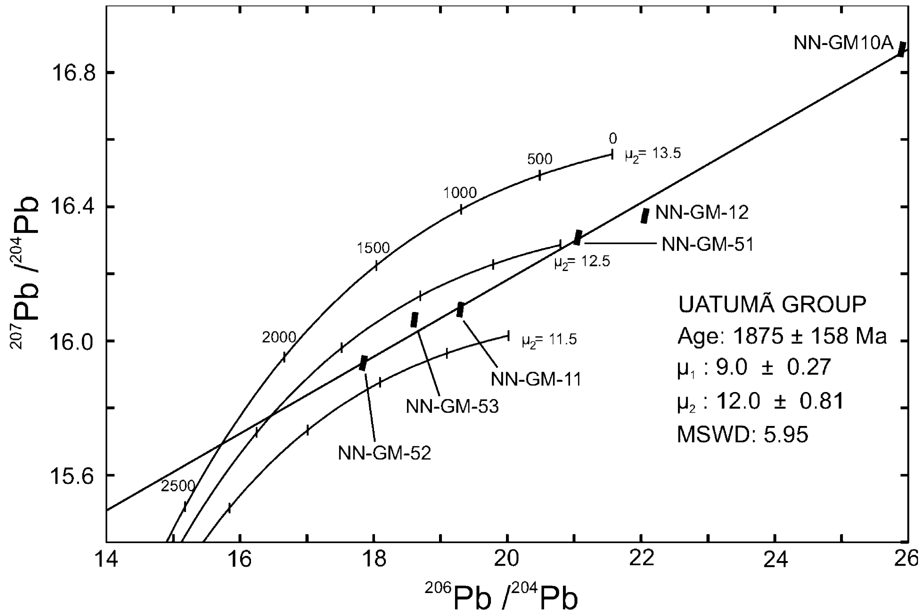

Fig. 6. $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram (whole-rock data) for the volcanic rocks of Sobreiro and Iriri formations of the Uatumã Group. μ_1 and μ_2 as in Fig. 3, three Stacey and Kramer (1975) second-stage growth curves are shown.

Table 4
Nd isotopic data for the Velho Guilherme intrusive suite, Uatumã Group, South Pará granite-greenstone terrane, and Rio Maria granite-greenstone terrane

Sample	Rock type	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{a144}Nd$	$^{143}Nd/^{b144}Nd$	ε_{Nd}[c] (at 1870 Ma)	$f_{Sm/Nd}$[d]	T-DM[e] (Ma)
Velho Guilherme								
Antônio Vicente massif (1867 ± 4 Ma)[f]								
N-S-6	Biotite-amphibole syeno- to monzo-granite[f]	30.37	153.16	0.1199	0.51108	−12.1	−0.39	3254
Mocambo massif (1862 ± 32 Ma)[f]								
NN-GM-17A	Muscovite syenogranite[f]	5.18	24.61	0.1274	0.51138	−7.9	−0.35	2976
Rio Xingu massif (1866 ± 3 Ma)[f]								
NN-AV-43	Porphyritic syeno- to alkali feldspar granite[f]	17.50	104.41	0.1013	0.51084	−12.2	−0.49	3023
Uatumã								
Sobreiro formation (1880 Ma)								
NN-GM-51	Andesite[f]	3.64	18.08	0.1219	0.51120	−10.1	−0.38	3106
Iriri formation (1880 Ma)								
NN-GM-10	rhyolite[f]	11.41	60.28	0.1145	0.51104	−11.6	−0.42	3129
NN-GM-12	rhyolite[f]	8.33	47.89	0.1052	0.51102	−9.7	−0.47	2876
South pará								
Tucumã Group (2868 ± 8 Ma)[g]								
NN-VG-72	Meta-andesite[f]	3.40	18.57	0.1109	0.51094	−12.7	−0.44	3170
Rio Maria granodiorite (2852 ± 16 Ma)[g]								
NN-VG-76	Biotite syeno-to monzogranite[f]	8.53	57.73	0.0893	0.51051	−15.9	−0.55	3150
Rio Maria								
Rio Maria granodiorite (2874 +9/−10 Ma)[i]								
Z-509B[h]	Biotite-hornblende quartz diorite	5.89	29.26	0.1216	0.51124	−10.1	−0.38	3010
HRM-284[h]	Hornblende-biotite granodiorite	3.06	18.60	0.0993	0.51083	−12.5	−0.50	2953
Arco Verde tonalite (2957 +25/−21 Ma)[i]								
MJ-08[h]	Biotite tonalite	2.55	18.60	0.0827	0.51052	−14.4	−0.58	2946

Age data from: [f] This work; [g] Avelar et al. (1999); [h] Dall'Agnol et al. (1999b); [i] Macambira (1992).

[a] Error on the Velho Guilherme and South Pará samples is 0.6%, that on the Rio Maria samples 0.5%.

[b] Normalized to $^{146}Nd/^{144}Nd = 0.7219$. External error on the Velho Guilherme and South Pará samples is 0.004%, that on the Rio Maria samples 0.003%.

[c] Calculated using chonditic ratios of $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$. Error on the Velho Guilherme and South Pará samples is ±0.43 ε-units, that on the Rio Maria samples ±0.35 ε-units.

[d] Sm–Nd fractionation factor (DePaolo, 1988).

[e] Depleted mantle model age (DePaolo, 1981).

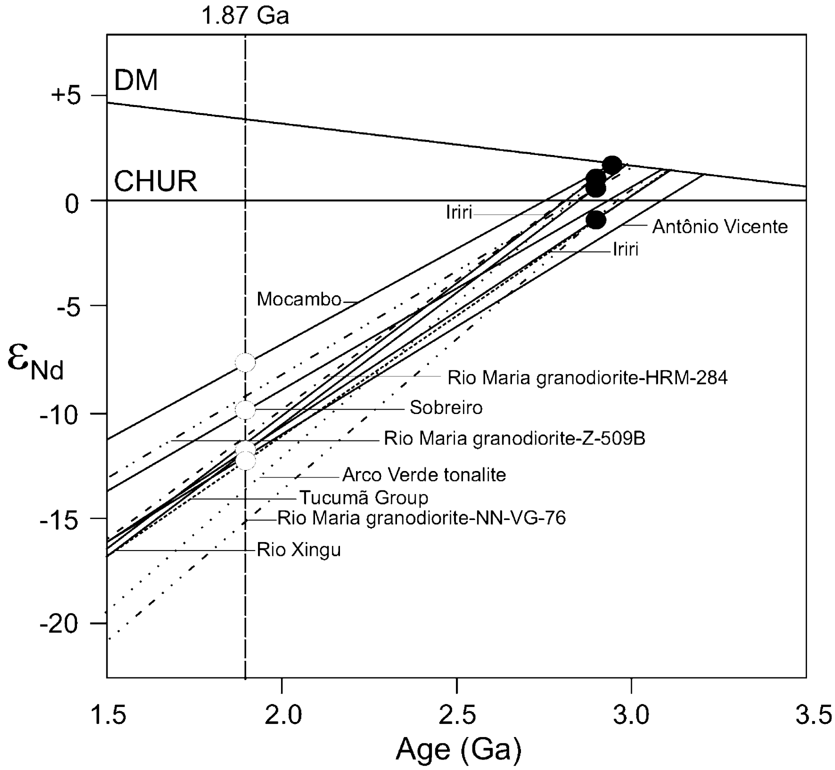

Fig. 7. ε_{Nd} versus age diagram showing the Nd isotopic composition of granitic rocks of the Velho Guilherme intrusive suite, volcanic rocks of the Uatumã Group and Archean rocks of the Rio Maria and São Felix do Xingu regions (Table 4). DM is depleted mantle evolution (DePaolo, 1981), CHUR is the Chondritic Uniform Reservoir (DePaolo and Wasserburg, 1976). Initial compositions of Velho Guilherme granitic rocks (open circles) and Archean country rocks (filled circles) are also indicated.

igneous rocks of the Velho Guilherme intrusive suite and the Uatumã Group suggest that the 1.87 Ga silicic magmatism may not have been directly related to this convergent event (Teixeira et al., 1998; Teixeira, 1999; Dall'Agnol et al., 1999a). It is possible, however, that the tectonic events in the adjacent portions of the Central Amazonian Province were directly responsible for the generation of this magmatism within the Archean craton. The region to the north of the Carajás Province is not well known geologically but this province is regarded as part of the 2.2–1.9 Ga Maroni-Itacaiúnas Province (Fig. 1a) formed by continental accretion during the Transamazonian event. If the studied granites and volcanic rocks were related to the convergent processes responsible for the development of this province, they were probably late relative to the main tectonic phase (Fig. 1a). Lamarão et al., 1999) summarized available geochronologic data on the Tapajós-Ventuari Province west of the Central Amazonian Province, and demonstrated the existence of two major periods of magmatic activity, at 2.01–1.97 Ga and 1.89–1.87 Ga. Although the present data do not allow conclusive interpretations, the contemporaneity of the ~1.88–1.87 Ga granitic rocks including the Velho Guilherme intrusive suite, major part of the Uatumã volcanic rocks, and rocks formed during the younger magmafic event of the Tapajós-Ventuary Province indicate a possible tectonic relationship between these magmatic events. Lamarão et al. (1999) consider the 1.88 Ga event as continent-scale, having affected large areas of the Amazonian craton. It could have marked the beginning of the taphrogenesis that followed the amalgamation of the Paleoproterozoic supercontinent and lasted throughout the Mesoproterozoic (Brito Neves, 1999). Because of absence of ample geological and geochronological data, however, the limits of the geochronological provinces remain poorly defined and the conclusions above serve merely as working hypotheses.

5. Conclusions

The single zircon Pb-evaporation ages of 1867 ± 4 Ma, 1862 Ma ± 16 Ma, and 1866 ± 3 Ma for the Antonio Vicente, Mocambo and Rio Xingu massifs, respectively, suggest an overall age of ~1870 Ma for the granite magmatism of Velho Guilherme intrusive suite. The 1875 ± 158 Ma Pb–Pb whole-rock reference age of the volcanic rocks of the Uatumã Group is comparable. The μ_1 values for the plutonic (9.2–9.3) and volcanic (9.0) rocks suggest an important crustal contribution for the generation of these rocks. The Nd model ages of the granitic (3.0–3.2 Ga) and the volcanic (2.9–3.1 Ga) rocks, along with the strongly negative ε_{Nd} (at 1.87 Ga) values for both rock types indicate that the magmas that generated these rocks probably derived from Mesoarchean rocks. However, a mantle contribution cannot be completely ruled out. A source with a distinct geochemical signature is envisioned for the Mocambo massif; these data can, however, also be interpreted to reflect mantle-crust mixing. In view of the similarity between the age of the Archean granulites (3.0 Ga) of the Pium complex and the Nd model ages of the protoliths of the studied granites and volcanic rocks (2.9–3.2 Ga), a granulitic and/or granitoid lower crust is a viable source for these Paleoproterozoic magmatic rocks.

Acknowledgements

This paper contains part of N.P.T.'s Ph.D. Thesis at the University of São Paulo and is a contribution to IGCP-426 (Granite Systems and Proterozoic Lithospheric Processes) and PRONEX (103-98/MCT/CNPQ; Regulation N^0 07/2000-CG). Pb–Pb and Nd isotopic analyses and field work were funded by FAPESP—Fundação de Amparo à Pesquisa do Estado de São Paulo—Brazil (Research Grant 96/3942-0 to J.S. Bettencourt). The authors would like to express their sincere thanks to the following institutions and people: CAPES (Fundação e Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) and UFPA (Universidade Federal do Pará) for financial support; Dr Thomas Scheller, M.Sc. Cintia Gaia and Cléris R. Sachett (UFPA) for Pb–Pb analysis (whole-rocks and zircon Pb evaporation); Drs Colombo C.G. Tassinari and Key Sato (USP) for discussion, and Liliane Petronilho, Ivone Sonaki and Hélen Sonaki (USP) for technical assistance during the Sm-Nd analysis; CPRM (Geological Survey of Brazil) for support during geologic mapping; São Francisco de Assis Mining Company (Mocambo Project) for support during geologic mapping; and Carlos Marcello Dias Fernandes for helping with illustrations.

References

Almeida, F.F.M., Brito Neves, B.B., Fuck, R.A., 1981. Brazilian structural provinces: an introduction. Earth Sci. Rev. 17, 1–29.

Anderson, J.L., Bender, E.E., 1989. Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America. Lithos 23, 19–52.

Araújo, O.J.B., Maia, R.G.N., Jorge João, X.S., Costa, J.B.S., 1988. A megaestruturação da Serra dos Carajás. In: Anais Seventh Congresso. Latinoamericano de Geologia, Belém Soc. Bras. Geol.Vol.1., pp. 324–338. (in Portuguese).

Avelar, V.G., Lafon J- M., Scheller, T., Araújo, O.J.B., Macambira, E.M.B., 1994. Geocronologia Pb–Pb por evaporação de zircões e Rb–Sr em rocha total do Granito Seringa, Província Mineral de Carajás. In: 38 Congr. Bras. Geol., Camboriú, Soc. Bras. Geol., Boletim de Resumos, Vol. 2, pp. 387–388. (in Portuguese).

Avelar, V.G., Lafon, J-M., Correia, F.C., Jr., Macambira, E.M.B., 1999. O magmatismo Arqueano da região de Tucumã-Província Mineral de Carajás: novos resultados geocronológicos. Rev. Bras. Geoc. 29, 453–460 (in Portuguese).

Bettencourt, J.S., Dall'Agnol, R., 1987. The Rondonian tin-bearing anorogenic granites and associated mineralization. In: International Symposium on Granites and Associated Mineralizations (ISGAM), Salvador, Bahia, Brazil, January 21–31, 1987, Excursion Guide, pp. 49–86.

Bettencourt, J.S., Tosdal, R.M., Leite, W.B. Jr., Payolla, B.L., 1995. Overview of the rapakivi granites of the Rondônia Tin Province. In: Bettencourt, J.S., Dall'Agnol, R., (Eds.), Symposium on Rapakivi Granites and Related Rocks,

Excursion Guide. Federal Univ. Pará, Belém, Brazil, pp. 5–16.
Bettencourt, J.S., Tosdal, R.M., Leite, W.B., Jr., Payolla, B.L., 1999. Mesoproterozoic rapakivi granites of the Rondônia Tin Province, southwestern border of the Amazonian craton, Brazil-I. Reconnaissance U–Pb geochronology and regional implications. Precambrian Res. 95, 41–67.
Brito Neves, B.B., 1999. América do Sul: quatro fusões, quatro fissões e o processo acrescionário andino. Rev. Brasil Geoci. 29, 379–392 (in Portuguese).
Brito Neves, B.B., Cordani, U.G., 1991. Tectonic evolution of South America during the Late Proterozoic. In: Stern, R.J., Van Schmus, W.R. (Eds.), Crustal Evolution in the Late Proterozoic. Precambrian Res. 53, pp. 23–40.
Collins, W.J., Beams, S.D., White, A.J., Chapell, B.W., 1982. Nature and origin of A-type Granites with particular reference to Southeastern Australia. Contrib. Mineral. Pet. 80, 189–200.
Costa, J.A., 1999. Tectônica da região nordeste do Estado de Roraima. Ph.D. Thesis, Center of Geoscíences, Federal University of the Pará, Brazil.
Costa, J.B.S., Araújo, O.J.B., Santos, A., Jorge João, X.S., Macambira, M.J.B., Lafon, J.-M., 1995. A Província Mineral de Carajás: Aspectos Tectono-Estruturais, Estratigráficos e Geocronológicos. Bol. Mus. Par. Emílio Goeldi Ciencias da Terra 7, 199–235 (in Portuguese).
Costi, H.T., Dall'Agnol, R., Moura, C.A.V., 2000. Geology and Pb–Pb geochronology of Paleoproterozoic volcanic and granitic rocks of Pitinga Province, Amazonian craton, northern Brazil. Int. Geol. Rev. 42, 832–849.
CPRM/DNPM, 1997. Programa Levantamentos Geológicos Básicos do Brasil. São Félix do Xingu, Folha SB-22-Y-B, Programa Grande Carajás, MME/SMM, Brasília-DF, Brazil. (in Portuguese).
Dall'Agnol, R., 1980. Etudes sur des granites du type 'Rondonian' en Amazonie Orientale et leurs transformations tardimagmatiques. Ph.D. Thesis, Univ. Paul Sabatier, France.
Dall'Agnol, R., Bettencourt, J.S., Jorge João, X.S., Medeiros, H., Costi, H.T., Macambira, M.J.B., 1987. Granitogenesis in the northern Brazilian region: a review. Rev. Brasil. Geoci. 17, 382–403.
Dall'Agnol, R., Teixeira, N.P., Magalhães, M.S., 1993. Diagnostic features of the Tin-specialized anorogenic granites of the Eastern Amazonian region. An. Acad. Bras. Ci. 65 (Suppl. 1), 33–50.
Dall'Agnol, R., Costi, H.T., Leite, A.A., Magalhães, M.S., Teixeira, N.P., 1999a. Rapakivi granites from Brazil and adjacent areas. Precambrian Res. 95, 9–39.
Dall'Agnol, R., Rämö, O.T., Magalhães, M.S., Macambira, M.J.B., 1999b. Petrology of the anorogenic, oxidised Jamon and Musa granites, Amazonian craton: implications for genesis of Proterozoic A-type granites. Lithos 46, 431–462.
Dall'Agnol, R., Silva, C.M.G., Scheller, T., 1999c. Fayalite-hedenbergite rhyolites of the Iriri Formation, Tapajós Gold Province, Amazonian craton. In: 1th Simp. sobre Vulcanismo e Ambientes Associados, Abstract, Gramado, Soc. Bras. Geol., p. 31.
DePaolo, D.J., 1981. Neodymium isotope in the Colorado Front Range and crust-mantle evolution in the Proterozoic. Nature 291, 193–196.
DePaolo, D.J., 1988. Neodymium isotope geochemistry. An introduction. Springer, Berlin.
DePaolo, D.J., Wasserburg, G.J., 1976. Nd isotopic variations and petrogenetic models. Geophys. Res. Lett. 3, 249–252.
Dupré, B., Arndt, N.T., 1990. Pb isotopic compositions of Archean Komatiites and sulfides. Chem. Geol. 85, 35–56.
Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: petrogenesis and tectonic implications. Geology 20, 641–644.
Emslie, R.F., 1991. Granitoids of rapakivi granite-anorthosite and related associations. Precambrian Res. 51, 173–192.
Fuck, R.A., Pimentel, M.M., Machado, N., Daoud, W.K., 1993. Idade U-Pb do Granito Madeira, Pitinga (AM). In: 4th Congresso, Brasileiro de Geoquímica, Brasília, Soc. Bras. Geoq., Abstract, pp. 246–248.
Gaudette, H.E., Mendoza, V., Hurley, P.M., Fairbairn, H.W., 1978. Geology and age of the Parguaza rapakivi granite, Venezuela. Geol. Soc. Am. Bull. 89, 1335–1340.
Gaudette, H.E., Olszewski, W.J., Santos, J.O.S., 1996. Geochronology of Precambrian rocks from the northern part of the Guiana Shield, state of Roraima, Brazil. J. S. Am. Earth Sci. 9, 183–195.
Haapala, I., Rämö, O.T., 1990. Petrogenesis of the Proterozoic rapakivi granites of Finland. Geol. Soc. Am. Spec. Pap. 246, 275–286.
Horbe, M.A., Horbe, A.C., Costi, H.T., Teixeira, J.T., 1991. Geochemical characteristics of cryolite-tin-bearing granites from Pitinga Mine, northwestern Brazil—a review. In: Rose, A.W., Taufen, P.M. (Eds), J. Geochemical Exploration 1989. Geochem. Explor. 40, 227–249.
Issler, R.S., Lima, M.I.C., 1987. Amazonian craton (Brazil) granitogenesis and its relation to geotectonic units. Rev. Brasil. Geoci. 17, pp. 426–441.
Jorge João, X.S., Santos, C.A., Provost, A., 1985. Granito Serra do Acari—geologia e implicações metalogenéticas (Folha Rio Mapuera—NW do Estado do Pará). In: Anais do 2nd Simpósio de Geologia da Amazônia, Belém, Soc. Bras Geol., Vol. 2, pp. 73–92.
Krober, B., 1987. Single grain evaporation conbined with Pb+ emitter bedding for $^{207}Pb/^{206}Pb$ investigations using thermal ion mass spectrometry, ans implications for zirconology. Contrib. Mineral. Pet. 96, 63–71.
Lafon, J.M., Pereira, E.D., Macambira, E.M.B., Vale, A.G., Barradas, J.A.S., 1991. Geocronologia Rb–Sr da região de São Félix do Xingu. Resultados preliminares. In: Anais do 3th Simpósio de Geolologia da Amazônia, Belém. Soc. Bras. Geol. Vol., pp. 21–35.
Lafon, J.M., Rodrigues, E., Macambira, E.M.B., Pereira, E.D., 1995. Magmatisme anarogénique du Protérozoique Inférieur dans la région de São Félix do Xingu-Tucumã (Amazonie Orientale, Brésil). Nouvelles données geochronologiques. C. R. Acad. Sci. Paris 320, 937–944.
Lamarão, C.N., Dall'Agnol, R., Lafon, J.-M., Lima, E.F, 1999. As associações vulcânicas e plutônicas de vila Riozinho e

Moraes Almeida. Província Aurífera do Tapajós. SW do Estado do Pará. In: 1th Simpósio sobre vulcanismo e Ambientes Associados, Gramado, Abstract, p. 93, (in Portuguese).

Lenharo, S.L.R., 1998. Evolução magmática e modelo metalogenético dos granitos mineraslizados da região de Pitinga, Amazonas, Brasil. Ph.D. Thesis, Politecnic School of the University of São Paulo, Brazil.

Loiselle, M.C., Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Geol. Soc. Am. Abstr. Progr. 11, 468.

Macambira, M.J.B., 1992. Chronologie U–Pb, Rb–Sr, K-Ar et croissance de la croûte continentale dans l' Amazonie du Sud-Est; exemple de la région de Rio Maria, Province de Carajás, Brésil. Ph.D. Thesis, Univ. Montpellier II, France.

Macambira, M.J.B., Lafon, J.-M., 1995. Geocronologia da Província mineral de Carajás: síntese dos dados e novos desafios. Bol. Mus. Par. Emílio Goeldi, Ciências da Terra 7, 263–288 (in Portuguese).

Machado, N., Lindenmayer, Z., Krogh, T.E., Lindenmayer, D., 1991. U–Pb geochronology of Archean magmatism and basement reactivation in the Carajás área, Amazon Shield, Brazil. Precambrian Res. 49, 329–354.

Medeiros, H., Gastal, M.C.P., Dall'Agnol, R., Souza, Z.S., 1987. Geology of the Rio Maria area (Estern Amazonian region—Brazil): an example of Archean granite-greenstone terrane intruded by anorogenic granites of Middle Proterozoic age. In: Final Meeting of IGCP Project 204, Carajás, Brazil, Ext. Abstr., pp. 97–109.

Moura, C.A.V., Gorayeb, P.S.S., Matsuda, N.S., 1999. Geocronologia Pb-Pb em zircão do riolito Vila Raiol, Formação Iriri—sudoeste do Pará. In: 6th Simpósio de Geologia da Amazônia, Manaus, Soc. Bras. Geol., Abstract, pp. 475–477.

Noce, C.M., Macambira, M.J.B., Soares, A.C.P., 2000. Chronology of Neoproterozoic-Cambrian granite magmatism in the Araçuai Belt, eastern Brazil, based on single zircon evaporation dating. Rev. Brasil. Geoci. 30, 25–29.

Pidgeon, R., Macambira, M.J.B., Lafon, J.-M., 2000. Th–U–Pb isotopic systems and internal structures of complex zircons from an enderbite from the Pium Complex, Carajás Province, Brazil: evidence for the ages of granulite facies metamorphism and the protolith of the enderbite. Chem. Geol. 166, 159–171.

Pitcher, W.S., 1979. The nature, ascent and emplacement of granitic magmas. J. Geol. Soc. London 136, 627–662.

Rämö, O.T., Haapala, I., 1995. One hundred years of Rapakivi Granite. Miner. Pet. 52, 129–185.

Richard, P., Shimizu, N., Allègre, C.J., 1976. $^{143}Nd/^{146}Nd$, a natural tracer: an application to oceanic basalts. Earth Planet. Sci. Lett. 31, 269–278.

Santos, J.O.S., Silva, L.C., Faria, M.S.G., Macambira, M.J.B., 1997. Pb–Pb single evaporation isotopic study on the post-tectonic, sub-alkalic, A-type Moderna Granite (Mapuera intrusive suite), state of Roraima, northern Brazil. In: Ferreira, V.P., Sial, A.N. (Eds.), Second International Symposium on Granites and Associated Mineralizations (ISGAM II) Ext. Abstr. Progr., August 24–29, 1997, Salvador, Bahia, Brazil, pp. 273–275.

Santos, J.O.S., Reis, N.J., Hartmann, L.A., McNaughton, N.J., Fletcher, I., 1999. Associação anortositocharnockito rapakivi no Calimiano do norte do craton Amazônico, Estado de Raraima, Brasil: evidências da geocronologia U-Pb em zircão e baddeleyita. In: 6th Simpósio de Geologia da Amazônia, Manaus, Soc. Bras. Geol., Abstract, pp. 502–505.

Santos, J.O.S., Hartmann, L.A., Gaudette, H.E., Groves, D.I., McNaughton, N.J., Fletcher, I., 2000. A new understanding of the provinces of the Amazonian craton based on integration of field mapping and U–Pb and Sm–Nd geochrnology. Gondwana Res. 3, 453–488.

Sato, K., Tassinari, C.C.G., Kawashita, K., Petronilo, L., 1995. O método geocronológico Sm–Nd no IG/USP e suas aplicações. An. Acad. Bras. Ci. 67, 314–336 (in Portuguese).

Schobbenhaus, C., Hoppe, A., Lork, A., Baumann, A., 1994. Idade Pb-Pb do magmatismo Uatumã no norte do craton Amazônico, Escudo das Guianas (Brasil): primeiros resultados. In: 38th Congr. Bras. Geol., Camburiú, Soc. Bras. Geol., Vol. 4, pp. 395–397.

Stacey, J.S., Kramer, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet Sci. Lett. 26, 207–221.

Tassinari, C.C.G., Macambira, M.J.B., 1999. Geochronological provinces of the Amazonian craton. Episodes 22, 174–182.

Taylor, R.G., Pollard, P.J., 1988. Pervasive hydrothermal alteration in tin-bearing granites and implications for the evolution of ore-bearing magmatic fluids. Recent Advances in the Geology of Granite-Related Mineral Deposits. Can. Inst. Min. Metal. Spec. 39, 86–95.

Teixeira, N.P., 1999. Contribuição ao estudo das rochas granitóides e mineralizações associadas da Suíte Intrusiva Velho Guilherme, Província Estanífera do Sul do Pará. Ph.D. Thesis, Univ. São Paulo, Brazil, (in Portuguese).

Teixeira, N.P., Dall'Agnol, R. 1991. Geologia e petrografia do Maciço Granítico Antônio Vicente. Região de São Félix do Xingu/PA. Bol. Mus. Para. Emílio Goeldi sér. Ci. Terra 3, 45–73, (in Portuguese)

Teixeira, N.P., Bettencourt, J.S., Moura, C.A.V., Dall'Agnol, R., 1998. Pb–Pb and Sm-Nd constraints of the Velho Guilherme intrusive suite and volcanic rocks of the Uatumã Group. South-Southeast Pará-Brasil. In: Van Schmus, W.R., Brown, B.A., Mudrey, M.G. Jr. (Eds.), Proterozoic Granite Systems of the Penokean Terrane in Wisconsin, USA. IGCP Project 426 International Field Conference, September 13–19, 1998. Wisconsin Geol. Nat. Hist. Surv. Open File Rep. 1998-10, pp. 178–180.

Vasques, M.L., Klein, E.L., Quadros, M.L.E., Bahia, R.B.C., Santos, A., Ricci, P.S.F., Sachett, C.R., Silva, C.M., Macambira, M.J.B., 1999. Magmatismo Uatumã na Província Tapajós—Novos dados geocronológicos. In: 6th Simpósio de Geologia da Amazônia, Manaus, Soc. Bras. Geol., Abstract, pp. 471–474.