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New insights on the origin for rapakivi granites: U-Pb and Lu-Hf in zircon from Alto Candeias Intrusive Suite, Amazonian Craton, Brazil

Novos insights sobre a origem dos granitos rapakivi: U-Pb e Lu-Hf em zircão da suíte intrusiva Alto Candeias, Cráton Amazônico, Brasil

Luiza Almeida Villar de Queiroz[1], Anderson Costa dos Santos[1], Laís de Oliveira Ferreira[1], Camila Cardoso Nogueira[1], Beatriz Debowski[1], Armando Dias Tavares[2], Cecilia Pavón Pivetta[3], Maria Virginia Alves Martins[1,4], Mauro César Geraldes[1]

[1] Universidade do Estado do Rio de Janeiro, Faculdade de Geologia. Rua São Francisco Xavier, 524, Maracanã, Rio de Janeiro, RJ, Brazil. (luizavq@gmail.com; andersonsantos@dmpi.com.br; lais.oferreira.lo@gmail.com; cnogueiracamila@gmail.com; biadebowski@hotmail.com; geraldes@uerj.br)
[2] Universidade do Estado do Rio de Janeiro, Instituto de Física. Rio de Janeiro, RJ, Brazil. (tavares@uerj.br)
[3] Universidad Nacional del Sur (Consejo Nacional de Investigaciones Científicas y Técnicas), Instituto Geológico del Sur. Bahía Blanca, Argentina. (cpavonpivetta@gmail.com)
[4] Universidade de Aveiro, Departamento de Geociências, GeoBioTec. Campus de Santiago, Aveiro, Portugal. (virginia.martins@ua.pt)

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ABSTRACT

The Southwestern Amazonian Craton, in Rondônia state, Brazil, comprises multiple orogens with ages ranging from 1.8 to 1.0 Ga, where successive magmatic, metamorphic, and deformational processes reworked ancient rocks and produced new complexes and juvenile continental crust. Identification of the geochronological and petrographic characteristics of granitoids and terranes generated during such events is crucial for the recognition and distinction of their magma sources. A total of 64 samples collected from the Alto Candeias Intrusive Suite outcrops in Rondônia state recognized four different groups: (1) Monte Negro unit (rapakivi granites), (2) Buriti unit (equigranular to porphyritic granodiorites), (3) Campo Novo unit (medium to coarse-grained charnockites), and (4) Jacilândia unit (fine-grained granites). U-Pb geochronological data were obtained for each unit, with the following ages: 1350 ± 5 Ma (Monte Negro unit), 1350 ± 2 Ma (Buriti unit), 1349 ± 3 Ma (Campo Novo unit), 1348 ± 3 Ma, and 1349 ± 1 Ma (Jacilândia unit). The ages of the four granitic units are the same within error. Lu-Hf isotopic results presented in this study indicate that the Alto Candeias Intrusive Suite has the mantle as the magmatic source and that the continental crust coeval to the subduction process. This process led to the formation of I-type granitoids generated in the SW margin of the Amazonian Craton around 1350 Ma during San Ignacio orogeny.

Keywords: Granitogenesis; Rondônia state, magma mingling; San Ignacio orogeny; Meso-proterozoic; Granitic magma sources; LA-ICP-MS.

RESUMO

O SW do Cráton Amazônico, no estado de Rondônia (N do Brasil), compreende múltiplos orógenos com idades variando de 1,8 a 1,0 Ga, onde sucessivos processos magmáticos, metamórficos e deformacionais trabalharam rochas antigas e produziram novos complexos e crosta continental juvenil. A identificação das características geocronológicas e petrográficas dos granitóides e terrenos gerados nesses eventos é fundamental para o reconhecimento e distinção de suas fontes magmáticas. Um total de 64 amostras coletadas dos afloramentos da suíte intrusiva Alto Candeias no estado de Rondônia permitiu o reconhecimento de quatro grupos diferentes: 1) Unidade Monte Negro (granitos rapakivi); 2) Unidade Buriti (granodioritos equigranulares a porfiríticos); 3) Unidade Campo Novo (charnockitos de granulação média a grossa, e 4) Unidade Jacilândia (granitos de granulação fina. Dados geocronológicos U-Pb forneceram, para cada unidade, as idades: 1350 ± 5 Ma, 1350 ± 2 Ma, 1349 ± 3 Ma, e 1348 ± 3 Ma, e 1349 ± 1 Ma, respectivamente. Os resultados isotópicos Lu-Hf apresentados neste trabalho sugerem o manto como fonte magmática para a suíte intrusiva Alto Candeias com participação da crosta continental durante o processo de subducção responsável pela formação de granitóides do tipo I gerados no SW margem do Cráton Amazônico por volta de 1350 Ma durante a orogenia de San Ignácio.

Palavras-chave: Granitogênese; Estado de Rondônia, mistura de magma; Orogenia San Ignacio; Mesoproterozoico; Fontes de magmas; LA-ICP-MS.

INTRODUCTION

Most primary tin deposits are associated with highly evolved granitic rocks that exhibit high contents of lithophilic elements (Rb, Cs, Li, Th, Nb, Ta, W, U) and are depleted in compatible elements such as Sr, Eu, Ba, Ti, Co and Ni. The origin of tin enrichment may be related to magmatic and hydrothermal processes; however, experimental data show the importance of magmatic fractionation processes (Lehmann, 1990). Secondary deposits originate from the weathering and erosion of primary deposits and are normally transported and concentrated on alluvial, eluvial, or colluvial systems.

The tin-bearing granite bodies can occur in a variety of tectonic environments. Most tin-bearing Precambrian provinces worldwide are associated with intracratonic and anorogenic environments (Bushveld, Central Africa, Amazonas and Rondônia). However, some younger provinces are associated with active margins (Tasmania, Erzgebirge, Cornwall, China and Bolivia; Lehmann, 1990).

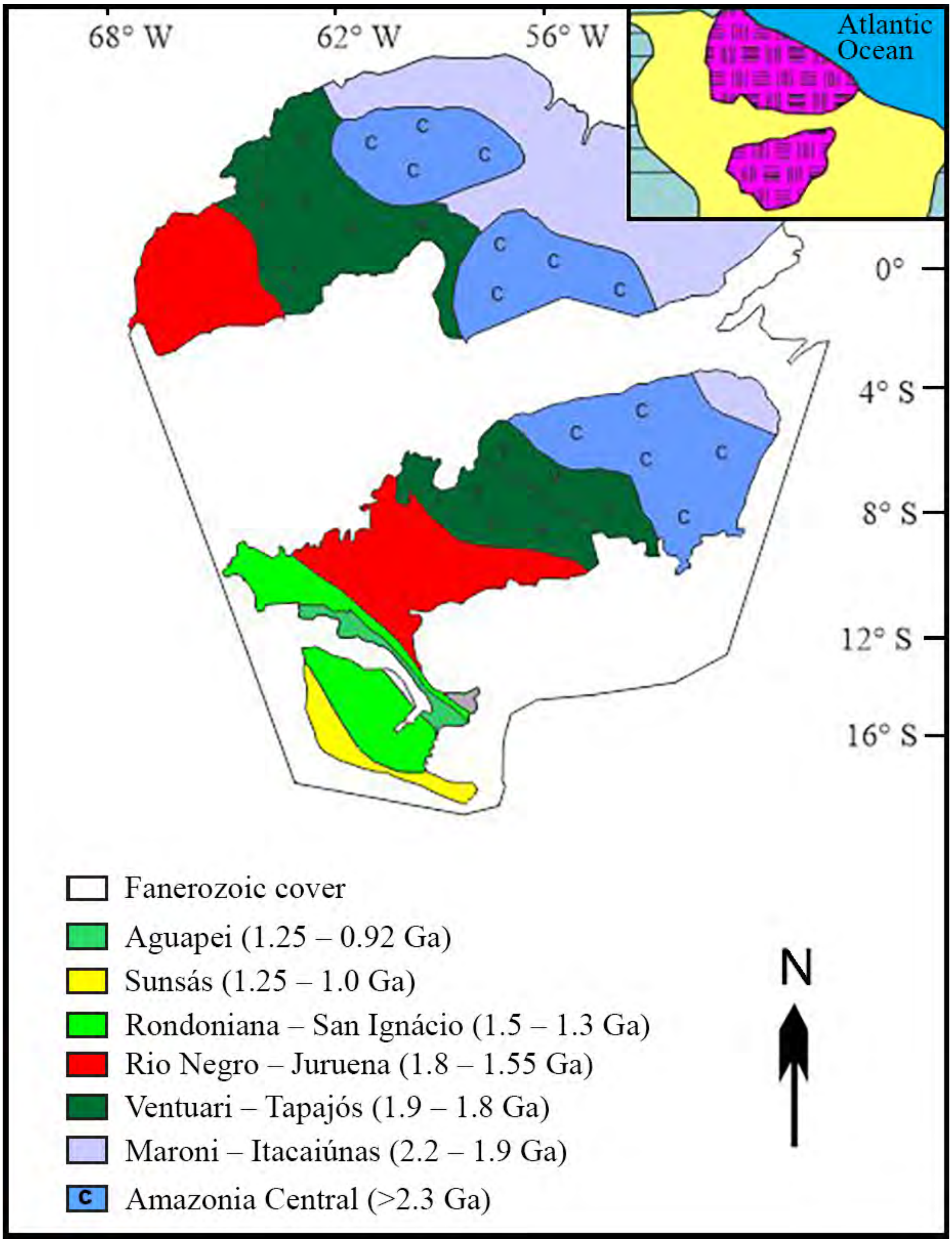
In the Tin Province of Rondônia, the tin-bearing granite bodies exhibit geochemical characteristics compatible with postcollisional/postorogenic A-type magmatism, associated with the final stages of the Rio Negro-Juruena (2200 – 1750 Ma), Rondoniano-San Ignacio (1750 – 1550 Ma), Rondoniano-San Ignacio (1500 – 1300 Ma), and Sunsás (1300 – 1100 Ma) (Litherland et al., 1986; Bettencourt and Dall'Agnol, 1987; Teixeira et al., 1989; Bettencourt, 1992). The primary mineralization of Sn, W, Ta, Nb, Zn, Cu, Pb, F and REE was associated with the more evolved granitic rocks and peraluminous character of the youngest intrusive suites.

The exploitation of cassiterite in Rondônia began in the early 1950s when the first occurrences were discovered in rubber plantations. The exploitation of cassiterite by miners continued in the 1960s until a federal program was developed in 1969 to assess the tin potential of the area. Thus, the Tin Province of Rondônia was created, comprising an area of approximately 87,000 km², such as the state of Rondônia and part of the states of Amazonas, Acre and Mato Grosso. From the early 1960s to the mid-1980s, the province was responsible for nearly 80% of all Brazilian tin production. Brazil became the second largest producer of this metal in 1986 and first in 1988, mainly after the discovery of the Bom Futuro Mine (Bettencourt and Pereira, 1995).

This work proposes a subdivision of the Alto Candeias Intrusive Suite based on facies observed during the geological mapping and the interpretation of new U-Pb and Lu-Hf geochronological data in zircon. The results acquired and described in this research represent essential contributions to our understanding of petrogenic models of anorogenic rapakivi granites from the SW Amazonian Craton.

REGIONAL GEOLOGY

Located north of South America, the Amazonian Craton is bordered to the south, east and southwest by Neoproterozoic mobile belts. It is divided into two shields, the Guaporé and the Guianas, separated by the Amazonas Paleozoic basin. According to Cordani et al. (1979) and Tassinari et al. (1996), the Amazonian Craton was divided into six geochronological provinces: Central Amazon (2.5 Ga), Maroni-Itacaiunas (2.2 – 1.95 Ga), Ventuari-Tapajós (1.95 – 1.8 Ga), Rio Negro-Juruena (1.8 – 1.55 Ga), Rondônian-San Ignacio (1.55 – 1.3 Ga) and Sunsás (1.3 – 1.0 Ga). These geochronological provinces (Figure 1) were generated from the Archean to Mesoproterozoic times, mainly added during the Paleoproterozoic orogenies and formed by a major crustal formation (Tassinari and Macambira, 2004; Geraldes et al., 2000, 2001).



Source: Tassinari and Macambira, 1999.

Figure 1. Simplified geochronological provinces of the Amazonian Craton.

The Rio Negro-Juruena province rocks comprise the basement units, including the Jamari Complex, Roosevelt Group (meta volcano-sedimentary rocks) and Mutum Paraná Formation (metasediments). The Rondônian-San Ignacio Province was divided into two groups. The first comprises migmatites and gneisses grouped into the Rio Crespo Suite and the Colorado Complex and the Nova Mamoré Metamorphic Suite. The latter phase comprises intrusive suites such as the Alto Candeias, Santo Antonio, Teotonio and Caripunas. Litherland et al. (1986) defined the San Ignacio orogeny as a metamorphic magmatic episode developed between 1.35 and 1.3 Ga (1.5 – 1.3 Ga in Figure 1). It is represented in the schists of San Ignacio Group, oriented in an NNE–SW direction and in syn- and post-tectonic granitic magmatism of calcium-alkaline nature.

During the Rondônian-San Ignacio orogeny, the basement rocks were lifted and the resulting erosion product generated a nonconformity in which the Sunsás group was deposited (Litherland et al., 1986; Geraldes et al., 2004; Scandolara, 2006). Between 1.3 and 1.0 Ga, sediments were deposited and distributed throughout the region of the SW Amazonian Craton (Litherland et al., 1989). Sunsas Province is divided into three groups: Sunsás Mobile Belt (Bolivia), Aguapeí Thrust Belt (Brazil), and the metavolcanic--sedimentary sequence Nova Brasilândia (Rondônia). The Sunsás group (Litherland et al., 1989; Santos et al., 2000; Teixeira et al., 2016) corresponds to the youngest known episodes in the basement of the SW Amazon Craton (1.1 and 0.95 Ga, 1.25 – 1 Ga in Figure 1), equivalent to the age of the primary deformation episode of the Grenvillian orogeny in North America. The magmatism associated with this event in Rondônia basement rocks corresponds to Santa Clara Intrusion (1.08 Ga) and the end pulse of stanniferous granites hosted in high crustal levels (1.0 and 0.95 Ga).

Kloosterman (1968a and 1968b) included several granitic complexes of Meso- to Neo-proterozoic age from the central-eastern area of Rondônia (Figure 2) under the initial designation of Youth Granites of Rondônia, owing to the challenge of adequately identifying each formation stage (Quadros and Rizzotto, 2007). In addition, Bettencourt et al. (1997) adopted that definition, and they encompassed only the granites with U-Pb zircon ages between 998 and 991 Ma, represented by the Ariquemes, Massangana, San Carlos, Caritianas, Pedra Branca, Santa Barbara and Jacundá. Bizzi et al. (2003) held the chronostratigraphic position of this stanniferous suite in the early Neoproterozoic but adapted the suite name Rondônia Intrusive Suite proposed by Isotta et al. (1978).

The basement rocks of the Alto Candeias intrusion indicate U-Pb ages (Table 1) in zircon by ICP-MS and TIMS, from 1.78 to 1.387 Ga, coherent with the ages of the Rio Negro-Juruena province (1.8 – 1.55 Ga, Figure 1). In the SW Amazonian craton, according to Tassinari and Macambira (1999) and Geraldes et al. (2008), the San Ignacio orogeny occurred from 1.45 to 1.30 Ga. However, recent literature show ages from 1.60 and 1.53 Ga (Scandolara, 2006). For the Alto Jamari rocks, the ages reported are from 1756 to 1754 Ma. Debowski et al. (2024) recorded U-Pb ages for the Serra da Providência rocks between 1.56 and 1.54 Ga (Scandolara et al., 2013).

Alto Candeias Intrusive Suite

The Alto Candeias Intrusive Suite, located in the Rondônian-San Ignacio Province (Figure 1), comprises mainly acid granitic rocks with rapakivi texture, typical of A-type granite settings. The origin of this unit is still debated, with different interpretations.

The term Alto Candeias Intrusive Suite was first proposed by Isotta (1978) based on its geological mapping. In addition, Isotta (1978) indicated that the suite comprises a granitic unit approximately 120 km long and 80 km wide. New studies by Bettencourt et al. (1999), Scandolara (1996) and Rizzotto and Quadros (2004) included the basic mapping and petrographic and geochronological features of this intrusive suite and defined new limits on this unit.

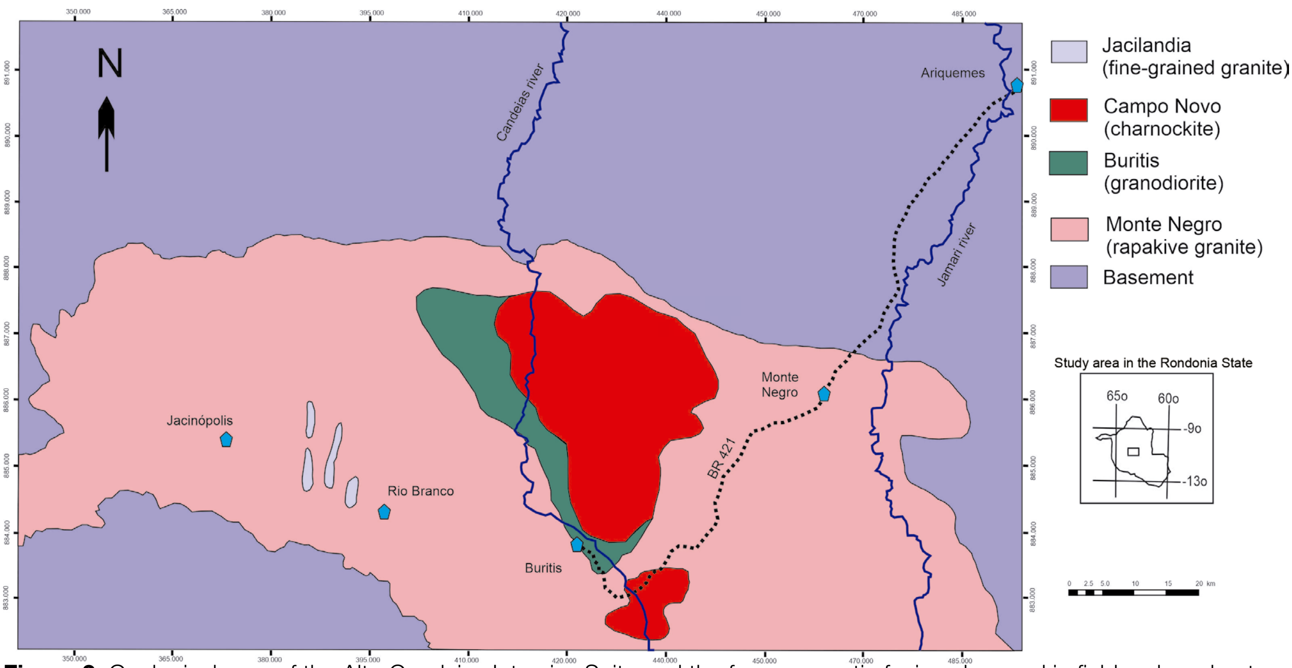


Figure 2. Geological map of the Alto Candeias Intrusive Suite and the four magmatic facies observed in fieldwork and petrographic studies.

Table 1. U-Pb ages of granitic units of the stanniferous province of Rondônia.
References: (1) Silva et al. (2002); (2) Tassinari (1996); (3) Tassinari et al. (1999); (4) Rizzotto (1999); (5) Bettencourt et al. (1999); (6) Santos et al. (2000); (7) Santos et al. (2001); (8) Bettencourt et al. (2001); (8a) Bettencourt et al. (2006); (9) Payolla et al. (2002); (10) Payolla et al. (1994); (11) Rizzotto et al. (2002); (12) Tohver et al. (2006); (13) Souza et al. (2003); (14) Debowski et al. (2019); (15) Nogueira (2016); (16) Queiroz et al. (2015); (17) Debowski et al. (2024).

Area	Sample	Rock	U-Pb Age (Ma)	TDM (Lu-Hf) Age (Ga)	ε(Hf) (crustal)	Metamorphism Age (Ma)	Reference
Alto Candeias Suite	1462-JS-396	Monzogranite	1333 ± 11	.....	.....	.....	6
	WO-52	Syenogranite gneiss	(z)1352 ± 08	.....	.....	.....	9
	RON-128B	Syenogranite	(z)1346 ± 5	.....	.....	.....	2
	RON-129	Syenogranite	(z)1346 ± 5	.....	.....	.....	2
	RON-127B	Syenogranite	(z)1338 ± 4	.....	.....	.....	2
	Monte Negro	Syenogranite	1350 ± 5	.....	.....	.....	16
	Buriti	Granite	1350 ± 2	.....	.....	.....	16
	Campo Novo	Charnockite	1349 ± 3	.....	.....	.....	16
	Jacilândia	Gabbro	1349 ± 1	.....	.....	.....	16
Teotônio Suite	MMRBP-3/1-6R	Syenogranite	(z)1406 ± 32	.....	.....	.....	5
	MMRBP-168-3R	Alkali-feldspar granite	(z)1387 ± 16	.....	.....	.....	5
São Lourenço/ Caripunas Suite	JC-264	Syenogranite	(z)1314 ± 13	.....	.....	.....	2
	JC-47	Monzogranite	(z)1312 ± 3	.....	.....	.....	2
	CR-68	Rhiolite	(z)1309 ± 24	.....	.....	.....	5
Serra da Providência	CN-MA-35	Biotite-Gneiss	1525 ± 6 Ma	2.00 to 1.83	-5.4 to +2.0	.....	14
	CN-MA-41	Biotite-Granite	1540 ± 6 Ma	2.16 to 2.06	-0.8 to +1.4	.....	14
	BD-Ma-06	Biotite-Granite	1574 ± 7 Ma	2.118 to 1.89	-0.7 to +4.9	.....	14
	BD-MA-18	Biotite-Gneiss	1558 ± 8 Ma	2.63 to 2.52	-9.3 to -7.4	.....	14
	BD-MA-10D	Biotite-Gneiss	1561 ± 29 Ma	2.63 to 2.52	-9.3 to -7.4	.....	14
	BD-MA-18	Biotite-Gneiss	1558 ± 8 Ma	2.63 to 2.52	-9.3 to -7.4	.....	14
	2150-GR-333	Monzogranite Gneiss	(z)1512s	.....	.....	.....	7
	WO-63	Augen-gneiss Granite	(z)1569 ± 18	.....	.....	.....	9
	SP-GR-76	Syenogranite	(z)1606 ± 24	.....	.....	.....	5
	SP-GR-21	Monzogranite	(z)1573 ± 15	.....	.....	.....	5
	P-GR-48	Monzogranite	(z)1566 ± 5	.....	.....	.....	5
	SP-GR-39	Monzogranite	(z)1566 ± 3	.....	.....	.....	5
	SP-GR-53	Syenogranite	(z)1554 ± 47	.....	.....	.....	5
	WB-36	Quartz-syenite	(z)1532	.....	.....	.....	9
	MS-6030	Granite Gneiss	(z)1570 ± 17	.....	.....	.....	5
	CR-48	Syeno/Monzogranite	(z)1588 ± 16	.....	.....	.....	5
	WB-46A/C	Augen-gneiss Monzogranite	(z)1560	.....	.....	.....	9
	AR-3/1	Monzogranite	(z)1544 ± 05	.....	.....	.....	9
	WB-44A	Augen-gneiss Syenogranite	(z)1526 ± 12	.....	.....	.....	9
	PG-JS-01	Monzogranite Gneiss	(z)1535 ± 27	.....	.....	.....	1
	PG-JS-1	Monzogranite Gneiss	(z)1535 ± 27	.....	.....	.....	1
	PG-JS-19	Syenogranite gneiss	(z)1545 ± 8	.....	.....	.....	1
Serra da Providência (metamorphic)	PG-JS-32	Monzogranite Gneiss	(z)1522 ± 10	.....	.....	.....	1
	ET 108	Charnockite Gneiss		.....	.....	1338 ± 19	12
	ET 121	Migmatized Charnockite Gneiss		.....	.....	1428 ± 9	12
	ET 125	Millonitized Granite Gneiss		.....	.....	1212 ± 45	12

Table 1. Continuation

Jamari Complex	PT-12	Psamo-pelitic Paragneiss	(z)1657 ± 16	.....	.....	.....	3, 4
	2492-JL-786	Tonalite Gneiss	1743	.....	.....	.....	6
	2492-GR-596	Tonalite Gneiss	1746	.....	.....	.....	6
	5260-GR-356	Quartz-diorite Gneiss	1757 ± 9	.....	.....	.....	6
	A-338/B-335	Tonalite Gneiss	(z)1750 ± 24	.....	.....	.....	3
	RO-08	Paragneiss	(z)1331 ± 8	.....	.....	.....	3
	WB-70	Enderbitic Granulite	(z)1730 ± 22	.....	.....	.....	9
	WB-250A	Tonalite Gneiss	(z)1750	.....	.....	.....	9
	98-JWB-3/A	Tonalite Gneiss	(z)1631 ± 8	.....	.....	.....	8
	98-JWB-10/A	Charnoenderbite Gneiss	(z)1655 ± 11	.....	.....	.....	8
	PG-JS-261	Tonalite Gneiss	(z)1728 ± 15	.....	.....	.....	
	WB-152	Paragneiss	(z*)31769	.....	.....	.....	10
	JWB-24A	Paragneiss	(z*)41797/1730	.....	.....	.....	10,12
	ET 110	Garnet Amphibolite		.....	.....	(m)1339 ± 2	12
	ET 122	Calc–silicate Rock		.....	.....	1215 ± 7	12
Jamari Complex/ Bom Futuro Mine	VS	.....	.....	.....	.....	(m)1327 ± 20	13
Roosevelt Group	2150-MQ-96	Metadacite	(z)1740	.....	.....	.....	6
	WO-74	Meta-rhyolitic Tuff	(z)1691 ± 73	.....	.....	.....	9

z = zircon; M = micas; z* = zircon Korbe method; m = metamorphic.

Alto Candeias granitic intrusion has an elongated direction WE. According to Scandolara (2006), the wall rock contact is marked by a transcurrent sinistral shear zone on its northern border, whereas basic rocks cover the southern border, Nova Floresta Formation, and the sedimentary rock formation Palmeiral ("Graben" of Pacaás Novos). It consists predominantly of coarse-grained porphyritic granites and, to a lesser extent, fine-grained equigranular granite, equigranular aplites and fine- to medium-grain syenites. The former is compositionally defined as hornblende–biotite monzogranites, biotite-quartz monzogranites with ovoid and tabular crystals centimeter alkali feldspar with perthitic plagioclase overgrowth. They represent the earlier stage, and contact with the thin equigranular granite is observed on the northeastern edge of the massif.

On the north rim, these granites exhibit a wide shear zone, transforming rocks into proto mylonites and mylonites. Internally, discrete ductile shear zones occur and are generally affected by brittle tectonics. The charnockite rocks (Figure 2) are also part of the suite, with the primary occurrence situated on the SE edge of the massive Alto Candeias and other bodies, not relevant in the central portion thereof, exhibiting transitional contact with the granites. Chemically, the suite is distinguished by its subalkaline character and chemical pattern that resembles the Serra da Providência Intrusive Suite (Bettencourt and Dall'Agnol, 1987).

Isotopic Rb-Sr data for porphyritic granite and perthitic plagioclase provided an isochron age of 1358 Ma, with an initial ratio of $^{87}Sr/^{86}Sr$ of 0.703 ± 0.009 (Bettencourt et al., 1995) and U-Pb age of 1345 Ma (Bettencourt et al., 1999). In addition, new U-Pb was interpreted by the authors as crystallization age, in agreement with the results reported by Isotta et al. (1978) and Scandolara et al. (1999). As this is the central subject of this work, the Alto Candeias unit will be detailed more in the following sections.

MATERIALS AND METHODS

This study utilizes data and 64 samples collected during fieldwork. The geological mapping was conducted on a regional scale (1:250,000). Therefore, we used the interpreted photo of Landsat 5 images from the National Institute for Space Research. Fieldwork was conducted using the local roads that cover a network over a large part of the studied intrusions. The collected samples were submitted for petrographic and geochemical analyses. In addition, petrographic analyses were conducted on 32 thin-section samples. The samples were mineralogically and texturally analyzed using an optical microscope instrument. Moreover, age was determined by U-Pb and Lu-Hf in zircon grains using laser ablation-inductively coupled plasma-mass spectroscopy (LA-ICP-MS) at the MultiLab (UERJ).

U-Pb and Lu-Hf geochronology

LA-ICP-MS was used to analyze U-Pb and is an important analytical tool for geosciences. This technique has been mostly developed by earth sciences researchers primarily because of its application in geological samples. Many essential improvements in the method were conducted, such as optimizing the wavelength of laser radiation, the laser beam optics, and the improvement of the sample holder camera to study minerals and rocks. With the current availability of such equipment, the LA-ICP-MS can perform isotopic composition measurements on individual crystals and parts of these minerals to the scale of a few tens of microns. Isotope analysis was conducted using LA-ICP-MS to identify Pb, U, and Th. The working frequency was 6 – 10 Hz, and laser energy was 30 – 40%; each analysis performed 40 cycles per second, simultaneously recording five isotopes (^{204}Hg, ^{206}Hg, ^{206}Pb, ^{207}Pb and ^{238}U).

U and Pb isotopes had an accuracy of 1.9 – 3.7% (2 sigma SD) and an accuracy of 0.6 – 3.8% for analyses of the mineral zircon, depending on the used standard. Three reference materials (GJ-1, 91,500 and 3 Mud Tank) were used for calibration and error reduction and for monitoring the state of the instruments throughout the analysis sequence such as (1) GJ-1 standard zircon from ARC National Key Center of Geochemical Evolution and Metallogeny of Continents, Australia, and (2) 91,500, from the Harvard Museum collection and national Tank zircon, collected from a carbonate rock in Australia.

Previous studies were conducted using scanning electron microscopy (SEM) performed before the U-Pb geochronological analysis of the Alto Candeias granite samples, by the LA-ICP-MS. The ages ^{206}Pb/^{207}Pb and ^{206}Pb/^{238}U were measured using 2σ uncertainties. The results were plotted on a concordia diagram using the Isoplot (Ludwig, 2003), and the analyses indicated discordance above 5% (comparing the ages ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U). Age calculations were conducted after correcting the initial common Pb based on the Pb evolution model in two stages (Stacey and Kramers, 1975) for the blocks of isotopic ^{204}Pb/^{206}Pb >0.0004 to reduce Pb common interference. After data processing, according to criteria established by Gaudette et al. (1998), the results were presented with 2σ deviations.

In addition, Lu-Hf isotopic data were determined for individual zircon grains using a Neptune multicollector–inductively coupled plasma-mass spectrometer (MC-ICP--MS), with a detector array of nine Faraday cups attached to a Photon Machines excimer laser ablation microsampling system (Geraldes et al., 2014). Analytical methods are described by Almeida et al. (2022) and Alves et al. (2022); the analyses of the Hf standard, GJ-01 and 91.500 during the analysis here reported yielded ^{176}Hf/^{177}Hf = 0.28216 ± 0.00002 (2 SD; n = 208, ca. ± 0.7 $\varepsilon_{Hf_{units}}$) and ^{176}Hf/^{177}Hf = 0.28216 ± 0.00002 (2 SD; n = 208, ca. ± 0.7 $\varepsilon_{Hf_{units}}$), respectively.

RESULTS

The results presented here correspond to the Alto Candeias Intrusive Suite geological map (Figure 2) produced during fieldwork based on the original SGB-CPRM cartography of 1:250,000. This map is the result of 64 outcrop descriptions, with 35 thin sections, resulting in the individualization of four facies: rapakivi granite (Monte Negro), granodiorite (Campo Novo), charnockite (Buritis), and a fine-grained granite (Jacilândia). One representative sample from each unit mapped was analyzed for U-Pb and Lu-Hf in zircon (Monte Negro, sample AC-04, Campo Novo sample AC-31, Buritis sample AC-09 and Jacilândia sample AC-22).

U–Pb and Lu–Hf in zircon results

The Monte Negro unit

Porphyritic granitic rocks (Figure 3), locally with rapakivi textures (as overgrowth in potassium feldspar by sodium

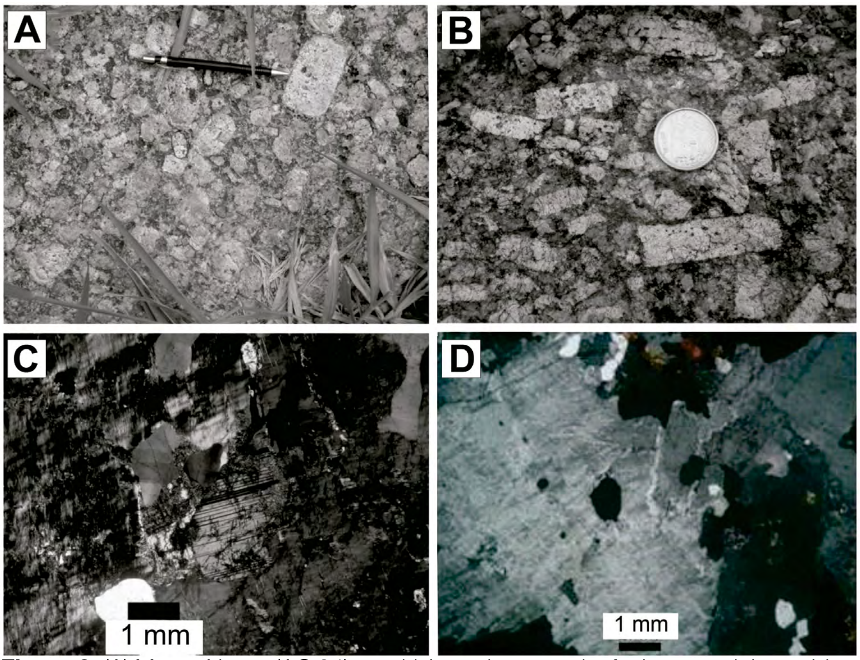


Figure 3. (A) Monte Negro (AC 04) rapakivi porphyry granite facies containing subhedral to ovoid feldspar. (B) Rapakivi porphyry granite facies containing slightly oriented euhedral crystals. (C) Rapakivi feature, in petrographic thin section. (D) Thin section with plagioclase and sericitized microcline.

feldspar), are included in this group. The mineralogy of the Monte Negro granite is mainly quartz, biotite, and partially sericitized feldspar. They have zircon, apatite, magnetite and ilmenite as accessory minerals, and amphibole grains are rarely observed.

They represent most of the intrusive body, that is, about 60% of the batholith surface. The characteristics of this material mainly vary around the porphyry crystals, which can be euhedral, subhedral, or ovoid. Orientation changes in the feldspar porphyritic crystals can be mainly found on the northern boundary, which can be attributed to magmatic flow structures or tectonic emplacement during the pluton rise.

The U-Pb geochronological results of the Monte Negro granite (sample AC-04), presented as a aurentia diagram (Ludwig, 2003), had analytical errors of the isotopic ratios of 1σ (Supplementary material, Table 1, U-Pb results).

The zircon grains in the sample AC 04 (Figure 4) indicate yellowish and bipyramidal shapes. In the SEM image, the crystals appear with fractures and two colors, revealing zonation in some grains. The aurentia diagram yielded the age of 1356 ± 20 Ma (Figure 5), defined by the upper intercept, and interpreted as crystallization age. The U/Th ratios of the analyzed grains ranged from 0.17 to 0.54, indicating a magmatic origin (Rubatto, 2002).

Buritis unit

This unit is characterized by lithologies with high concentrations of mafic minerals comprising granodiorites, hornblende granodiorite, and tonalite (Figure 6). The crystal size in this unit varies from coarse to fine and is sometimes porphyritic. Unlike Monte Negro (rapakivi granites), the porphyries in Buritis are only 2 cm in size. Approximately 15% of the intrusive body corresponds to this unit, outcropping in the eastern center of the batholith, as noted on the geological map (Figure 2). The contact relationships between these rocks with the rapakivi granite are gradual.

Under the microscope, the zircons are translucent and reddish in color, and their shapes vary from elongated to subrounded (Figure 4). In this sense, the U-Pb results (Supplementary material, Table 1, U-Pb Results) for the 13

Figure 4. Zircon grains used for U-Pb analysis using LA-ICP-MS.

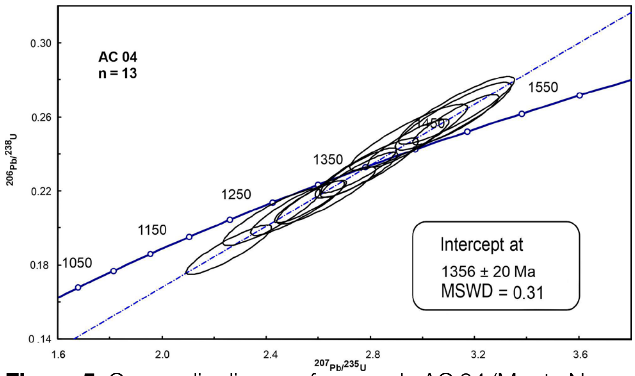


Figure 5. Concordia diagram for sample AC 04 (Monte Negro unit). The upper intercept indicates an age of 1356 ± 20 Ma for 13 zircon grains analyzed.

zircon grains of the Buritis facies plotted in a Concordia diagram yielded an upper intercept age of 1347 ± 20 Ma (Figure 7). This U-Pb age obtained for the zircons of the Buritis unit is the crystallization age.

Jacilândia unit

Felsic rocks, such as fine-grained granites, syenogranite, and quartz-rich granitoids, were grouped in this unit (Figure 2). These lithologies were found in diverse relationships with the rocks of the Monte Negro unit. Locally, it is observed that the fine-grained granitic facies are intruded into the rapakivi granite, or the rapakivi granite is intruded into the Jacilândia unit, and in other places, the two coexist with gradual contacts.

Felsic rocks account for 20% of the surface of the batholith and are dispersed throughout its extension. They comprise quartz, microcline, plagioclase and biotite, and contain accessory minerals such as zircon, apatite, magnetite and ilmenite (Figure 8); locally, they have amphibole and feldspar porphyry.

Under the microscope, zircon grains in the Jacilândia unit are bipyramidal and elongated, and their colors range from translucent red to milky yellow (Figure 4). The SEM images allowed us to identify the growth edges and inclusions. The crystals are predominantly subhedral with a major to minor axis ratio on the order of 3:1 to 2:1, with eroded and rounded edges appearing in smaller frequency. Zonation was recognized; however, the crystal core and edge indicated similar ages.

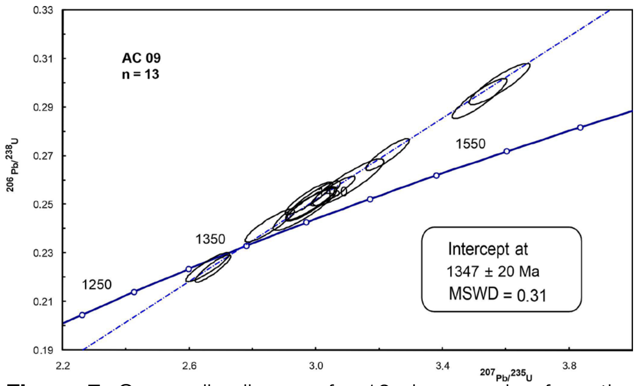


Figure 7. Concordia diagram for 13 zircon grains from the Buritis unit (sample AC-09); the upper intercept indicates an age of 1347 ± 20 Ma for the rock analyzed.

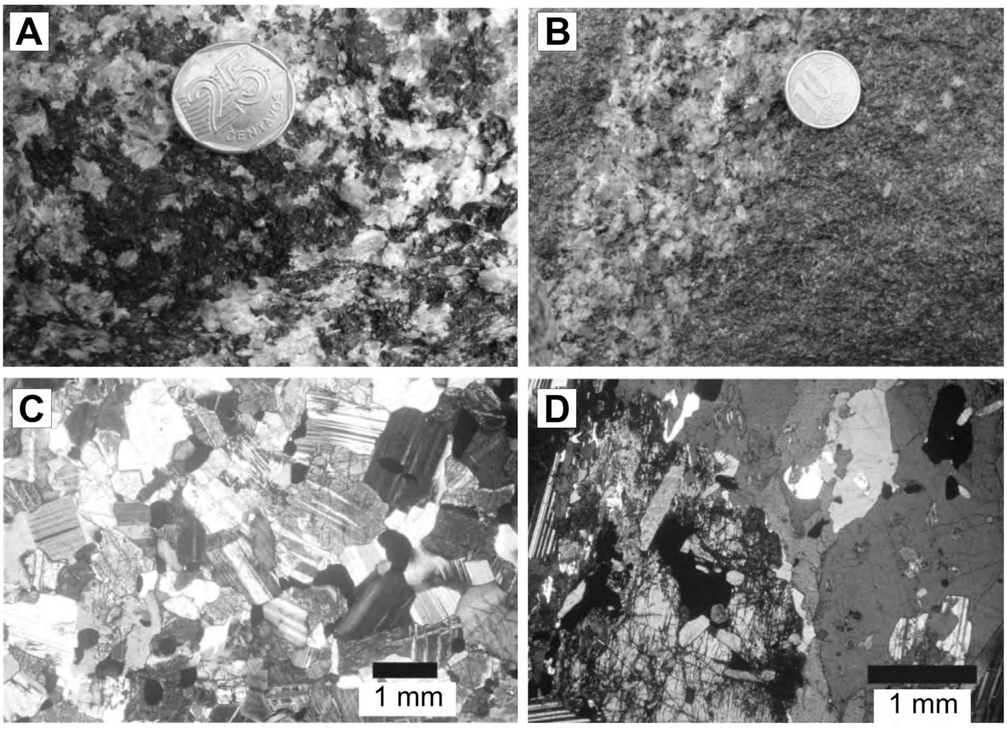


Figure 6. Buritis unit (sample AC-09). (A) Facies containing enriched portions of mafic minerals. (B) Facies in granodiorite outcrop. (C) Petrographic section containing amphibole minerals. (D) Petrographic feature of granodiorites.

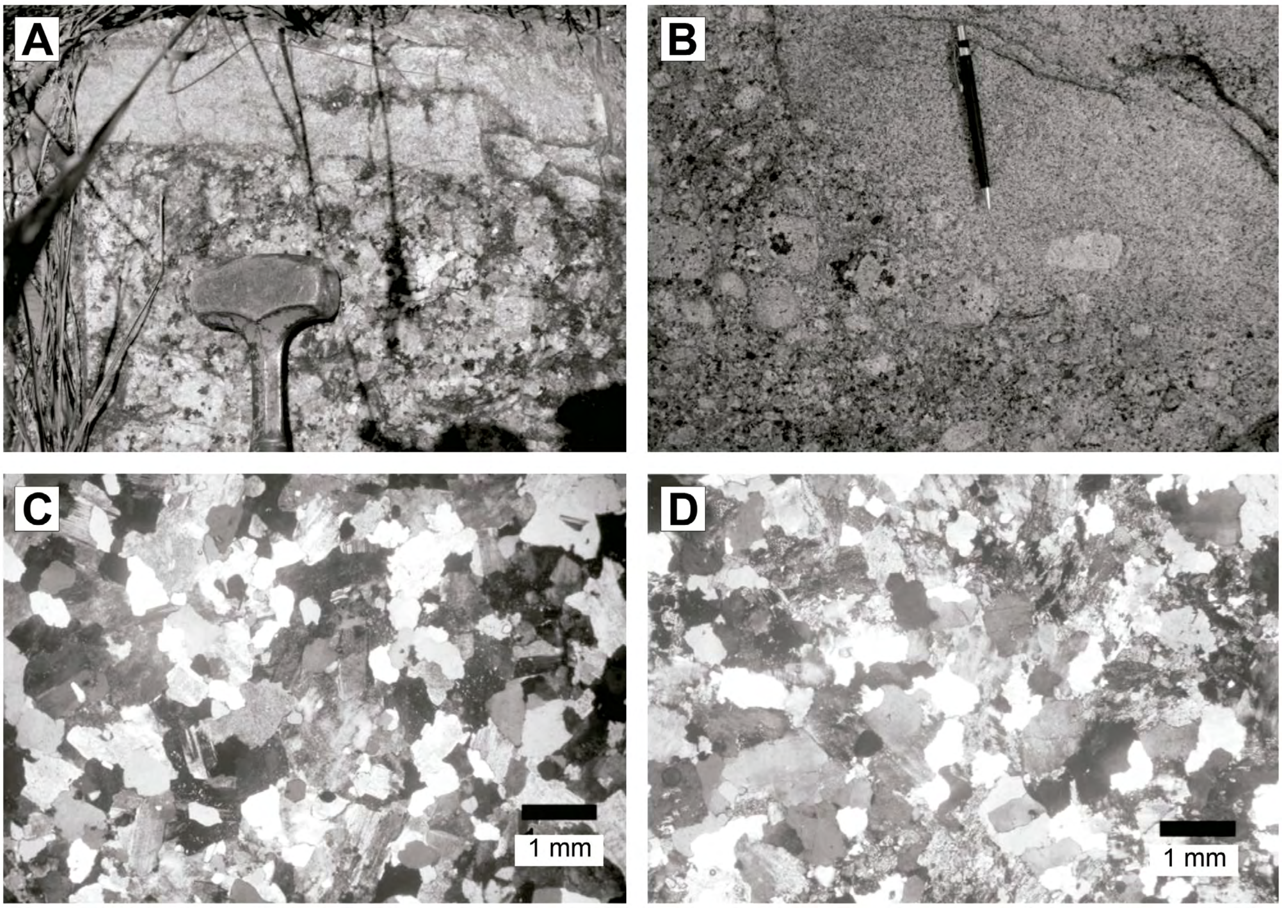


Figure 8. Jacilândia unit (sample AC-22). (A) Fine-grained syenogranite intruded into rapakivi granite; (B) Gradual contact between fine-grained granite and rapakivi granite; (C) Quartz-rich granitoid in a thin section; (D) Fine-grained granite with amphibole and isotropic texture.

The results (Supplementary material, Table 1, U-Pb results, sample AC 22) obtained from a aurentia diagram give the U-Pb age of 1338 ± 15 Ma (Figure 9), which can be considered the crystallization age. Th/U ratios range from 0.13 to 0.73, suggesting that zircons grew in a magmatic environment. Queiroz et al. (2015) reported for the same rock using Pb evaporation single zircon technique; a crystallization age of 1348 ± 3 Ma (for fine-grained granite) was determined using the Kober (1987) method.

Campo Novo unit

This unit is observed between the contacts of Monte Negro and Buritis and comprises charnockite rocks (Figure 10). This contact is gradual, and it is often challenging to characterize these units in the field. This unit has been individualized by clinopyroxenes and evidenced only in petrography after the first fieldwork and confirmed in the second sampling work.

Two types of zircon grains were observed in the charnockite under the microscope; the first group has a yellow color, and the second has a grayish-yellow to translucent gray color. Moreover, grains with growing edges and sub rounded edges, zonation, and fractured crystals were observed (Figure 4).

The aurentia diagram was plotted with 18 analytical results (Supplementary material, Table 1, U-Pb results) for zircon grains analyzed using the LA-ICP-MS and resulted in an upper intercept with an age of 1349 ± 8.9 Ma (Figure 11). Magmatic signature Th/U ratios ranged from 0.14 to 0.56 (Supplementary material, Table 1, U-Pb Results). Geochronological results of the analysis indicate ages of 1349 ± 8.9 Ma, which is similar to the rocks of the other units analyzed in this work.

Lu-Hf results

A total of 39 Lu-Hf isotopic analyses of concordant zircons from three dated samples are presented in this contribution (Supplementary material, Table 2, Lu-Hf results and Figure 12), along with isotopic analyses for the same grains used for U-Pb age determination (Supplementary material, Table 1, U-Pb results). Crustal residence time (T_{DM}) model ages were calculated for a $^{176}Lu/^{176}Hf$ value of 0.0113 for the average continental crust and juvenile crust Hf model ages: $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ of 0.0384 and 0.283165, respectively (Dhuime et al., 2011).

Ten spot analyses were conducted on 10 zircon grains from sample AC-09 (Buritis unit; Supplementary material, Table 2, Lu-Hf Results). The concordant zircons used for the Lu-Hf analysis have initial $\varepsilon_{Hf}(t)$ values of –15.8 to –12.5 and crustal model ages (T_{DM} Hf) varied between 3.12 and 2.95 Ga (Figure 12).

Nine Lu-Hf spot analyses were conducted on nine zir-

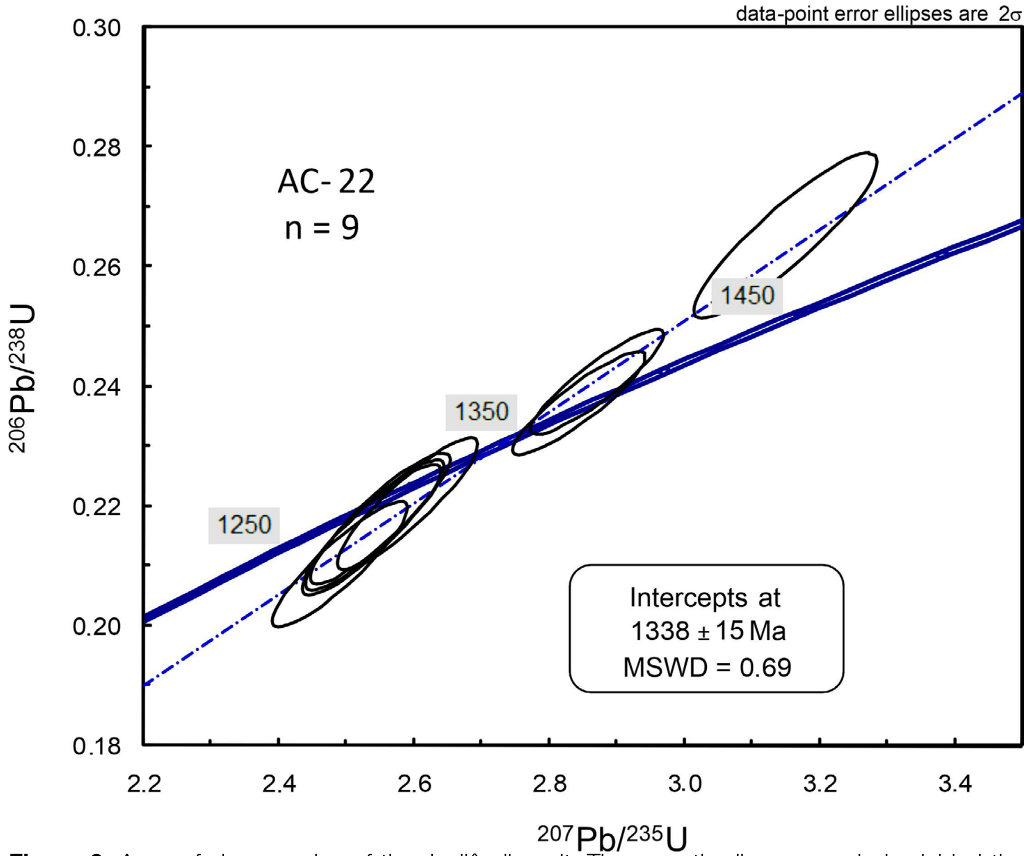


Figure 9. Ages of zircon grains of the Jacilândia unit. The aurentia diagram analysis yielded the U-Pb age at 1338 ± 15 Ma.

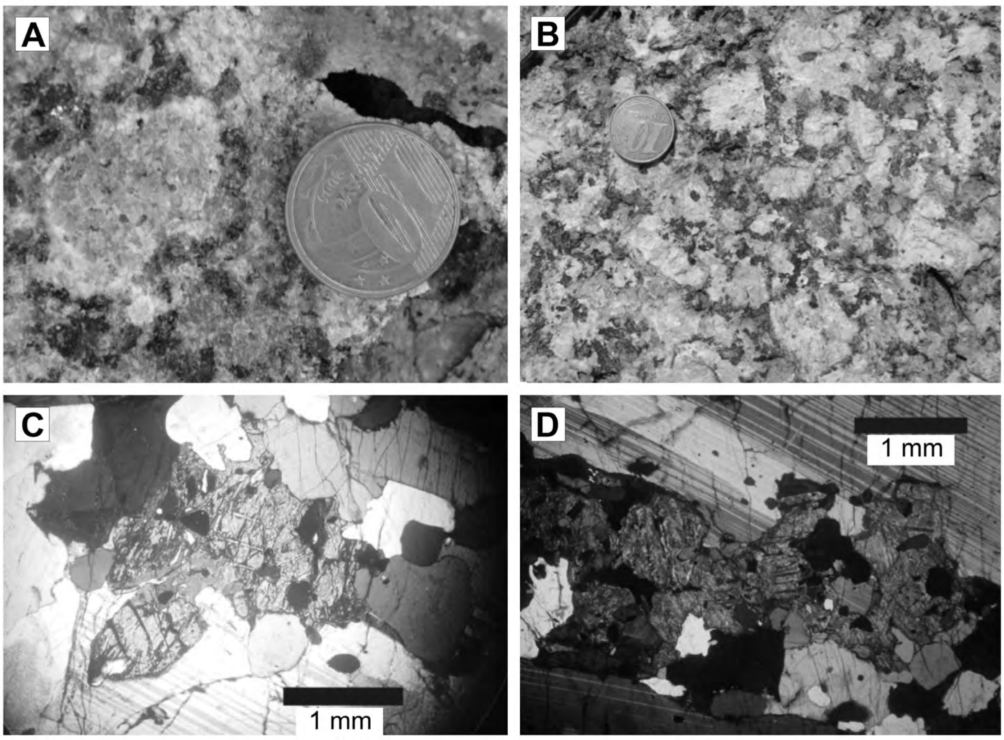


Figure 10. Campo Novo unit (sample AC-31). (A) Charnockite feature with overgrown feldspar porphyries, (B) charnockite face, (C) thin section containing intergrown clino- and ortho-pyroxene, (D) clino- and ortho-pyroxene and quartz between plagioclase grains.

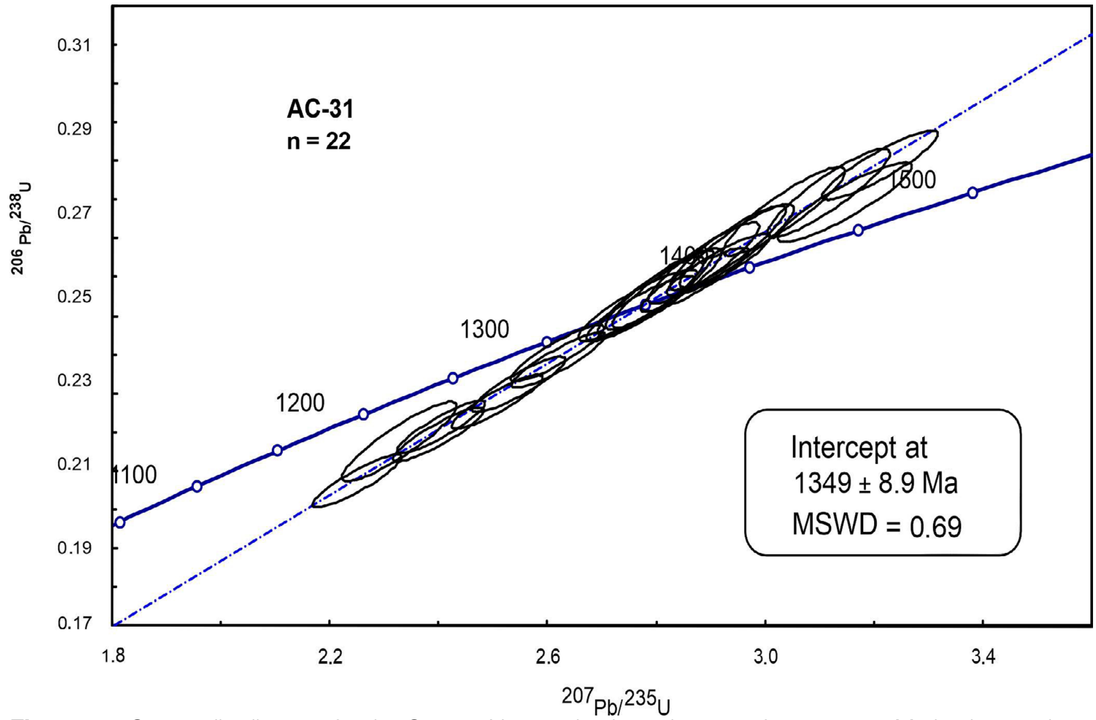


Figure 11. Concordia diagram for the Campo Novo unit where the age of 1349 ± 8.9 Ma is observed.

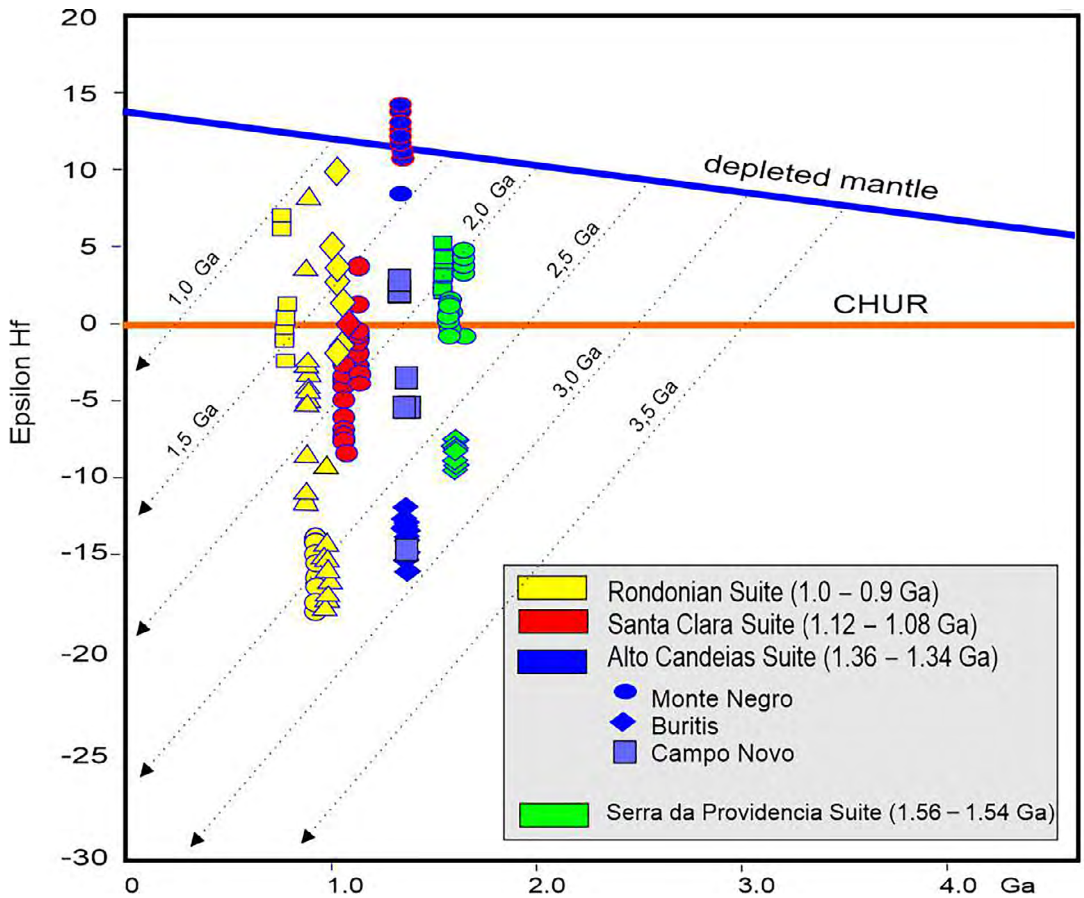


Figure 12. Age vs. ε_{Hf} values for Alto Candeias Suite. Lu-Hf results from SW Amazonian Craton in Tin Province of Rondônia are also plotted. The depleted mantle growth curves (solid lines) and the chondritic uniform reservoir are plotted. Rondônian aure (Debowski et al., 2019); Santa Clara Suite (Nogueira, 2016); Serra da Providência (Debowski et al., 2024).

con grains from the Monte Negro (sample 04) and yielded initial ε_{Hf}(t) values of +8.6 to +16.0 and Hf crustal model ages (T_{DM} Hf) between 2.04 and 1.83 Ga (Supplementary material, Table 2, Lu-Hf Results; Figure 11). Ten Lu-Hf spot analyses were conducted on seven zircon grains from sample Campo Novo (AC-31). These yielded initial ε_{Hf}(t) values between –14.3 and +2.7 and Hf crustal model ages (T_{DM}) between 2.39 and 2.51 Ga (Figure 11).

The Buritis granodiorite sample (AC-09) shows ε_{Hf}(t) values that are strongly negative suggesting a crustal source. However, the zircon Hf isotopic signature of Monte Negro (samples AC-04) yielded positive ε_{Hf} values, which precludes a model that all of the younger granitic rocks are differentiated from the regional basement (Jamari complex).

The zircon ε_{Hf}(t) values of the granite sample AC-31 are negative, suggesting a crustal source; however, two zircon grains yielded positive ε_{Hf}(t) values, indicating mantle contribution. This implies that the A-type granitic rocks probably originated from mixing mantle-derived mafic magma, with the least contribution from crustal-derived melts. The mixing model is supported by field and isotopic observations: (1) The younger granites occur close to the mafic rocks (ca. 1.35 Ga bimodal igneous activity) and contain mafic enclaves, and (2) granites have slightly lower ε_{Hf}(t) values than the granodiorites.

DISCUSSION

The units comprising the Alto Candeias Intrusive Suite presented in this work were divided into four units based on mineralogical composition, grain size, and textural characteristics. They were assigned to the following lithologies: porphyritic rapakivi granite (Monte Negro), granodiorites (Buritis), fine-grained granite (Jacilândia), and charnockites (Campo Novo). The combination of these rock types suggests the presence of anorthosite, mangerite, granite, and charnockite (AMCG) suites described in the literature. Therefore, the petrographic and isotopic results of Alto Candeias rocks support the idea of the bimodal suite with mixed magmas.

An additional view is a magmatic fractionation, which occurs from granodiorite rocks to syenogranites (high in K) through intermediate to acidic compositions. The extensive anorogenic features evidenced in these rocks can be attributed to the fact that few areas of the Alto Candeias batholith have orientation given mostly by biotite and feldspar porphyry, and its origin can be interpreted as magmatic flow.

Originally, Souza et al. (1975) recognized that the heterogeneous composition of the Alto Candeias batholith is granitoids and interpreted it as having been formed during an orogenic event. Subsequently, Isotta et al. (1978) and Bettencourt et al. (1999) proposed an extensional tectonic setting correlated with the Grenvillian event. Moreover, Souza et al. (2006) classified the rocks rich in potassium intrusive body as an S-type granite. By contrast, the granodiorites may be interpreted as an I-type and the monzogranites as an A-type, that is, they have associated magmas originating from different sources.

According to the latest proposal by Bettencourt et al. (2009), the Alto Candeias Suite was associated with late to post-tectonic events during the Rondônian-San Ignacio orogeny (1370 – 1320 Ma). In addition, they divided this orogeny into two phases: the subduction period (1370 – 1340 Ma) and the collisional period (1340 – 1320 Ma) and the results reported here support the hypothesis.

The Pb-Pb ages obtained by Queiroz et al. (2015) using the Kober method were quite homogeneous, with variations within the analytical errors: rapakivi granite (Monte Negro), 1350 ± 5 Ma; granodiorites (Buritis unit), 1350 ± 2 Ma; charnockites (Campo Novo unit), 1349 ± 3 Ma; fine-grained granite, 1348 ± 3 Ma; and fine-grained quartz granitoid, 1349 ± 1 Ma (Jacilândia unit). These results suggest that the magmatic processes implicated in the rock formation occurred over shorter periods than the resolution of the Pb-Pb method.

In the regional context, the rocks of the Alto Candeias Suite can be temporally correlated to the rocks of the São Laurencio-Caripunas and Santo Antonio suites, of equivalent ages and with clear A-type granite signatures (Bettencourt et al., 1999). On the contrary, the Alto Candeias Suite can be temporally correlated to the Colorado complex rocks (in Rondônia) and the El Pensamiento complex (in Bolivia). These complexes, with an age of approximately 1350 Ma, were interpreted as having been generated in a magmatic arc environment (Rizzotto and Quadros, 2004; Matos et al., 2009).

The geochemical results reported by Queiroz et al. (2015) and the Hf isotopic results of this work support the bimodal magmatic suite hypothesis. The treatment of chemical results is presented using Harkers' and tectonic discrimination diagrams, suggesting that the magmas that produced these rocks originated from crustal and mantle sources. According to Eby (1992), the composition of A-type granite is not direct evidence of an anorogenic process because A2-type granites are formed in orogenic environments. The A2-type granites, found in the studied rocks that make up the Alto Candeias Suite, have crustal contributions, in this case, from the lower portion of the crust, suggesting that these rocks were generated from the melting of the crustal base.

Santos et al. (2008) named the event that produced these granites as the Alto Candeias orogeny and included in this event other granitic bodies found in the region, such as the Ariquemes granite and coeval metamorphic events (Table 1) in granulite facies in rocks from the Rio Crespo and the Colorado suites. The REE diagrams corroborate this hypothesis, indicating a progressive magmatic fractionation where the most primitive terms are the gabbroic rocks and the most evolved terms are the rapakivi granitic rocks.

CONCLUSION

The variation in ε_{Hf} values and T_{DM} ages acquired in this work in the Alto Candeias Suite (Rondônian-San Ignacio Province, Brazil) may be correlated with the heterogeneity of the magmatic sources. The rocks studied here intruded different suites and terrains, which are represented by the Serra da Providência and Rio Crespo suites and the Jamari Complex. The ε_{Hf} data of the rocks studied here, which presented negative and positive values for this parameter, confirmed the mantle components. The sample collected in the area corresponding to the Buritis facies has negative ε_{Hf} values. In addition, the sample from the Monte Negro unit presented only ε_{Hf} positive values and T_{DM} ages between 2.04 and 1.83 Ga, suggesting a mantle-derived magma source.

The Alto Candeias Intrusive Suite has A-type characteristics, mainly in its eastern part, where the richest rocks in potassium were found owing to its very weak or nonexistent deformation. Thus, the Alto Candeias Intrusive Suite may have been generated under an extensional or nontranstensive regime. I-type granites are evident in the eastern center of the batholith, with granodioritic and gabbroic rocks. The presence of amphibole and pyroxene also strongly indicates the I-type characteristic of these rocks. The presence of a calcium-alkaline suite supports this hypothesis. In this way, we can correlate the origin of Alto Candeias Intrusive Suite to a subduction process and the generation of I-type granitic rocks on the border of the Amazonian Craton around 1350 Ma. In this sense, it can be suggested that the proximity of this volcanic arc provided enough heat to flow toward the plate interior and partially melted the mantle and part of the lower crust. If this hypothesis is correct, the rock formation of the Alto Candeias Intrusive Suite is syn-orogenic.

The product obtained by all dated samples indicates the contemporaneous crystallization of all rock types found in the study batholith. These results allow us to reach two hypotheses regarding the analyzed suites. The first hypothesis for the generation of the Alto Candeias Intrusive Suite (Rondônia, SW of the Amazonian Craton-Brazil) is the AMCG suite resulting from a mixture of magmas, supported by charnockites and granites, as proven by petrography. The second is an evolution from the same magma controlled by fractionation of mantle origin, represented by evolved basic features related to calcic alkaline–related expanded overgrows. Paradoxically, both hypotheses are supported by petrography and geochronology.

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