MANTLE ISOTOPIC CHARACTERISTICS BELOW THE SW AMAZONIAN CRATON: U-PB, 40AR/39AR AND ND-SR EVIDENCE...


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Mesoproterozoic mantle heterogeneity in the SW Amazonian Craton: $^{40}Ar/^{39}Ar$ and Nd-Sr isotopic evidence from mafic-felsic rocks

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ABSTRACT: Isotopic and geochemical evidences of mafic-felsic rocks from the SW Amazonian Craton allow new insights into the Mesoproterozoic crustal evolution. The Serra da Providência Intrusive Suite mafic rocks give an $^{40}Ar/^{39}Ar$ age of 1556 Ma; the $\varepsilon_{Nd(T)}$ (+2.5/+2.8 and -0.9/+0.4) and $\varepsilon_{Sr(T)}$ (-12.0; -3.3/+11.7) values are consistent with DMM to CHUR-like magma sources. A metagabbro from the Colorado Metamorphic Suite yields a U/Pb crystallization age of 1352+4/-3 Ma with coeval mafic rocks preserving $^{40}Ar/^{39}Ar$ ages of 1327-1315 Ma. The $\varepsilon_{Nd(T)}$ (0.0/+5.2) and $\varepsilon_{Sr(T)}$ (-5.0/–30.7) values are consistent with magma sources with significant influence of a DMM end-member. In the Nova Brasilândia Sequence (1.21–1.05 Ga), the mafic-felsic intrusions yield $^{40}Ar/^{39}Ar$ ages between 1025 and 982-970 Ma. The mafic rocks show $\varepsilon_{Nd(T)}$ (+3.1/+5.0) and $\varepsilon_{Sr(T)}$ (-2.4/+34.2) values that indicate derivation from oceanic crust. The observed mantle heterogeneity is interpreted as the result of long-lived intra-oceanic arc convergence during Mesoproterozoic times.

1 INTRODUCTION

The Amazonian Craton, one of the largest units of Western Gondwanaland, is made of an assortment of Archean and Proterozoic provinces that show internally coherent structural and age patterns – see Teixeira et al. (1989), Tassinari et al. (2000) and Cordani & Teixeira (2006) for a review of the classical model of the Craton. The inner cratonic core encompasses the Central Amazonian (Archean) and the Maroni-Itacaiunas (Paleoproterozoic) provinces which resulted from amalgamation of independent fragments of the Amazonian and West African protocratons, as suggested by paleomagnetic data (Nomade et al. 2003) and geochronologic evidence (Tassinari et al. 2000). These provinces achieved tectonic stability after the Transamazonian orogeny (2.25 – 2.10 Ga), and acted from then on as a Paleoproterozoic backdrop for the magmatic arcs that successively began to be accreted along its margin at about 2.0 Ga ago. This multi-arc system gave rise to four major Proterozoic provinces that comprise the entire south-western half of the Amazonian Craton, such as: the Ventuari-Tapajós (2.00 - 1.83 Ga), Rio Negro-Juruena (RNJ; 1.80 - 1.55 Ga), Rondonian-San Ignacio (RSI; 1.55 - 1.30 Ga) and Sunsas-Aguapeí (SA; 1.25 - 0.97 Ga) – Fig. 1.

Although other tectonic models showing different positions for the tentative boundaries between provinces of the Amazonian Craton have been proposed (e.g., Santos et al. 2000, 2003), these subdivisions are mainly based on reconnaissance scale structural investigation combined with age determinations of some lithotypes. The lack of detailed field information and petrological, geochemical and structural data does not support these revisions as opposed to the classical model adopted in this paper.

From the geodynamic point of view, this giant segment of crust encompasses a range of distinct terrains through stacking, lateral growth and amalgamation of Cordilleran-type accretionary belts, intra-oceanic zones and intervening blocks, the origin of which lies in long-lived plate convergence from 2.0 to 1.0 Ga ago (e.g., Cordani & Teixeira 2006). Consequently, the complexity of the tectonic framework reflects orogenic collages during which juxtaposition of distinct rock assemblages took place, combined with multiphase deformation and metamorphism, and extensional/transpressional tectonics. In addition, successive rift basins filled with volcano-sedimentary rocks and episodes of mafic-felsic igneous complex emplacement are widespread throughout the Mesoproterozoic (e.g, Payolla et al. 2002, Santos 2003). We note that each anorogenic magmatic episode is accompanied by deposition of volcano-sedimentary cover within the stable tectonic crust, episodes that are linked to a particular event among the succession of magmatic arcs that accreted along the cratonic margin (e.g., Tassinari et al. 2000).

In such a multi-arc scenario, precise radiometric ages from key igneous complexes combined with their Nd-Sr primary signatures, constitute powerful tools not only for dating the stepwise crustal evolution, as well as for establishing regional stratigraphic correlations. Moreover, the intra-oceanic magmatic products (i.e., plutonic and volcanic felsic-mafic rocks) and their typical juvenile $\varepsilon_{Nd(T)}$ - $\varepsilon_{Sr(T)}$ signatures constitute indirect tracers of the mantle-derived material accreted to the crust (e.g., Sengör & Natal'in 1996, Cordani & Sato 1999).

This paper reports new $^{40}Ar/^{39}Ar$ and U/Pb zircon age data and Nd-Sr analyses obtained from rocks of three distinct Mesoproterozoic geologic units, in the SW fringe of the Amazonian Craton: *i*) The Serra da Providência Intrusive Suite; *ii*) The Colorado Metamorphic Sequence and; *iii*) The Nova Brasilândia Sequence. The results, when integrated to the previous geochronologic information, provide insights into the geotectonic model of the Craton during the Mesoproterozoic. In addition, the new isotopic characteristics address issues related to mantle composition throughout time. Finally, our work has important bearing on paleotectonic reconstructions – assuming convergence between Laurentia, Baltica and the SW Amazonian proto-fragments and their eventual agglutination in the Rodinia supercontinent (Tohver et al. 2006).

2 THE SW AMAZONIAN CRATON REVIEWED

The RNJ, RSI and SA provinces (Figs. 1 and 2) comprise polycyclic basement rocks exposed in the Brazilian states of Rondônia and Mato Grosso and in the Bolivian territory, that are partially covered by Phanerozoic sediments (e.g., Litherland et al., 1986, Tassinari et al., 2000, Geraldes et al. 2001). Table 1 presents a summary of the main geologic and tectonic characteristics observed in these Proterozoic provinces.

Calc-alkaline tonalitic gneisses and enderbitic granulites (1.76 - 1.73 Ga) predominate in the RNJ province, and, together with paragneiss associations, make up the oldest recognized crust in the northern part of the state of Rondônia. Deposition of the paragneiss protolith is bracketed between 1.66 – 1.59 Ga, as evidenced by U-Pb age determinations of detrital zircons (Payolla et al. 2003a). The 1.54 Ga U-Pb age of monazite from these rocks (Payolla et al. 2003b) constrains at least one main episode of thermal metamorphism of the paragneiss, spatially and temporally related to the emplacement of the Serra da Providência Intrusive Suite (1.60 – 1.53 Ga) – one of the several granitoid intrusive suites of MCG type (mangerite-charnockite-granite) and associated mafic rocks recognized in the state of Rondônia (e.g., Bettencourt et al. 1999a, Tassinari et al. 2000, Payolla et al. 2002, Santos 2003). The calc-alkaline gneisses show positive to slightly negative $\varepsilon_{Nd(T)}$ isotopic signatures, roughly between +4.0 and -2.0, suggesting that juvenile accretionary events played a major role in their tectonic evolution (e.g., Payolla et al. 2002, Cordani & Teixeira 2006). It is noteworthy that the Roosevelt volcano-sedimentary sequence (1.74 Ga; Figs. 1 and 2) that crops out along the southern flank of the RNJ displays positive $\varepsilon_{Nd(T)}$ values and T_{DM} ages similar to the crystallization age (Santos 2003), consistent with the genetic interpretation of the RNJ calc-alkaline rocks.

Table 1. Summary of the main characteristics in the Proterozoic provinces, Amazonian Craton. See text for details.

Characteristics of the Province	Main tectono-metamorphic events	Main regional geological units and crustal structures	Main intrusive complexes
Rio Negro-Juruena (1.78 - 1.55 Ga) Accretionary belts, with plutonic recurrent pulses. Regional cooling at ca. 1.55 – 1.50 Ga Foreland for the younger orogenies	• Medium- to high-grade metamorphism (1.75 - 1.73 Ga). • Cachoeirinha orogen (1.59 – 1.52`Ga). • Metamorphic overprints due to the Rondonian-San Ignacio events (1.50 Ga; 1.35 Ga). • Tectonic reactivations due to the SA orogeny (1.18 – 1.12 Ga).	Granite-greenstone terrane and syn orogenic plutonism. Calc-alkaline rocks. MCG associations. Medium- to high-grade gneissic associations. Volcano-sedimentary sequences (Roosevelt and correlatives). Serra da Providência Intrusive Suite: bimodal magmatism.	Anorogenic plutonism: Serra da Providência Intrusive Suite (1.60 - 1.53 Ga); Rio Branco Intrusive Suite (1.47 - 1.42 Ga). Younger Granites of Rondônia (0.99 - 0.97 Ga).
Rondonian-San Ignacio (1.55 - 1.30 Ga) Collisional orogeny combined with accretionary domains. Voluminous orogenic plutonism. Regional cooling (1.31 Ga). Foreland for the Sunsas orogeny.	• Rio Crespo Intrusive Suite (1.49 Ga). • Rio Alegre orogen (1.51 - 1.48 Ga). • Santa Helena arc (1.44 - 1.42 Ga). • Tectonomagmatic event and medium- to high-grade metamorphism (1.36 – 1.32 Ga). • Tectonic reactivations due to the Sunsas-Aguapeí orogeny.	Ocean floor mafic-ultramafic rocks. Calc-alkaline rocks. MCG associations. Colorado Metamorphic Suite (1.36 – 1.35 Ga): bimodal magmatism San Ignacio syn- to late-tectonic granitoids (1.34 – 1.32 Ga). Graben basins tectonically linked with the Sunsas-Aguapeí orogeny: Pacaas Novos, Uopione, Aguapeí, Palmeiral and Nova Brasilândia.	Late to post-tectonic plutonism: [e.g., Alto Candeias (1.34 Ga) and mafic sills]. Anorogenic plutonism: Santa Clara Intrusive Suite (1.08 – 1.07 Ga), Younger Granites of Rondônia (0.99 - 0.97 Ga).
Sunsas-Aguapeí; (1.25 – 0.97 Ga) Collisional orogeny with supracrustal belts.	• Deformation and Metamorphism: thrust and shear belts (1.10 Ga). • Local thermal overprint due to granite emplacement. • Final cratonization, regional cooling and exhumation (1.00 – 0.92 Ga)	Passive margin supracrustal assemblages variably affected by metamorphism. Syn- to late orogenic plutonism. Nova Brasilândia Sequence (1.21 – 1.05 Ga): bimodal magmatism.	Pos-tectonic plutonism: (0.97 - 0.92 Ga). Mafic intrusions.

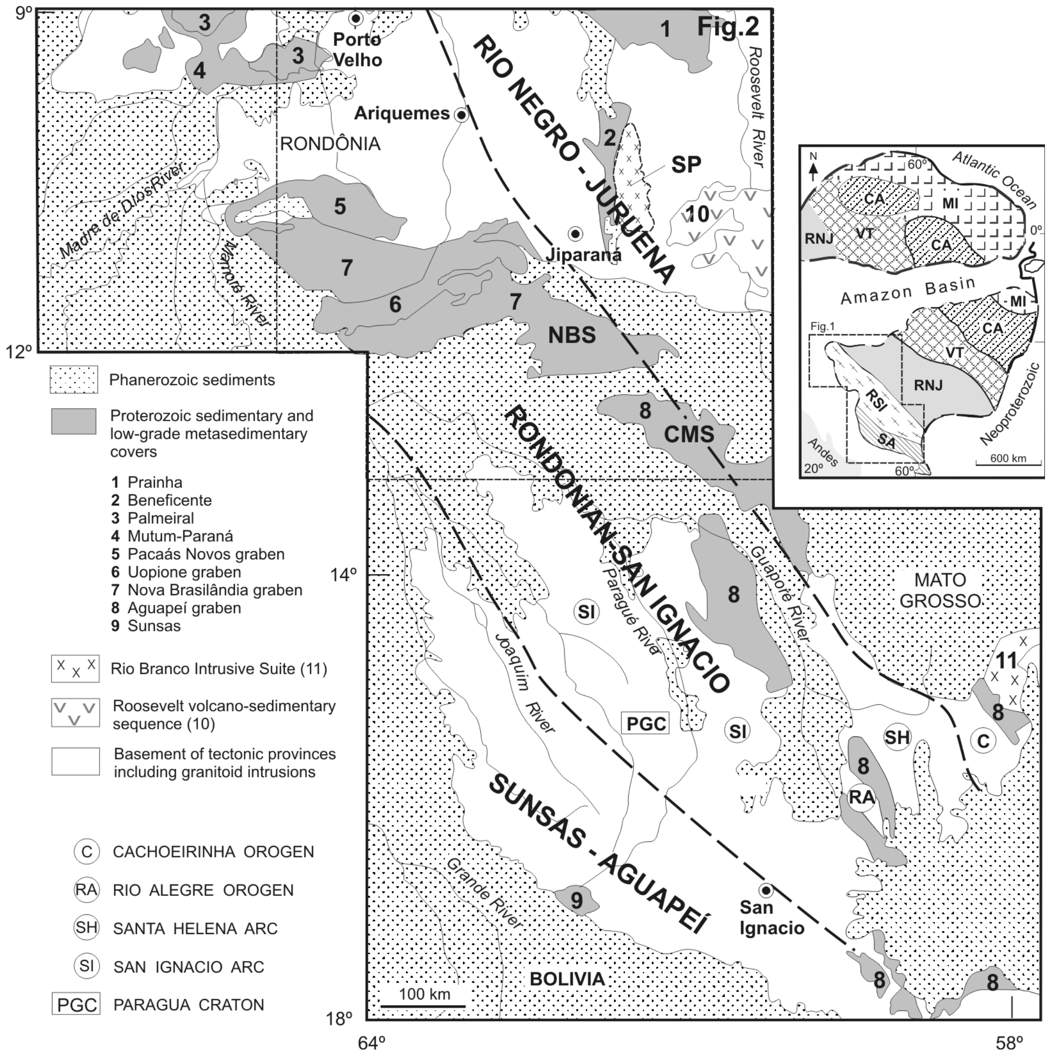

Figure 1. Simplified geologic outline of the SW margin of the Amazonian Craton showing the studied units, the main Proterozoic covers and the inferred boundaries (partially concealed) between the provinces (Adapted from Cordani & Teixeira 2006). Keys: SP = Serra da Providência batholith, CMS = Colorado Metamorphic Sequence; NBS = Nova Brasilândia Sequence. Inset: geochronological provinces of the Amazonian Craton: Central Amazonian – CA (> 2.6 Ga); Maroni-Itacaiunas – MI (2.25 – 2.05 Ga); Ventuari-Tapajós – VT (1.98 – 1.81 Ga); Rio Negro-Juruena – RNJ (1.78 – 1.55 Ga); Rondonian-San Ignacio – RSI (1.55 – 1.30 Ga) and Sunsas-Aguapeí – SA (1.25 – 0.97 Ga). See text for details.

The Serra da Providência Intrusive Suite (pink granites, charnockites and gray granites) were variably affected by tectonometamorphic events (Payolla et al. 2002). The large, oval shaped 1.60 – 1.53 Ga Serra da Providência batholith and several related satellite stocks of this Suite occur in central-southeast Rondônia (Fig. 2). They are composed of undeformed and deformed rapakivi granites showing mingling features and associated mafic and intermediate members. Some of these rocks exhibit additional shearing and mylonitization which took place at 1.35 Ga (Tohver et al. 2006). The granitoid rocks have subalkaline slightly peraluminous composition, and exhibit A-type affinities; they are epizonal in nature, in accordance with the presence of sedimentary rocks as roof pendants within the batholith (see Bettencourt & Dall'Agnoll 1995, Santos et al. 2003, Rizzotto et al. 1995). Diabases, metabasites, gabbroic and metagabbroic dikes, and amphibolites are also genetically related to the Serra da Providência Intrusive Suite, as deduced from similar ages, tectonic setting, and common field relationships (Payolla et al. 2002).

The granitic and charnockitic gneisses show petrogenenetic features ($\varepsilon_{Nd(T)}$ varying from -0.6 to +2.0) suggestive of magmas derived from mixture of slightly older crustal sources and depleted mantle (Bettencourt et al. 1999a, b, Payolla et al. 2002), induced by intrusion of basaltic magma into the lower crust and crustal underplating (Bettencourt et al. 1997). This interpretation agrees well with the model proposed for the Finnish rapakivi granites (Haapala et al. 2005). Tectonically, the Serra da Providência magmatism represents an anorogenic event within the RNJ province, probably triggered by subduction-related events of the Cachoeirinha orogen, developed farther southeast in the state of Mato Grosso – Fig. 1 (see Tassinari et al. 2000). This orogeny produced tonalite and granitic plutons of calc alkaline affinity, that exhibit U-Pb zircon ages between 1.59 - 1.52 Ga and $\varepsilon_{Nd(T)}$ values from -0.8 to +1.0 (Geraldes et al. 2004) – Table 1.

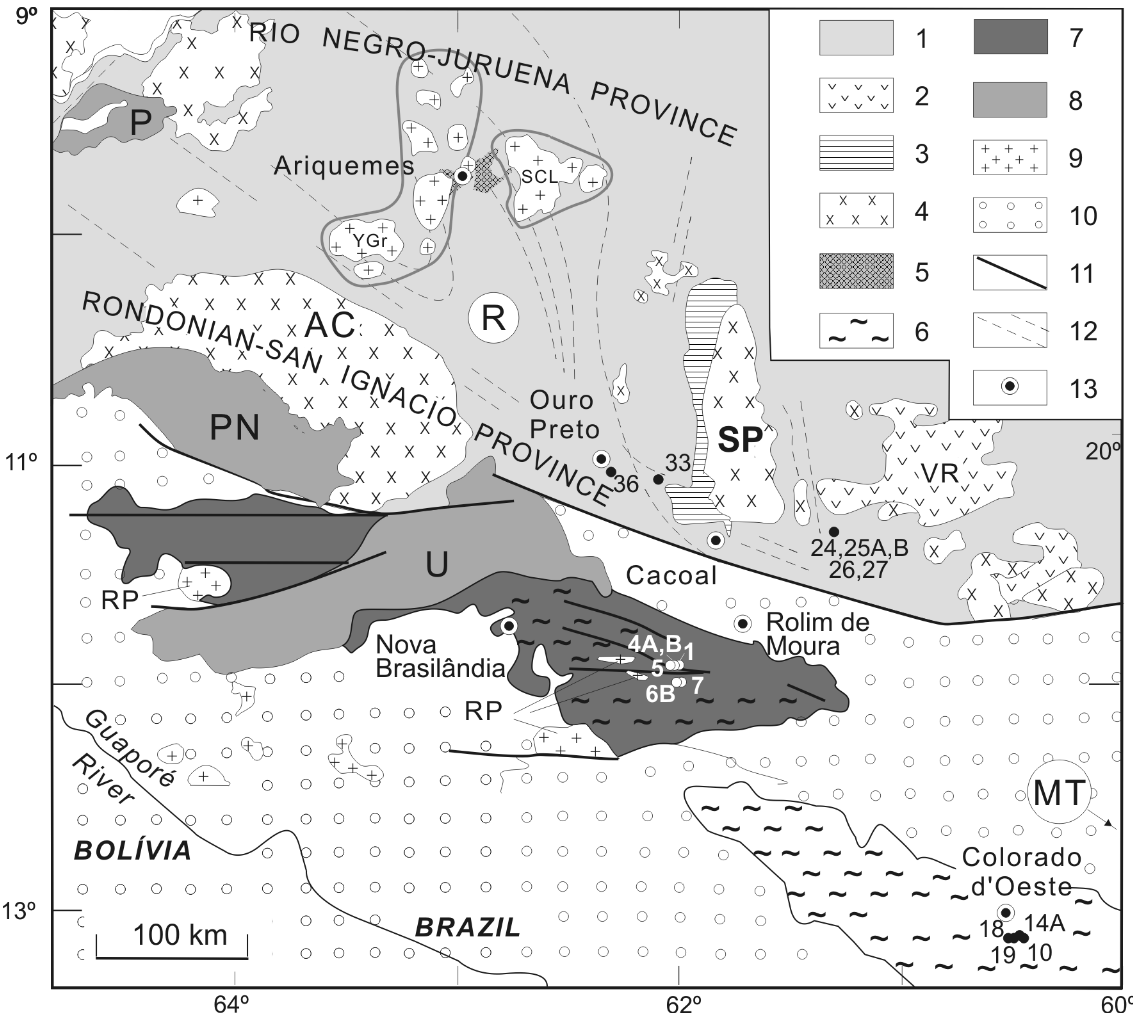

Figure 2. Geologic outline of the investigate area, with location of the studied samples (adapted from Rizzotto et al. 2002, Bettencourt & Dall'Agnoll 1995, Bettencourt et al. 1999a). 1) polycyclic basement rocks partially reworked by the Rondonian-San Ignacio and Sunsas-Aguapeí orogenies; 2) Roosevelt volcano-sedimentary sequence (VR; 1.74 Ga); 3) Beneficente volcano-sedimentary sequence (1.69 Ga); 4) Intrusive granitoid suites of different ages (AC = Alto Candeias, 1.34 - 1.35 Ga; SP = Serra da Providência, 1.60 – 1.53 Ga); 5) Rio Crespo Intrusive Suite (1.49 Ga); 6) Colorado Metamorphic Suite (1.36 - 1.35 Ga); 7) Nova Brasilândia Sequence (Sunsas-Aguapeí orogeny); 8) Volcano-sedimentary covers related with the Sunsas-Aguapeí orogeny (P = Palmeiral; PN = Pacaas Novos and U = Uopianes; 1.20 – 1.03 Ga); 9) Post-tectonic and anorogenic granitoid suites (SCL = Santa Clara, 1.08-1.07; RP = Rio Pardo, 1.05 Ga; YGr = Younger Granites, 0.99-0.97 Ga); 10) Phanerozoic; 11) Main structures; 12) Main shear zones. Keys: [R] State of Rondônia; [MT] State of Mato Grosso (located southeastward of the studied area).

The RSI orogeny produced at least three main lithological associations. Farthest to the SE, in the state of Mato Grosso, the 1.51 - 1.48 Ga Rio Alegre orogen (Geraldes et al. 2004) comprises mafic-ultramafic rocks, BIF, chert and plutonic rocks ($\varepsilon_{Nd(T)}$ = +2.5 to +4.7) of island arc affinity (Fig. 1; Table 1), whereas in central-southeast Rondônia the 1.49 Ga Rio Crespo Intrusive Suite (Payolla et al. 2002, Bettencourt et al. 2006) is composed of a granitic gneiss and charnockitic granulite association (see Fig. 2) showing juvenile isotopic signatures ($\varepsilon_{Nd(T)}$ = +1.0 to +1.8; Bettencourt et al. 2006). Adjacent to the Rio Alegre orogen the Santa Helena calc-alkaline granitoids occur (1.44 - 1.42 Ga; $\varepsilon_{Nd(T)}$ = +2.6 to +4.0) – see Tassinari et al. (2000) and Geraldes et al. (2001), originated as part of a major juvenile orogenic event. These rocks are coeval with the Rio Branco Intrusive Suite (1.47 – 1.42 Ga) which mafic and felsic lithotypes (MCG type) are intrusive into the granite-greenstone terrane in the southeast segment of the RNJ province (Fig. 1; Table 1).

In southeast Rondônia, the Colorado Metamorphic Suite is assigned to the RSI youngest orogenic phase (Fig. 2). This suite consists of amphibolite facies monzonitic gneiss associated with amphibolite, gabbro and metadiabase, that were originated in an extensional setting (Rizzotto et al. 2002), intercalated with sillimanite schist, paragneiss and BIF. The monzonitic gneisses yield an age of 1.36 Ga and exhibit $\varepsilon_{Sr(T)}$ and $\varepsilon_{Nd(T)}$ values of +6.5 and +1.4, respectively, suggestive that the protoliths have had short crustal residence. The Colorado rocks were intruded by mafic-ultramafic rocks and granitic injections (derived from melting of the pelites) that accompany strike-slip regional shearing and the development of mylonitic foliation, producing anastamosing portions and boudinage of the amphibolitic rocks – see Rizzotto et al. (2001, 2002) for review.

A high-grade metamorphic episode of this age (1.35 – 1.33 Ga) also overprinted the Rio Crespo Suite located ~ 700 km northward (Bettencourt et al. 2006), and is also concomitant with emplacement of rapakivi granites of the 1.34 - 1.35 Ga Alto Candeias Intrusive Suite in northern Rondônia (Fig. 2). However these plutons are anorogenic in relation to the previous stabilized RNJ crust (Bettencourt et al. 1999a, b, Payolla et al. 2002). Widespread preservation of 1.35 Ga ages in hornblende throughout the basement rocks of north-central Rondônia is reported by Thover et al (2005a, 2006). The contemporaneous San Ignacio orogeny is registered in the rocks of Bolivia (Litherland et al. 1986), marked by voluminous syn- to late tectonic granitoids (1.34 - 1.32 Ga and $\varepsilon_{Nd(T)}$ = -0.9 to +3.9; Boger et al. 2005 and Darbyshire 2000, respectively) and coeval metamorphism in the supracrustal belts.

As a consequence of this polycyclic evolution, the boundary between the RNJ and RSI provinces is very complex, therefore it is not drawn in Fig. 2. The network of extensive shear zones, fault blocks, fracture systems, and tectonic overprints in the country rocks in Rondônia may reflect the Rondonian-San Ignacio collision front within the RNJ province (Cordani & Teixeira 2006). It is noteworthy that a high grade metamorphic overprint of the RNJ rocks is revealed by U-Pb SHRIMP ages (1.30 - 1.35 Ga) on zircon overgrowths and monazite (Bettencourt et al. 1999a, Payolla et al. 2002) along this front, in agreement with the above interpretation.

A younger metamorphic episode, marked by development of shear zones and mylonitic belts (1.18 - 1.15 Ga; Bettencourt et al. 1996, Tohver et al. 2005a, b), affected the country rocks of the RSI province. We interpret this as a reflection of the SA orogeny (1.25 - 0.97 Ga) originally characterized by Litherland et al. (1986) in eastern Bolivia and along the Brazil-Bolivia border. This orogeny was accompanied by voluminous granite intrusions emplaced along mylonitic zones (e.g., transpression tectonics), succeeded by post-tectonic (e.g., Santa Clara Intrusive Suite, 1.08 - 1.07 Ga, Rio Pardo Intrusive Suite, 1.05 Ga) and anorogenic intrusions (0.99 - 0.97 Ga; Younger Granites of Rondônia), emplaced into both the RNJ and RSI provinces (e.g., Bettencourt et al. 1996, 1999a) – Fig. 2. In addition, sedimentary processes under an extensional regime (Palmeiral, Pacaas Novos, Uopianes, Nova Brasilândia, Aguapeí grabens; Figs. 1 and 2) and mafic flow and sill pulses are similarly geologic markers linked with the SA orogeny (Tohver et al. 2002, 2005b).

The SA province consists of passive-margin sedimentary sequences that were subsequently deformed and metamorphosed under low- to medium-grade conditions, giving rise to the 1.08 – 0.95 Ga Sunsas/Aguapeí mobile belt that developed along the southern margin of a subcontinental stable fragment ("Paragua Craton" of Litherland et al., 1986 – Fig. 1) in eastern Bolivia and in Rondônia and Mato Grosso states, Brazil (e.g., Tassinari et al., 2000).

The Nova Brasilândia metaplutonic-metasedimentary belt overprint the Colorado Metamorphic Suite and is covered unconformably by the Palmeiral and Pacaas Novos sedimentary rocks (Fig. 2). According to Rizzotto et al. (2001), the Nova Brasilândia lithologies are characteristic of intracontinental rifts evolved from passive margins, transformed into metasediments by injection of coeval felsic to mafic metaplutonic and plutonic rocks (sills and lenses of gabbro, metagabbro, amphibolite, metadiabase, and A-type granite) that reached in places amphibolite to granulite facies metamorphism. In contrast, Tohver et al. (2004, 2005a) interpreted the Nova Brasilândia metamorphic belt as the result of the crustal thickening through imbrication caused by the transpressive suturing of the Amazonian and Paragua cratons at ~1.10 Ga, on the basis of detailed structural data, supported by thermobarometric calculations, and geochronological information.

SHRIMP U-Pb analyses of detrital zircons from the Nova Brasilândia pelitic rocks yield an age of 1.21 Ga (the youngest group of zircons) interpreted as the maximum sedimentation age for the sequence (Santos 2003). Metamorphic ages (U-Pb: titanite, monazite; $^{40}Ar/^{39}Ar$: amphibole, biotite) range from 1.09 - 1.06 Ga to 0.97 - 0.91 Ga throughout the belt (e.g., Thover et al. 2004, 2006). This reveals a long history of metamorphism, tectonic exhumation and cooling. Detailed geochemical and isotopic data (Rizzotto et al. 2001) indicate that the magmatic evolution initiated with coeval gabbroic and monzogranitic rocks that emplaced at 1.11 Ga during an extensional phase of the oceanic lithosphere, in agreement with the postulated rift model. The isotopic constraints suggest a DMM-like signature of the mafic rocks ($\varepsilon_{Nd(T)}$ = +4.3 to +5.0), whereas the $\varepsilon_{Nd(T)}$ value (-0.4) of the felsic rocks is consistent with derivation from magma sources slightly contaminated with previously derived crustal materials. The extensional stage was succeeded by a transpressional regime accompanied by crustal shortening, as evidenced by regional EW and WNW-ESE structures, and medium- to high-grade metamorphism. Injection of granitic melts at 1.10 Ga ($\varepsilon_{Nd(T)}$ = -1.5) was contemporaneous with this stage. The distension phase and final orogenic collapse of the Nova Brasilândia belt was accompanied by late- to post-tectonic granites dated at 1.05 Ga ($\varepsilon_{Nd(T)}$ = +0.5).

3 RESULTS

Ten $^{40}Ar/^{39}Ar$ step-heating (in triplicate) and U/Pb age determinations (isotopic dilution) were carried out on mafic and felsic intrusive rocks. Additional geochemical and isotopic analyses of Nd-Sr were restricted to the mafic rocks. The investigated rocks belong respectively to: 1) The Serra da Providência Intrusive Suite (1.60 - 1.53 Ga); 2) The Colorado Metamorphic Suite (1.36 – 1.30 Ga) and 3) The Nova Brasilândia Sequence (1.21 – 1.05 Ga) – see previous section.

The age determinations and isotopic geochemistry were performed at the Geochronological Research Center (CPGeo) of the Institute of Geosciences, University of São Paulo, Brazil (see Krogh 1973, Sato et al. 1995 and Vasconcelos et al. 2002 for chemical routines of the U-Pb, Nd-Sr and $^{40}Ar/^{39}Ar$ methods and their particular analytical uncertainties at the CPGeo). Due to space limitations the complete analytical data and a summary of the geochronological methods applied to the studied samples are available as auxiliary material at the website www.igc.usp.br/teixeira/database2006/ (Tables 2, 3, 4 and 5).

The $^{40}Ar/^{39}Ar$ spectra from mica and amphibole (one to three grains for each analysis from an individual rock) are shown in Figs. 3, 5 and 6. As can be seen from the degassing spectra after the initial, low temperature steps, most samples exhibit undisturbed plateaus. This suggests a simple cooling history, as corroborated by minimal compositional variation in the Ca/K ratios (not shown). The U/Pb zircon age of a leucogabbro (Colorado Metamorphic Suite) is presented in Fig. 4 whereas Fig. 7 shows the Nd-Sr characteristics of rocks from each of the investigated geological units.

3.1 *Serra da Providência Intrusive Suite*

The selected mafic samples for $^{40}Ar/^{39}Ar$ geochronology and Nd-Sr isotopic geochemistry (see Fig. 2 and Table 1) include metamorphosed rocks, such as amphibolites (24, 27), metagabbro

(25B, 26), metadiabase (33, 36), as well as undeformed diabase (25A). Samples from outcrops 24, 27, 33 and 36 were taken from dikes intruded into metacharnockites. The mafic dikes, charnockites and rapakivi granites are part of a bimodal association included in the Serra da Providência Intrusive Suite (e.g., Payolla et al. 2002). Outcrop 25 comprises foliated metagabbro and diabase, in contrast with nearby outcrop 26 which is made up of a strongly sheared metagabbro with granitic injections.

The amphibolites exhibit granoblastic texture and consist of plagioclase (andesine), hornblende, apatite, opaque minerals, and clinopyroxene (in some samples). The granulite facies equivalents are characterized by labradorite and the two pyroxene assemblages. The diabases (subophitic texture) are made up of clinopyroxene, plagioclase, brown olivine, apatite and opaque minerals. In the metadiabases plagioclase laths and pyroxenes are igneous relicts in a granoblastic assemblage formed mainly by plagioclase, hornblende and pyroxene. The metagabbros show granoblastic texture, and are mainly composed of labradorite and clinopyroxene and minor amounts of hornblende.

The $^{40}Ar/^{39}Ar$ age determinations of amphibole were carried out on four samples (24, 25B, 26, 27; Figs. 2 and 3); located to the southeast of the Serra da Providência batholith. The triplicate $^{40}Ar/^{39}Ar$ analyses of amphibole 24 yielded plateau ages of 1554 ± 6 Ma, 1552 ± 6 Ma and 1558 ± 4 Ma, respectively. The resulting age probability diagram (ideogram) yields an age of 1556 ± 6 Ma. The metagabbro 25B yielded two plateau ages of 1555 ± 7 Ma and 1450 ± 30 Ma, whilst the third amphibole (two grains) gives an integrate age of 1517 ± 19 Ma (see $^{40}Ar/^{39}Ar$ analytical data and Fig. 3a at the website). Triplicate $^{40}Ar/^{39}Ar$ analyses from metagabbro 26 indicate excess argon in the very low temperature steps but analyses 2 and 3 provided plateau ages of 1572 ± 16 Ma and 1566 ± 4 Ma for more than 50% of the argon released. The other amphibole (2 grains) yielded an integrated age of 1617 ± 3 Ma, possibly due to the influence of excess argon. Selected steps of analyses 1, 2 and 3 provide an ideogram age of 1552 ± 14 Ma (Fig. 3). Finally, amphibolite 27 revealed argon disturbance in the first steps of the triplicate analyses, as similarly indicated by variation of the correlated Ca/K ratio (not shown). This explains the distinct age variation: plateau ages (1521 ± 2 Ma and 1558 ± 7 Ma) and the much younger integrated age of 1421.0 ± 1.3 Ma (third analysis; 2 grains). The ideogram age of 1556 ± 6 Ma can be interpreted as a minimum estimate for cooling of these samples subsequent to the main metamorphic episode of the RNJ paragneisses (see previous section). The uniform exhumation of the studied portion is envisaged, given the epizonal characteristics of the plutons of the Serra da Providência batholith (see previous section). Nevertheless, younger massifs (1.53 Ga) of the Serra da Providência Intrusive Suite were not studied by $^{40}Ar/^{39}Ar$ thermochronology, therefore this cooling age (1556 Ma) can not be extrapolated to the whole Suite.

3.2 *Colorado Metamorphic Suite*

Four samples of this Suite were studied by U/Pb, $^{40}Ar/^{39}Ar$ geochronology and Nd-Sr isotopic geochemistry (samples 10, 14A, 18, 19; see Fig. 2). Outcrop 10 is a coarse grained leucogabbro showing igneous structure and incipient metamorphic foliation. Sample 14A is a weakly-foliated, garnet-muscovite granitoid associated with boudins of amphibolite (14B), representing late injection that cut the foliation of the amphibolites. The nearby outcrops 18 and 19 are constituted by amphibolites, showing subvertical foliation, isoclinal folding and shearing. Late granitic injections along the foliation planes are also similarly observed in these outcrops. Late hydrothermal fluids have affected both rock types.

The amphibolites (14A, 18 and 19) are made up of hornblende, plagioclase (andesine-labradorite), apatite, titanite and opaque minerals. The texture is usually granoblastic. The gabbros (sample 10) are made up of plagioclase (labradorite), clinopyroxene, olivine, rare orthopyroxene and opaque minerals. Partially serpentinized olivine, some larger prismatic plagioclase and clinopyroxene are cumulate phases. However, the majority of these minerals constitute a heterogranular, granoblastic polygonal texture, which suggests metamorphic re-equilibrium.

Prismatic zircons with rare small fractures from leucogabbro 10 were selected for U-Pb geochronology. Three zircon fractions define an upper intercept age of 1352 +4/-3 Ma (MSWD = 0.18), interpreted as the minimum crystallization age of this rock – Fig. 4. This sample shows

$\varepsilon_{Nd(T)}$ = +2.7 (see the database at the website) which is consistent with the $\varepsilon_{Nd(T)}$ = +1.4 value reported for nearby 1.36 Ga monzonitic gneiss (Rizzotto et al. 2002).

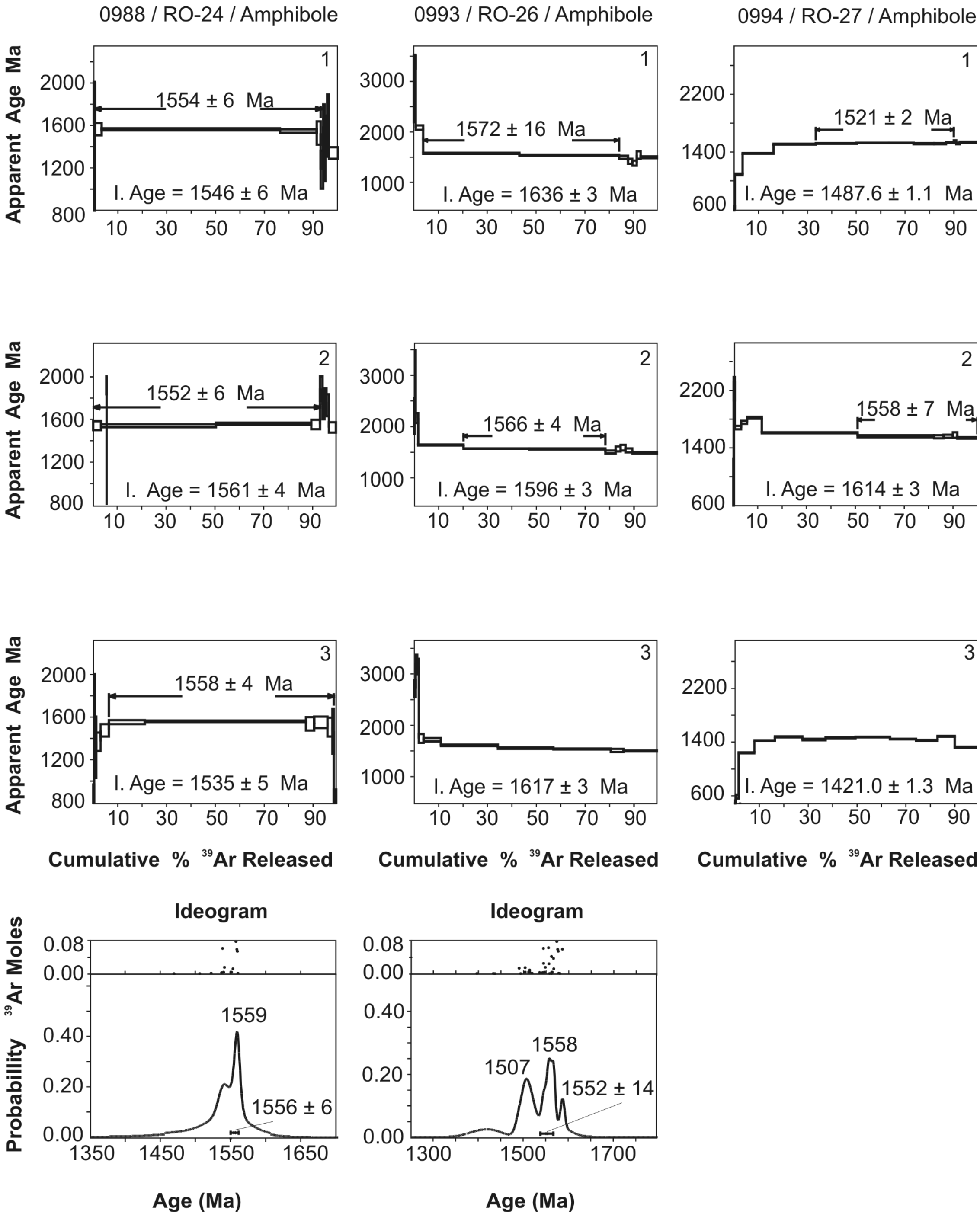

Figure 3. Caption of $^{40}Ar/^{39}Ar$ age spectra for triplicate analyses in amphibole from selected rocks of the Serra da Providência Intrusive Suite (I. Age = Integrated Age).

The $^{40}Ar/^{39}Ar$ analyses were performed on muscovite from granitic veins (sample 14A), and amphibole from amphibolites (18, 19) – Fig. 5. Muscovite 14A yields plateau ages of 1315 ± 3 Ma, 1306.3 ± 1.6 Ma and 1309 ± 4 Ma, respectively. The resulting ideogram age is 1309 ± 4 Ma (three runs). However, runs 2 and 3 showed argon loss in the very first step-heating analysis. Therefore 1315 ± 3 Ma is the best age estimate for the metamorphic cooling of this late granitic injection. Amphibole from sample 18 yielded two plateau ages at 1311 ± 6 Ma and 1320 ± 6 Ma with argon loss in the first steps of the analysis; the third run gives a much younger, meaningless age (1205 ± 7 Ma). The ideogram age (first two runs, amphibole) is 1315 ± 9 Ma, in agreement with the plateau age of muscovite RO-14A. Finally, amphibolite 19 provided contrasting plateau ages in triplicate analyses of amphibole: 1312 ± 3, 1324 ± 3 and 1330 ± 4.3 Ma with indication of argon loss in the first steps of the analysis. The ideogram age (runs 2, 3) is 1327 ± 5 Ma (Fig. 5). From the above the 1327 - 1315 Ma $^{40}Ar/^{39}Ar$ plateau ages are assigned to the period of metamorphic cooling of the Colorado Metamorphic Suite. In addition, the similar $^{40}Ar/^{39}Ar$ ages in amphibole and muscovite from 19 and 14A suggests a fast cooling rate following the 1.36 - 1.32 Ga RSI orogenic phase (Table 1).

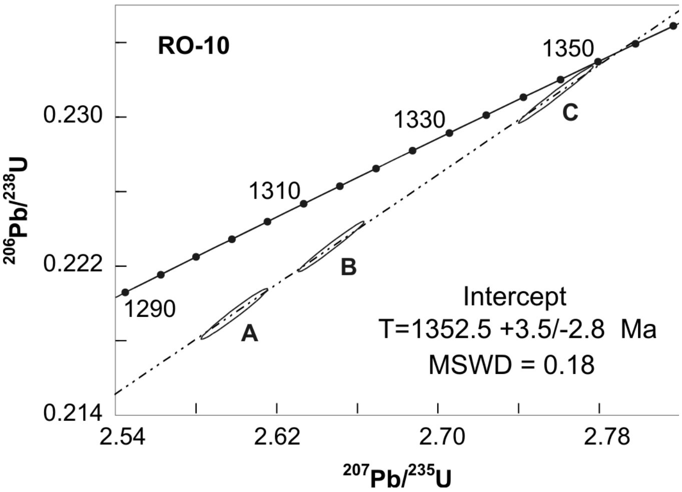

Figure 4. Caption of U-Pb (isotopic dilution, zircon) concordia plot of leucogabbro (Colorado Metamorphic Suite).

3.3 *Nova Brasilândia Sequence*

Three $^{40}Ar/^{39}Ar$ age determinations were carried out on biotite from mafic and felsic rocks (outcrops 4, 6 and 7, see Fig. 2). The first outcrop comprises syntectonic granite (4A) injected along with amphibolitized sills (Rizzotto et al. 2001), with a variable degree of deformation and shearing. Similarly metagabbro and syntectonic granite coexist in outcrop 6, whereas sample 7 was taken from gabbro with thin hydrothermal veins containing biotite. The Nd-Sr analyses were carried out on mafic rocks from outcrops 1, 4, 5 and 7 (see below).

The investigated gabbros (samples 5, 7) are constituted of plagioclase (labradorite), clinopyroxene, olivine, biotite, hornblende and opaque minerals, and show ophitic texture. Clinopyroxene is altered to hornblende and biotite, and olivine is partially altered to iddingsite. The metadiabases (4B) are made of plagioclase (labradorite), clinopyroxene, hornblende, apatite and opaques. The original subophitic texture was partially recrystallized, as shown by small grains of newly formed clinopyroxene and hornblende that replace the original clinopyroxenes (recovery) and the partially granoblastic plagioclase. The amphibolites (01) are formed of hornblende, plagioclase (andesine-labradorite), clinopyroxene, apatite, titanite, quartz and opaque minerals. The texture is predominantly nematoblastic and clinopyroxene is in equilibrium with hornblende.

The analyses of biotite from granite 4A yielded plateau ages of 979 ± 2 Ma, 982.9 ± 1.7 Ma and 984.3 ± 1.6 Ma respectively (Fig. 6), indicating argon loss in the first steps of the analysis. The resulting ideogram age is 982 ± 2 Ma, and probably reflects the shearing overprint (see above). Biotite from granite 6B yielded $^{40}Ar/^{39}Ar$ plateau ages of 1027.6 ± 1.4 Ma, 1018.7 ± 1.7 Ma and 1023.0 ± 1.8 Ma respectively, supporting similarly argon loss in the first steps. The ideogram age (three runs) yields 1025 ± 3 Ma (Fig. 6). Finally, biotite from gabbro 7 yields plateau ages of 971.7 ± 1.6 Ma, 969 ± 2 Ma and 968.7 ± 1.6 Ma. The resulting ideogram age (three runs) is 970 ± 2 Ma, which is probably related to the hydrothermal alteration affecting this gabbro. Based on the $^{40}Ar/^{39}Ar$ data, the ideogram age (1025 Ma) may be extrapolated as the time of regional cooling which is subsequent to shearing and metamorphism (1.10 Ga; Tohver et al., 2004, 2005a) that overprinted the RSI rocks, as response of the SA orogeny (Table 1).

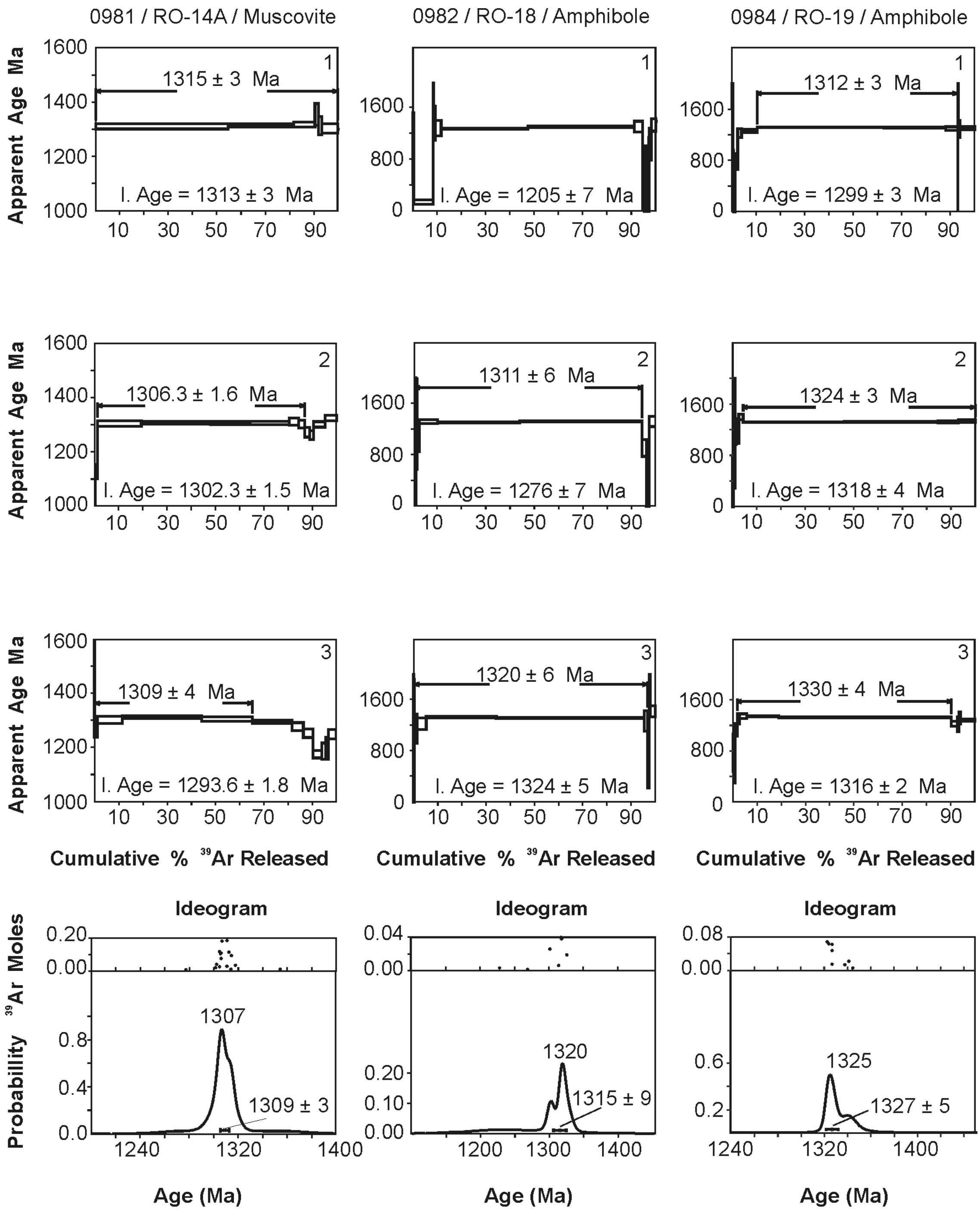

Figure 5. Caption of $^{40}Ar/^{39}Ar$ age spectra for triplicate analyses in muscovite and amphibole from mafic and felsic rocks of the Colorado Metamorphic Suite (I. Age = Integrated Age).

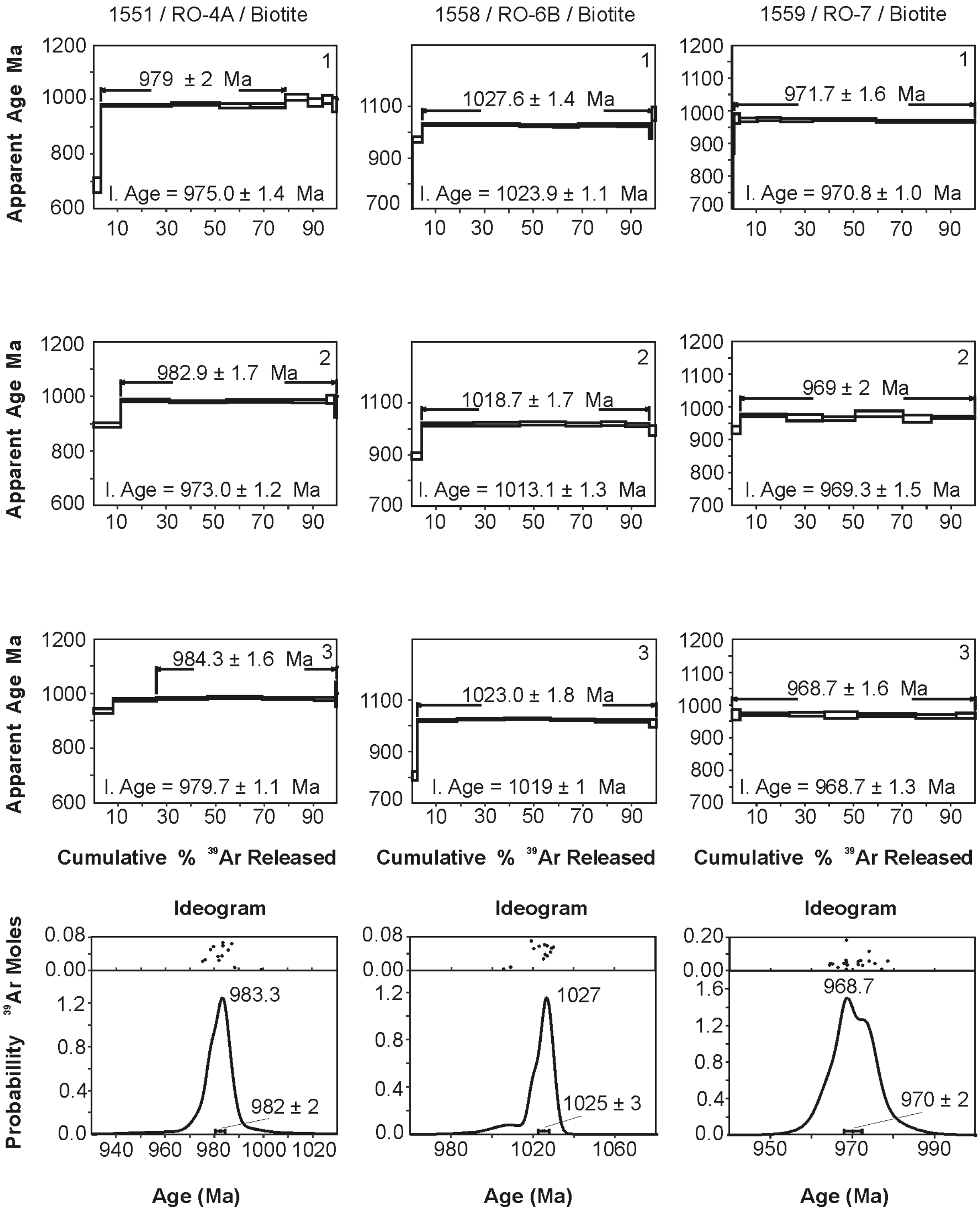

Figure 6. Caption of $^{40}Ar/^{39}Ar$ age spectra for triplicate analyses in biotite from mafic and felsic rocks of the Nova Brasilândia Sequence (I. Age = Integrated Age).

3.4 *Nd-Sr isotopic geochemistry*

The mafic rocks of the Serra da Providência Intrusive Suite, Colorado Metamorphic Suite and Nova Brasilândia Sequence include igneous and metamorphic mafic rocks, as already seen. Except for one cumulate olivine gabbro of the Colorado Suite (mg# 0.61), the mg# ranges from 0.51 to 0.14 [(mg# = atomic Mg/Mg+Fe^2) ratio; assuming Fe_2O_3/FeO=0.15]. All samples display increasing Fe_2O_3t, TiO_2, P_2O_5, K_2O, Na_2O, MnO and incompatible trace-elements contents, while Al_2O_3, CaO, Cr and Ni decrease, with decreasing mg#. The Sr content is generally constant. These trends are consistent with tholeiitic magmas derived from parent melts by gabbro fractionation, and the tholeiitic affinity of all samples is shown by the AFM diagram (Rizotto et al. 2001, Girardi et al. 2005).

Element mobility induced by metamorphism has been checked by MPR (molecular proportional diagrams; see Pearce, 1968 and Beswick, 1982), using LILE and HFSE as normalizing elements, assuming that the former are mobile (e.g., Rb, K), and the latter are immobile. The resulting diagrams (not shown) display straight lines, which do not pass trough their origin, thus suggesting that the recognized metamorphic events overprinting the studied rocks did not change the igneous trends.

The $\varepsilon_{Sr(T)}$ values lower than 40 and do not trend towards EMII (Fig. 7). The lack of correlation between the initial ratios of $^{87}Sr/^{86}Sr$ (Sri) and $^{143}Nd/^{144}Nd$ (Ndi) with chemical parameters such as SiO_2, K_2O, and $(La/Yb)_n$ indicate that the degree of crustal contamination is negligible. Therefore, the geochemical data are consistent with the assumption that the igneous geochemistry of the studied samples was undisturbed by post-magmatic events. Moreover, the absence of significant element mobility during the post-igneous events indicates that disturbance of the Rb-Sr isotopic system was negligible**.**

Fourteen Rb-Sr and Sm-Nd isotopic analyses were performed on the selected mafic rocks (Fig. 2) and the $\varepsilon_{Sr(T)}$ and $\varepsilon_{Nd(T)}$ values (data are shown in the website in table 3, ver observação no parágrafo anterior) were calculated assuming average ages of 1.55, 1.35 and 1.10 Ga for the Serra da Providência, Colorado and Nova Brasilândia units, respectively, in accordance with the geologic and geochronologic information.

Fig. 7 displays the isotopic compositional fields of the studied mafic rocks. The Colorado samples plot in the left-hand quadrant that corresponds to the most depleted field ($\varepsilon_{Nd(T)}$ = 0.0 to +5.2 and $\varepsilon_{Sr(T)}$ = -5.0 to –30.7), indicating the significant influence of the DMM end-member reservoir on the origin of the magmas. Tectonically, this signature is compatible with magmas originating in intraoceanic settings. The Nova Brasilândia mafic samples show slightly positive $\varepsilon_{Nd(T)}$ (+0.1 to +1.6) and variable $\varepsilon_{Sr(T)}$ (-2.4 to +34.2) values. Other mafic rocks from the Nova Brasilândia Sequence have strongly positive $\varepsilon_{Nd(T)}$ values (+3.1/ +5.0; Rizzoto et al. 2001), indicating the primary signature of ocean floor-like magmas. In contrast, the mafic rock reservoirs from the Serra da Providência Intrusive Suite are heterogeneous: *i*) two samples (33, 36) plot in the depleted quadrant ($\varepsilon_{Nd(T)}$ = +2.5 to +2.8; $\varepsilon_{Sr(T)}$ = -12.0), implying derivation from DMM-like sources ; *ii)* four samples (24, 25A,B, 26) have $\varepsilon_{Nd(T)}$ = -0.9 to +0.4 and $\varepsilon_{Sr(T)}$ = -3.3 to +11.7, and plot nearby the “Bulk Earth”, indicating an approximately “chondritic” composition. This latter isotopic signature is compatible with $\varepsilon_{Nd(T)}$ values (-0.6 to +2.0) of coeval rapakivi granites (Payolla et al. 2002), suggesting a minimal crustal component in the magma genesis. This reinforces the interpretation that the mafic-felsic rocks in the Serra da Providência Suite are derived mainly from juvenile sources.

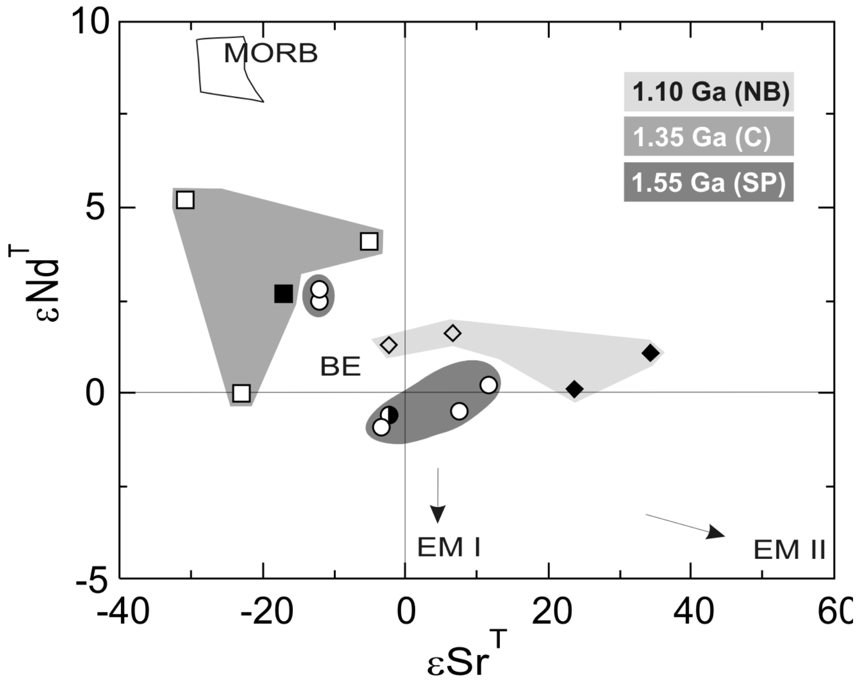

Figure 7. Caption of $\varepsilon_{Nd(T)}$ - $\varepsilon_{Sr(T)}$ variation isotopic fields for mafic rocks of selected Mesoproterozoic units. Key symbols: Serra da Providência Intrusive Suite – SP (1.55 Ga): open circles (amphibolite, metagabbro); half circles (diabase); Colorado Metamorphic Suite – C (1.35 Ga): open square (amphibolite, metagabbro), filled square (gabbro; R0-10); Nova Brasilândia Sequence – NB (1.10 Ga): open diamond (amphibolite, metadiabase), filled diamond (gabbro). See text for details.

4 AGE PATTERNS, MANTLE CHARACTERISTICS AND TECTONIC IMPLICATIONS

The new radiometric ages together with the geologic and geochronologic background allow the following remarks:

1) The mafic rocks from the Serra da Providência Suite yielded an average $^{40}Ar/^{39}Ar$ age of 1556 ± 6 Ma. This cooling age is in agreement with U-Pb zircon ages of granitic rocks of the Suite and U-Pb monazite ages in the adjacent paragneisses thermally affected by these plutons (Payolla et al. 2002, 2003b). Therefore, these felsic-mafic rocks are part of a bimodal magmatic association, anorogenic in relation to the 1.76 - 1.73 Ga gneisses and granulites of the RNJ orogeny, and possibly associated with the Cachoeirinha calc alkaline plutonic arc ~700 km to the SE in the state of Mato Grosso.

2) The mafic intrusions of the Colorado Metamorphic Suite originated at 1352 +4/-3 Ma, as indicated by the gabbro U/Pb zircon age. The influence of the DMM end-member reservoir in the magma genesis is observed in the mafic rocks ($\varepsilon_{Nd(T)}$ values from 0.0 to +5.2) and coeval gneisses ($\varepsilon_{Nd(T)}$ = +1.4), suggesting an important differentiation/accretion of juvenile crust related to the RSI orogeny. This conclusion is also supported by regional tectonic overprint in Rondônia and by comparable radiometric ages in country rocks (1.30 - 1.35 Ga; see previous section). The $^{40}Ar/^{39}Ar$ ages in the range 1327 - 1315 Ma reflect the regional cooling following this major event.

3) The Nova Brasilândia mafic-felsic intrusions display $^{40}Ar/^{39}Ar$ ages from 1025 to 982 - 970 Ma, and is in rough agreement with the onset of the SA collision. The oldest age pattern (1025 Ma) is comparable with U-Pb (titanite, monazite) ages and $^{40}Ar/^{39}Ar$ ages of country rocks in the State of Rondônia, indicating regional cooling after tectonic stabilization at 1050 Ma ago (Tohver et al. 2004). The youngest $^{40}Ar/^{39}Ar$ ages (982 - 970 Ma) may be somewhat related to the regional mylonite zones (Rizzotto et al. 2001, Tohver et al. 2005b). However, these apparent ages may also reflect thermal influence from the emplacement of the Younger

Granites of Rondônia as they induced pervasive hydrothermal overprints in their host rocks within the RSI province (Bettencourt et al. (1999a, b).

4) The Nd-Sr isotopic data (Fig. 7) display contrasting signatures among the investigated Mesoproterozoic rocks, and permit two conclusions. The first concerns the heterogeneity of the mantle source during Mesoproterozoic times in this region of the Amazonian Craton, as indicated by the high degree of isotopic variation particularly for the Colorado and Serra da Providência mafic samples. The second relates to the nature of the mantle components. The influence of the DMM end-member is variable, but can be discerned in all of the investigated units. Similarly Rizzotto et al. (2001) reported strongly positive $\varepsilon_{Nd(T)}$ (+3.1/+5.0) signatures for the Nova Brasilândia gabbros, whereas the coeval (1.10 Ga) monzogranites have $\varepsilon_{Nd(T)}$ from -0.4 to +0.5. The isotopic signatures reported for these gabbros are consistent with oceanic crust and demonstrate the significant role of accreted juvenile materials in the Nova Brasilândia tectonic setting. On the other hand, the majority of the Serra da Providência Suite values plots near the "Bulk Earth" isotopic field, suggesting a EMI component in the magma genesis. However, the absence of samples with $\varepsilon_{Sr(T)}$ values higher than 40, or trending towards EMII, indicates that this component probably did not play an important role in the mantle composition through Mesoproterozoic time, thus suggesting a negligible influence of continental sediments on the isotopic signature of the investigated rocks.

5) The juvenile characteristic of the mafic-felsic rocks revealed by $\varepsilon_{Nd(T)}$ and $\varepsilon_{Sr(T)}$ values indicates Mesoproterozoic crustal growth under a mantle-accretion regime via "docking"of juvenile arcs. This accretion was roughly coeval with episodic emplacement of the bimodal magmatism within the more stable craton at that time. In other words, the Amazonian Craton evolved by the steady westward crustal growth during long-lived plate convergence marked by the accretion of intra-oceanic magmatic arcs. This process led to progressive amalgamation of the accretionary belts to the evolving continental margin due to consumption of the oceanic lithosphere and episodic reworking of the pre-existent, stabilized crust.

6) Finally, the multi-arc scenario and similarities in the geologic framework suggests that the geometry of the collage is similar between SW Amazônia and Eastern Laurentia/Baltica during Mesoproterozoic times, although the exact temporal match advanced by Rämö et al. (2001) is disputable. Details aside, the paleocontinental margin of the Grenville orogen appears to agree with the Rodinia supercontinent (1.2 – 1.0 Ga).

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