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Trace element geochemistry and Sr-Nd characteristics of Mesoproterozoic mafic intrusive rocks from Rondônia, Brazil, SW Amazonian Craton: Petrogenetic and tectonic inferences

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The Amazonian Craton comprises an Archean domain surrounded by four successively younger Proterozoic tectonic provinces. Within the Rio-Negro-Juruena province the Serra da Providência Intrusive Suite (1.60 and 1.53 Ga) consists of A-type rapakivi granites, charnockites and mangerites genetically associated with diabase dikes, gabbros and amphibolites. The original mafic melts were derived from a depleted mantle source ($\varepsilon_{Nd(T)}$ +2.5 to +2.8; $\varepsilon_{Sr(T)}$ –12.1). Underplated mafic magma induced melting of a short-lived felsic crust, thus originating coeval felsic-mafic magmatism in a continental intraplate setting. The Colorado Complex, assigned to the Rondonian-San Ignacio province, comprises 1.35–1.36 Ga intrusive bimodal magmatism represented by monzonite gneisses associated with amphibolite, gabbro and metadiabase dikes intercalated with metasediments with detrital zircon that yield U-Pb ages of 1.35 to 1.42 Ga. Mafic samples display juvenile signatures ($\varepsilon_{Nd(T)}$ 0.0 to +5.2; $\varepsilon_{Sr(T)}$ –5.0 to –30.7) and are less contaminated than the Serra da Previdência and Nova Brasilândia ones. The generation of the basaltic magma is related to the subduction of an oceanic slab below the peridotite wedge (intraoceanic arc setting). Fluids and/or small melts from the slab impregnated the mantle. The Nova Brasilândia Sequence (Sunsas-Aguapeí province) comprises a metasedimentary sequence intruded by 1.10–1.02 Ga metadiabases, gabbros, meta-gabbros, and amphibolites associated with granitic plutons (bimodal magmatism). The original tholeiitic magmas, derived from a depleted source ($\varepsilon_{Nd(T)}$ = +3.1 to +5.0), in a proto-oceanic setting, underwent subsequent contamination by the host rocks, as indicated by the isotopic and trace element data.

Introduction

The tectonic scenario of the southwestern Amazonian Craton partly is assigned to three successively younger Proterozoic provinces: the 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) (Figure 1), which result from several orogenic belts. These provinces

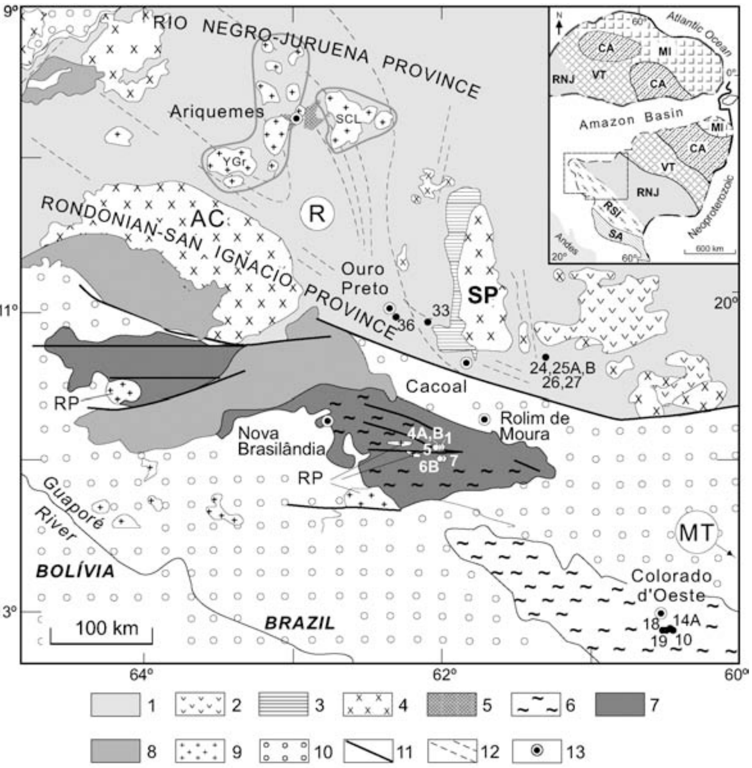

***Figure 1** Geologic framework of the area, with location of the studied samples (adapted from Rizzotto et al., 2002). 1) Basement rocks partially reworked by Mesoproterozoic orogenies; 2) Roosevelt volcano-sedimentary sequence (1.74 Ga); 3) Beneficente volcano-sedimentary sequence (1.69 Ga); 4) Intrusive granitoid suites (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 Complex (1.36–1.35 Ga); 7) Nova Brasilândia Sequence; 8) Volcano-sedimentary cover related to the Sunsas-Aguapeí orogeny 9) Post-tectonic and anorogenic granitoid suites (SCL = Santa Clara, 1.08–1.07; RP = Rio Pardo, 1.05 Ga; YGr = Younger Granites of Rondônia, 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). 13) Towns.*

can be distinguished, on the basis of lithology, structure, geochronology (U-Pb zircon ages) and isotopic signatures (Sr-Nd-Pb). According to Cordani and Teixeira (2007), the regional features of the SW part of the craton resulted from: a) continued Proterozoic soft-collision/accretion events (i.e., juvenile accretion and crustal reworking processes), b) development of thrust and fold belts, c) shear zones and rift basins accompanied by significant igneous activity represented by bimodal igneous suites (basalt-rhyolite, rapakivi, mangerite-charnockite-granite). The lower age limit of each province represents the cratonization stage of the country rocks, which is inferred from U-Pb and Pb-Pb radiometric ages of distinct rapakivi suites, mafic dikes and undeformed volcanic-sedimentary covers (e.g., Teixeira et al., 1989; Tassinari et al., 2000; Tassinari and Macambira, 2004). Alternative tectonic models based on precise SHRIMP and TIMS U-Pb ages in zircons, coupled with correlation of geologic units and regional scale structures have been presented (e.g. Santos et al., 2003) aiming at establishing subdivisions and tentative boundaries between the referred Proterozoic provinces. However these approaches do not preclude the classical model herein adopted, which is reinforced by the general conformity of the radiometric ages with the geological framework expected for a given province.

Table 1 Summary of the main characteristics in the Proterozoic provinces, Amazonian Craton (cf. Tassinari and Macambira, 1999, 2004 and therein references). MCG—mangerite-charnockite-granite. See text for details.

Characteristics of the Province	Main tectono-metamorphic events	Main regional geological units	Main intrusive complexes
Rio Negro-Juruena (RNJ); (1.78-1.55 Ga) Juvenile accretionary belts, with plutonic recurrent pulses.	• Medium- to high-grade metamorphism (1.75-1.73 Ga). • Cachoeirinha orogen (1.59-1.52 Ga). • Metamorphic overprint and tectonic reactivation due to the RSI (1.50 Ga; 1.35 Ga) and Sunsas (1.18-1.12 Ga) events.	Granite-greenstone terrane, Medium- to high-grade gneissic associations. Syn-orogenic felsic-mafic plutonism. Calc-alkaline rocks. MCG associations. Volcano-sedimentary sequences (Roosevelt and correlatives).	Serra da Providência Intrusive Suite (MCG): 1.60-1.53 Ga. Younger Granites of Rondônia (0.99-0.97 Ga).
Rondonian-San Ignacio (RSI); (1.55-1.30 Ga) Collisional orogen and subordinate juvenile accretionary belts.	Orogenic cycles: (1.51-1.48 Ga), (1.44-1.42 Ga), (1.36-1.32 Ga). Rio Crespo Intrusive Suite (1.49 Ga). Medium- to high grade metamorphism. • Reactivations due to Sunsas orogen.	Calc-alkaline rocks. MCG associations. Colorado Complex (1.36-1.35 Ga): bimodal magmatism Syn- to late-tectonic granitoids (1.34-1.32 Ga). Rift and aulacogenic-type basins (coeval with the Sunsas orogen): Pacaas Novos, Uopione, Aguapeí, Palmeiral, Nova Brasilândia.	Alto Candeias Intrusive Suite (1.34 Ga). Santa Clara Intrusive Suite (1.08-1.07 Ga). Younger Granites of Rondônia (0.99-0.97 Ga).
Sunsas-Aguapei (SA); (1.25-0.97 Ga) Sunsas collisional orogen. Cratonization/ regional cooling (1.00-0.92 Ga)	• Deformation, metamorphism and thrust/shear supracrustal belts (Aguapeí 1.10 Ga). • Thermal overprint due to granite emplacement.	Rift- to passive margin assemblages affected by metamorphism, crustal shortening processes, intruded by syn- to late tectonic plutons: Nova Brasilândia Sequence (1.21-1.05 Ga).	Pos-tectonic/ anorogenic granitoid plutons: 0.97-0.92 Ga. Mafic intrusions.

This work aims to advance our understanding on the nature of the sources and genetic models for mafic rocks associated with the Serra da Providência Intrusive Suite, Colorado Complex and Nova Brasilândia Sequence, which are tectonically and genetically related to the evolution of the RNJ, RSI, and SA provinces. For this purpose, we have combined geochemical and isotope data from the literature (Bettencourt et al., 1999a; Payolla et al., 2002; Rizzotto et al., 2001, 2002; Girardi et al., 2005; Teixeira et al., 2006; Rizzotto and Quadros, 2007) with new trace element data on mafic rocks to allow interpretations concerning the tectonic framework of the studied geological units. The integration of these data supports proposals for the tectonic settings of Serra da Providência Intrusive Suite (Bettencourt et al., 1999a and Payolla et al., 2002) and Nova Brasilândia Sequence (Rizzoto et al., 2001 and Tohver, 2004), and to suggest a new model for the origin of the Colorado Complex.

Geological framework

The geotectonic scenario of the Amazonian Craton was recently reviewed by Cordani and Teixeira (2007). The geologic framework of the RNJ province (Figure 1) and the isotopic constraints of its granitoid rocks suggest the important role of juvenile magmatic arcs combined with minor reworking of crustal material formed in previous accretionary phases, in the interval 1.78–1.55 Ga (cf. Tassinari and Macambira, 2004). In addition, the geographic distribution of the ages throughout the province suggests that the accretionary wedges evolved from northeast to southwest (present position), adjacent to the cratonized Ventuari-Tapajós province, or cutting through its marginal zone within an Andean-type tectonic setting. A short time after regional cooling of the RNJ province at ca 1.55–1.50 Ga, the accretionary cycle was resumed, giving rise to the RSI province that occupies large parts of the Rondônia and Mato Grosso States (Brazil) and the Santa Cruz Department (Bolivia). The RSI province is characterized by granitoid rocks with radiometric ages between 1.50 and 1.30 Ga, which in contrast with the juvenile nature of most of the RNJ rocks, were formed in a collisional type environment. This hypothesis is supported by the large shear zones and granulite belts occurring along its northern border with the RNJ province. Regional cooling of the RSI province took place at 1.32–1.31 Ga (e.g., Teixeira et al. 2006).

The RNJ and RSI provinces behaved as a foreland for the collisional-type orogen (1.25–1.00 Ga) that gave rise to the SA province, at the southwestern edge of the Amazonian Craton. The main geologic units of the SA province are low- to medium-grade metamorphic rocks and sedimentary basins originated in an extensional setting (e.g., Sunsas and Nova Brasilândia belts), subsequently subjected to transpression and crustal shortening as a result of the Sunsas orogen (e.g., Litherland et al., 1986; Sadowski and Bettencourt, 1996; Saes, 1999; Santos et al., 2000; Rizzotto et al., 2001).The Sunsas orogeny produced voluminous syn-tectonic plutonism, followed by post-tectonic (e.g., Santa Clara Intrusive Suite, 1.08–1.07 Ga, Rio Pardo Intrusive Suite, 1.05 Ga) and anorogenic intrusions (e.g., Geraldes et al., 2001). The anarogenic Younger Granites of Rondônia (0.99–0.97 Ga) were emplaced within the RNJ and RSI provinces (e.g., Bettencourt et al. 1996, 1999a) (Figure 1). Moreover, sedimentary basins and mafic flows and sills related to extensional tectonics are also present in the SA province. After these plutonic and sedimentary events, the Amazonian Craton attained tectonic stability (Table 1).

The Serra da Providência Intrusive Suite

This is one of the several rapakivi suites (mangerite-charnockite-granite and associated mafic rocks) which occur in northern Rondônia State, RNJ province (Bettencourt et al., 1999a; Payolla et al., 2002; Santos, 2003). The rapakivi granites have subalkaline, slightly peraluminous composition, and exhibit A-type affinities (Bettencourt and Dall'Agnol 1995; Santos et al., 2003; Rizzotto et al., 1995). Diabases, metabasites, gabbroic and metagabbroic dikes, as well as amphibolites are also genetically related to this suite, as deduced from similar radiometric ages, tectonic setting, and field relationships (Payolla et al., 2002).

The Serra da Providência magmatism represents an intrusive event within the already cratonized RNJ crust (e.g., Tassinari et al., 2000), and was emplaced between 1.60 and 1.53 Ga, according to U-Pb zircon geochronology (Payolla et al., 2002). This site is coeval with the Cachoeirinha orogen (1.59-1.52 Ga) that developed farther southeast in the Mato Grosso State (Geraldes et al., 2004). Furthermore, the Serra da Providência rocks were variably affected by metamorphic events (Payolla et al., 2002), as were the host rocks, as a result of the tectonic reflex of the RSI and Sunsas orogenies (e.g., Santos et al., 2000; Teixeira et al., 2006) (Table 1).

The granitic and charnockitic rocks display $\varepsilon_{Nd(T)}$ values from –0.6 to +2.0, suggesting derivation from a mixture of predominantly juvenile sources with a slightly older crustal component (Bettencourt et al., 1999a; Payola et al., 2002). Additional $^{40}Ar/^{39}Ar$ geochronology of eleven selected mafic samples from this suite, including amphibolite, metagabbro, metadiabase and diabase, indicates a minimum estimate age for cooling of these rocks at 1556±6 Ma (see Teixeira et al., 2006).

The Colorado Complex

The Colorado Complex in the northern Rondônia region (Figure 1) is the main magmatic event of the RSI province, and succeeded tectonic stability of the Cachoeirinha orogen (Table 1). The orogenic dynamics involved amalgamation of intra-oceanic arcs and accretionary prisms culminating with continental collision against the SW boundary of the RNJ province (e.g., Teixeira et al., 2006; Cordani and Teixeira, 2007).

The Colorado Complex consists of extension-related (passive-margin basin) amphibolite facies monzonitic gneiss genetically associated with amphibolite, gabbro and metadiabase intercalated with sillimanite schist, paragneiss (metaturbidites) and BIF. The metasedimentary 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 anastomosing portions and boudinage of the amphibolitic rocks, and accompanying the closure of the basin (Rizzotto et al., 2001; 2002). In addition, one high-grade metamorphism overprinted the Colorado Complex which is similarly recognized over large areas of the RSI province (e.g., Payolla et al. 2002, Cordani and Teixeira, 2007), such as over the Rio Crespo Intrusive Suite (1.49 Ga) that occur ca. 700 km to the north in Rondônia (Figure 1).

Based on the comprehensive geochronologic and isotopic database of Rizzotto et al. (2002), Teixeira et al. (2006) and Rizzotto and Quadros (2007), the evolution of the Colorado Complex can be summarized as follows:

SHRIMP U/Pb detrital zircon ages of paragneisses range between 1.35–1.42 Ga. The youngest zircons estimate the maximum depositional age of these rocks, interpreted as originated in a passive margin basin (see above). The coeval monzonitic gneiss yields a Rb/Sr whole rock isochron age of 1.36 Ga, and $\varepsilon_{Sr(T)}$ and $\varepsilon_{Nd(T)}$ values of +6.5 and +1.4, respectively. One metagabbro yields a U/Pb TIMS zircon crystallization age of 1352 +4/–3 Ma. The granitic rocks have SHRIMP U/Pb zircon ages between 1346 and 1337 Ma and show positive $\varepsilon_{Nd(T)}$ values from +2.8 to +2.0. Therefore, radiometric and isotopic data from felsic and mafic intrusives and intercalated metasedimentary rocks indicate their contemporaneity, and short crustal residence for the felsic suite protholith. Furthermore, the available $^{40}Ar/^{39}Ar$ analyses on muscovite from granitic veins and amphiboles from the amphibolites date from 1315±3 to 1327±5 Ma, indicating the age of metamorphic cooling of the Colorado Complex.

The Nova Brasilândia Sequence

The Nova Brasilândia Sequence (Rizzotto et al., 2001, 2002) is assigned to the SA province (Figure 1). Tectonic evolution involved passive margin sedimentation with a maximum depositional age of 1.21 Ga, as supported by the SHRIMP U-Pb ages of the youngest group of detrital zircons (Santos, 2003). The observed strong deformation and high-grade metamorphism of the Nova Brasilândia rocks are contemporary with the onset of the Sunsas orogen (Litherland et al., 1986), and were accompanied by the emplacement of coeval felsic to mafic metaplutonic and plutonic rocks (sills and lenses of gabbro, metagabbro, amphibolite, metadiabase, and A-type granite) (Rizzotto et al., 2001). Nevertheless, an alternative tectonic view for the evolution of the Nova Brasilândia sequence advocates that throughout the SA province, transpressional suturing between Laurentia and Amazonia at ca. 1.10 Ga (see Tohver et al., 2004, 2006) produced strong deformational and metamorphic features, along with emplacement of voluminous magmatic rocks with U-Pb ages in the range of 1.08–1.07 Ga and 0.99–0.92 Ga (e.g., Litherland et al., 1986; Sadowski and Bettencourt, 1996).

According to Rizzotto et al. (2001, 2002), the magmatic evolution of the Nova Brasilândia sequence initiated with coeval gabbroic and monzogranitic magmas emplaced at 1.11 Ga, during an extensional phase of the oceanic lithosphere, giving rise to MORB-like magmas. This is in agreement with isotopic signatures of the most depleted mafic rocks ($\varepsilon_{Nd(T)}$ = +3.1 to +5.0). The felsic rocks give $\varepsilon_{Nd(T)}$ value of -0.4 suggesting contamination from metasedimentary host-rocks ($\varepsilon_{Nd(T)}$ = –3.1 to –4.3). Injection of granitic melts at 1.10 Ga ($\varepsilon_{Nd(T)}$ = –1.5) was contemporaneous with the transpressional regime and crustal shortening of the Nova Brasilândia sequence as a result of the Sunsas orogen, as evidenced by regional EW and WNW-ESE structures, and medium- to high-grade metamorphism. The extensional phase and final orogenic collapse of the Nova Brasilândia sequence was accompanied by emplacement of late- to post-tectonic granites dated at 1.05 Ga ($\varepsilon_{Nd(T)}$ = +0.5).

Nova Brasilândia mafic rocks have $^{40}Ar/^{39}Ar$ plateau ages in the range of 1025 to 982–970 Ma (Teixeira et al., 2006). This age span is comparable with U-Pb (titanite, monazite) ages and $^{40}Ar/^{39}Ar$ ages of the country rocks in the state of Rondônia, indicating regional cooling after tectonic stabilization at 1050 Ma (Tohver et al., 2004). The youngest $^{40}Ar/^{39}Ar$ ages (982–970 Ma) may be related to shearing and mylonitization episodes at a regional scale (Rizzotto et al., 2001; Tohver et al., 2005). However, the latter age data may also reflect thermal influences from the emplacement of the Younger Granites of Rondônia that induced hydrothermal overprinting in their host rocks within the RSI and RNJ provinces (Bettencourt et al., 1999a, b).

Analytical methods

Bulk rock and trace element analyses were carried out at laboratories of the Departamento de Mineralogia e Geotectônica, Instituto de Geociências, Universidade de São Paulo, Brazil and reported in Table 2. Major element determinations were carried out at the X-ray fluorescence laboratory by wavelength dispersive X-ray spectrometery (Philips PW 2400) using fused glass discs according to the procedures described in Mori et al. (1999). Detection limits are on the order of 1–10 ppm. The precisions are better than 2%. Trace element analyses were performed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Samples were dissolved in Parr bombs in a microwave furnace as described by Navarro et al. (2008). Accuracy, determined with respect to the reference standards BHVO-2 and BR, is 0.5–2%. A comprehensive description of the U-Pb and $^{40}Ar/^{39}Ar$ age determinations and Nd-Sr isotopic geochemistry applied to the investigated units, including chemical routines and analytical uncertainties, are reported in Sato et al. (1995), Payolla et al. (2002) and Vasconcelos et al. (2002).

Table 2 Major and trace element analyses of selected samples of mafic intrusions and averaged values with standard deviations (in parenthesis) of the three suites. Legends: Amph. = Amphibolite, Metad. = Metadiabase, Oliv. Gab. = Olivine Gabbro, Oliv. Diab. = Olivine Diabase, Metag. = Metagabbro.

Rock Type	Nova Brasilândia					Colorado					Serra da Providência						
	Amph.	Metad.	Oliv.Gab.	Oliv.Gab.	Average	Oliv.Gab.	Amph.	Amph.	Amph.	Average	Metad.	Metad.	Amph.	Oliv.Gab.	Metag.	Amph.	Average
Sample	RO-1	RO-04B	RO-5	RO-07A		RO-10	RO-14	RO-18	RO-19		RO-33	RO-36	RO-24	RO-25A	RO-25B	RO-26	
SiO_2 (%)	48.42	50.19	49.16	48.1		48.03	47.59	46.42	46.85		49.53	51.43	49.12	47.72	44.24	48.5	
TiO_2	1.496	1.807	1.147	0.377	1.21 (0.62)	0.155	0.662	1.364	1.441	0.91 (0.61)	1.138	2.546	1.265	0.47	3.379	0.175	1.50 (1.23)
Al_2O_3	13.51	13.25	16.24	17.71		22.07	15.67	16.89	19.16		15.44	13.1	13.39	14.86	11.26	15.74	
Fe_2O_3	1.53	1.65	1.21	1.04		0.48	1.28	1.29	1.09		1.37	1.78	1.66	1.34	2.85	1.33	
FeO	11.34	12.25	8.99	7.71		3.57	9.49	9.54	8.11		10.16	13.15	12.3	9.96	21.1	9.92	
FeOT	11.58	12.51	9.18	7.87		3.64	9.69	9.74	8.28		10.37	13.43	12.56	10.17	21.55	10.12	
Fe_2O_3T	12.87	13.9	10.2	8.75		4.05	10.77	10.83	9.2		11.53	14.93	13.96	11.3	23.95	11.23	
MnO	0.192	0.224	0.167	0.141		0.075	0.179	0.167	0.135		0.185	0.205	0.229	0.179	0.322	0.175	
MgO	6.6	6.64	8.99	10.28		7.3	9.04	7.8	5.63		7.56	4.53	7.74	11.24	4.44	7.9	
CaO	11.5	10.94	11.29	11.23		14.73	13.11	13.01	13.25		10.48	8.05	11.58	11.55	9.7	11.23	
Na_2O	2.44	2.43	2.09	1.84		1.59	1.39	2.04	2.72		2.37	2.73	2.14	1.59	2.07	2.69	
K_2O	0.92	0.33	0.28	0.22	0.44 (0.32)	0.08	0.27	0.30	0.37	0.20 (0.13)	0.43	1.5	0.26	0.18	0.17	0.35	0.48 (0.51)
P_2O_5	0.138	0.187	0.115	0.027	0.12 (0.07)	0.008	0.047	0.092	0.134	0.07 (0.05)	0.102	0.385	0.148	0.051	0.229	0.195	0.19 (0.12)
LOI	0.94	< 0.01	0.04	0.56		1.4	1.34	0.84	0.72		0.94	< 0.01	< 0.01	0.6	< 0.01	0.84	
Total	99.03	99.9	99.72	99.24		99.49	100.07	99.75	99.61		99.71	99.41	99.83	99.74	99.76	99.78	
mg#	0.31	0.30	0.44	0.51		0.61	0.43	0.39	0.35		0.37	0.21	0.33	0.47	0.14	0.39	
Rb	17	8.45	10.7	11.8	11.99 (3.62)	15.3	9.73	3.21	11.2	9.86 (5.02)	14.3	37.1	3.70	3.60	2.48	3.8	10.83 (13.60)
Sr	230	105	123	146	151 (55)	211	103	221	223	190 (58)	227	222	147	39.8	144	130	152 (69)
Y	33.0	38.6	26.3	7.52	26.4 (13.5)	3.99	18.0	30.7	35.4	22.0 (14.1)	20.6	46.6	28.9	15.4	36.4	18.6	27.8 (12.0)
Zr	72.7	135	88.2	15.6	77.9 (49.0)	6.59	14.2	81.0	63.0	41.2 (36.5)	65.8	208	78.2	33.8	121	54.9	93.6 (63.1)
Nb	2.54	3.66	2.33	0.21	2.19 (1.44)	0.20	0.77	0.69	2.01	0.92 (0.77)	0.94	5.87	3.39	1.34	5.79	3.45	3.46 (2.10)
Cs	0.48	0.26	0.52	1.21	0.62 (0.41)	0.35	0.44	0.09	0.37	0.31 (0.15)	0.82	1.85	0.08	0.06	0.07	0.07	0.49 (0.73)
Ba	102	93.2	65.1	60.1	80.1 (20.6)	34.4	52.0	25.9	40.0	38.1 (10.9)	99.5	315	55.8	69.6	79.9	121	124 (97)
La	6.45	10.6	7.30	1.99	6.59 (3.55)	0.69	1.44	1.85	2.79	1.69 (0.88)	4.06	17.8	8.57	3.04	9.31	9.88	8.78 (5.26)
Ce	15.4	23.7	17.5	4.54	15.29 (7.98)	1.81	4.31	6.15	7.42	4.92 (2.44)	10.2	40.2	20.6	7.12	22.5	20.7	20.2 (11.6)
Pr	2.39	3.62	2.41	0.59	2.25 (1.24)	0.23	0.71	1.24	1.21	0.85 (0.48)	1.53	6.80	2.93	0.95	3.63	2.71	3.09 (2.06)
Nd	12.3	17.6	11.6	3.04	11.13 (6.02)	1.35	4.17	8.31	8.03	5.47 (3.33)	8.43	31.0	14.0	4.51	17.6	11.6	14.5 (9.2)
Sm	3.83	5.12	3.33	0.89	3.29 (1.77)	0.41	1.51	3.28	3.10	2.08 (1.37)	2.61	7.75	3.85	1.26	4.72	2.62	3.80 (2.27)
Eu	1.21	1.53	1.04	0.47	1.06 (0.44)	0.23	0.58	1.30	1.38	0.87 (0.56)	1.14	2.20	1.32	0.41	1.87	1.10	1.34 (0.63)
Gd	4.87	5.84	3.45	0.95	3.78 (2.13)	0.49	1.79	4.34	4.47	2.77 (1.96)	3.15	7.86	4.49	1.54	5.96	2.78	4.30 (2.31)
Tb	0.88	1.12	0.68	0.17	0.71 (0.40)	<0.1	0.38	0.87	0.86	0.55 (0.38)	0.58	1.37	0.83	0.33	0.99	0.48	0.76 (0.38)
Dy	5.52	6.95	4.50	1.28	4.56 (2.41)	0.69	2.86	5.40	5.42	3.59 (2.28)	3.62	8.07	5.14	2.51	6.13	3.02	4.75 (2.11)
Ho	1.24	1.56	1.04	0.28	1.03 (0.54)	0.14	0.71	1.21	1.25	0.83 (0.52)	0.81	1.75	1.15	0.63	1.39	0.68	1.07 (0.44)
Er	3.43	4.40	2.77	0.78	2.85 (1.53)	0.43	1.99	3.25	3.50	2.29 (1.41)	2.17	4.75	3.14	1.80	3.82	1.95	2.94 (1.18)
Tm	0.54	0.66	0.42	0.10	0.43 (0.24)	<0.1	0.31	0.50	0.55	0.37 (0.20)	0.33	0.73	0.48	0.29	0.60	0.30	0.46 (0.18)
Yb	3.35	4.17	2.71	0.77	2.75 (1.45)	0.42	2.05	3.13	3.50	2.28 (1.38)	2.14	4.47	3.05	1.92	3.80	1.99	2.90 (1.06)
Lu	0.49	0.66	0.42	0.10	0.42 (0.23)	<0.1	0.33	0.48	0.53	0.36 (0.19)	0.34	0.66	0.48	0.31	0.58	0.32	0.45 (0.15)
Hf	2.52	3.84	2.34	0.45	2.26 (1.39)	0.18	0.58	2.25	2.29	1.33 (1.10)	1.76	5.63	2.12	0.96	3.07	1.44	2.50 (1.69)
Ta	0.14	0.27	0.22	0.06	0.18 (0.10)	0.11	0.10	0.10	<0.01	0.08 (0.05)	0.04	0.22	0.38	0.14	0.08	0.18	0.17 (0.12)
Pb	0.31	1.75	2.45	11.1	3.91 (4.88)	0.33	0.91	2.01	2.31	1.39 (0.93)	5.93	5.50	1.75	0.56	0.56	1.60	2.65 (2.43)
Th	1.11	1.71	1.30	0.22	1.09 (0.63)	<0.01	0.05	0.12	0.11	0.07 (0.05)	0.34	2.76	0.22	0.16	0.32	1.02	0.80 (1.00)
U	0.28	0.45	0.35	0.10	0.30 (0.15)	<0.01	0.03	0.18	0.68	0.23 (0.31)	0.15	1.62	0.05	0.05	0.19	0.30	0.39 (0.61)
Eu/Eu*	0.86	0.85	0.93	1.55	1.36 (0.84)	1.57	1.08	1.05	1.13	1.21 (0.24)	1.21	0.85	0.97	0.90	1.08	1.24	1.04 (0.16)

Petrography and geochemistry of the mafic suites

Petrography

The mafic rocks of the Serra da Providência Intrusive Suite include amphibolites, diabases, metadiabases, and gabbros. The amphibolites exhibit granoblastic texture and consist of andesine, hornblende, apatite, opaque minerals, and clinopyroxene. The granulite facies equivalents are characterized by labradorite and two-pyroxene assemblages. The diabases display subophitic texture and are made up of clinopyroxene, plagioclase, brown olivine, apatite and opaques. Within 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 with minor amounts of hornblende.

Intrusive mafic rocks of the Colorado Complex comprise amphibolites, gabbros and metadiabases. The Colorado amphibolites consist of hornblende, plagioclase (andesine-labradorite), apatite, titanite and opaque minerals. The texture is usually granoblastic. The gabbros are composed of plagioclase (labradorite), clinopyroxene, olivine, rare orthopyroxene and opaque minerals. In some of the amphibolites the texture is granoblastic polygonal, suggesting metamorphic re-equilibration. Metadiabases are made up of plagioclase, hornblende, clinopyroxene, orthopyroxene, quartz, apatite and opaque minerals. These rocks display two superimposed textures: the relict original subophitic one, and the granoblastic recrystallized assemblage, composed of plagioclase, hornblende and quartz.

The mafic rocks of the Nova Brasilândia Sequence comprise gabbros, metadiabases and amphibolites. The gabbros display ophitic texture and are made up of plagioclase (labradorite), clinopyroxene, olivine, biotite, and opaque minerals. Olivine is partially altered to iddingsite, whereas hornblende and biotite replace clinopyroxene. Metadiabases are constituted by plagioclase, clinopyroxene, hornblende, apatite and opaque minerals. The original subophitic texture was partially recrystallized, as shown by small grains of newly formed clinopyroxene and hornblende that replace original clinopyroxenes. The amphibolites exhibit nematoblastic texture and consist of plagioclase (andesine-labradorite), hornblende in equilibrium with clinopyroxene, apatite, titanite, quartz and opaque minerals.

Trace element geochemistry

Girardi et al. (2005) previously reported major element geochemistry by XRF analyses of the mafic igneous and metamorphic rocks from the studied units. MPR (molecular proportional diagrams; see Pearce, 1968 and Beswick, 1982) and geochemical trends of mg# [(mg#=atomic Mg/Mg+Fe^2) ratio; assuming Fe_2O_3/FeO= 0.15] versus other elements display preservation of magmatic trends. The AFM diagram shows tholeiitic affinity. Decreasing Al_2O_3, CaO, Cr and Ni, increasing Fe_2O_3, TiO_2, P_2O_5, K_2O, Na_2O, MnO and incompatible trace elements, with decreasing mg# (0.61 to 0.14) and constant Sr content, indicate evolved tholeiitic magmas derived from parental melts through gabbro fractionation. Rizotto et al. (2001) came to similar conclusions by studying mafic rocks of the Nova Brasilândia Sequence.

In order to study the trace element geochemistry of the three investigated geologic units, fourteen selected samples were analyzed by ICP-MS (Table 2). Results show that the Serra da Providência and Nova Brasilândia display similar averaged values higher than those of the Colorado Complex (Figure 2). When compared with patterns and ratios presented by Sun and McDougall (1989) the REE from Serra da Providência and Nova Brasilândia samples are similar to E-MORB, whereas those from the Colorado ones tend to fit N-MORB, as shown also by La/Yb and Ce/Y ratios. Some other ratios display similar behavior (e.g. Zr/Y and Ce/Zr in Serra da Providência, Ti/Y and Ce/Y in Nova Brasilândia, and Th/La in the Colorado

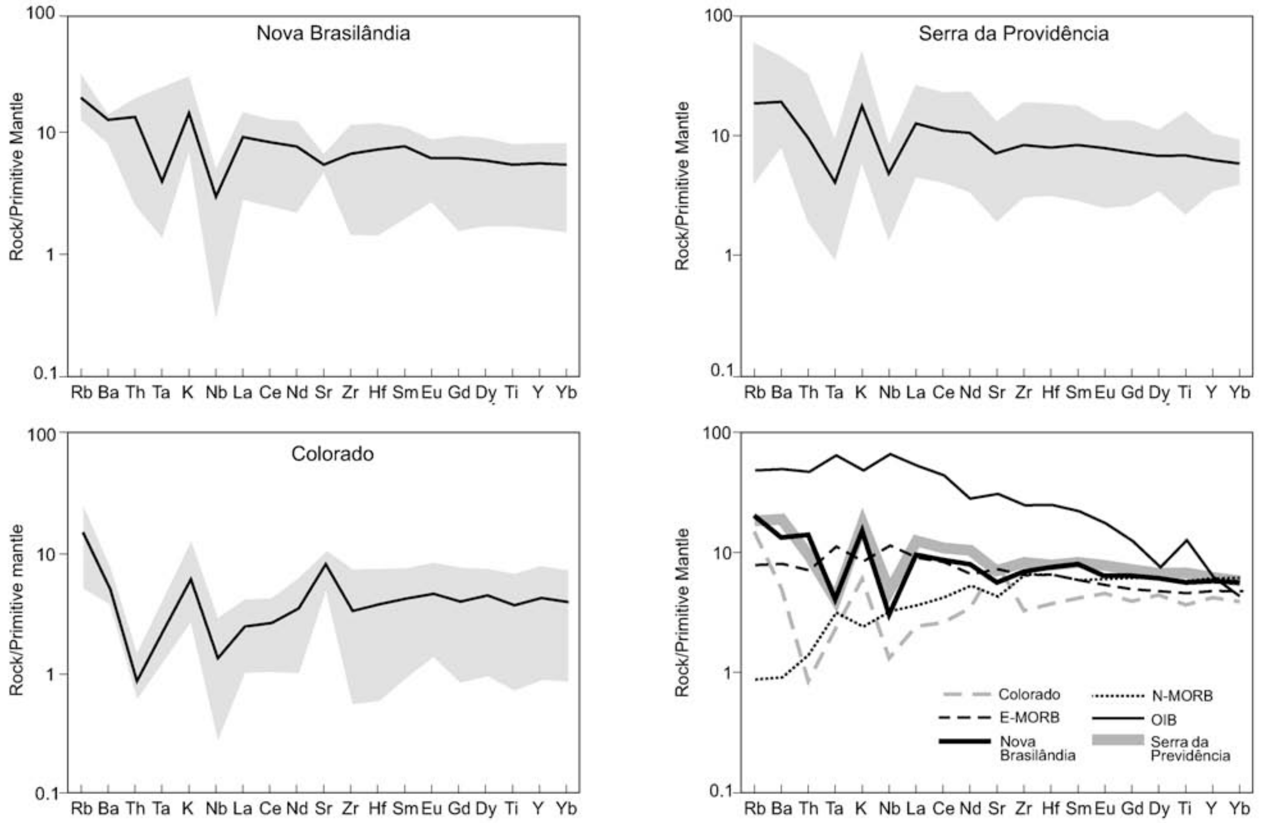

Figure 2 Primitive mantle normalized incompatible element patterns (averaged values and compositional fields) for selected mafic intrusives. OIB, N-MORB, E-MORB and primitive mantle from Sun and McDonough (1989).

unit, cf. Table 3). Some samples exhibit positive anomalies of Sr and Eu likely related to plagioclase crystallization (Table 2 and Figure 2). However, there are strong differences between the three studied units and the E-MORB and N-MORB patterns and ratios due to the presence of pronounced positive spikes of Rb, Ba, K, and remarkable negative peaks of Nb and Ta (Figure 2), which produce high LILE/HSFE and LREE/HSFE ratios (Table 3). These features characterize basalts typical of island arcs and intra-continental settings (e g. Brenan et al., 1994), and can be explained either by melts which experienced crustal contamination in the magma chamber or during ascent through the crust, or else originated from previously contaminated mantle, which underwent metasomatism or recycling of oceanic/continental crust (see discussion below). Table 3 displays also incompatible ratios of the intracratonic swarms from Uauá (Bellieni et al. 1995) and Salvador (Moraes Brito et al. 1989) (São Francisco Craton, Brazil), Goiás (Correa da Costa and Girardi, 2005) (Archean Block of Goiás, Brazil), and Uruguay (Bossi et al. 1993) (Rio de La Plata Craton) for comparison.

Sr-Nd isotopes

Sr-Nd isotopic data for 14 selected samples from the mafic units are listed in Table 4. Initial $^{87}Sr/^{86}Sr$ (Sr_i) ratios as well as $\varepsilon_{Sr(T)}$ and $\varepsilon_{Nd(T)}$ values were calculated assuming ages of 1.55, 1.35 and 1.10 Ga for the Serra da Providência, Colorado and Nova Brasilândia units, respectively. The $\varepsilon_{Sr(T)}$–$\varepsilon_{Nd(T)}$ plots (Figure 3) of 4 Colorado samples lie in the depleted quadrangle field ($\varepsilon_{Nd(T)}$ 0 to +5.2, $\varepsilon_{Sr(T)}$ –30.7 to –5), showing the significant role of the DMM component in their genesis.

The Nova Brasilândia unit (4 samples of the unit) also display positive, but lower $\varepsilon_{Nd(T)}$ values (+0.1 to +1.6) and a larger $\varepsilon_{Sr(T)}$ variation (–2.4 to +34.2). The Serra da Providência Suite (6 samples) forms two distinct compositional fields. The larger group lies close to "Bulk Earth" ($\varepsilon_{Nd(T)}$ –0.9 to +0.2, $\varepsilon_{Sr(T)}$ –3.3 to 11.7), which suggests a "chondritic" affinity, whereas the smaller is near to the Colorado field, and indicates a depleted composition ($\varepsilon_{Nd(T)}$ +2.5 to +2.8, $\varepsilon_{Sr(T)}$ –12.1).

Table 3 Averages and ranges of incompatible trace element ratios for the selected samples of mafic intrusions, compared with OIB, N-MORB, E-MORB (Sun and McDonough (1989) and other dyke swarms: Uauá (Bellieni et al., 1995) and Salvador (Moraes Brito et al. 1989) (São Francisco Craton, Brazil), Goiás (Correa da Costa and Girardi, 2005) (Archean Block of Goiás, Brazil), and Uruguay (Bossi et al. 1993) (Rio de La Plata Craton).

	Nova Brasilândia	Colorado	Serra da Providência	N-MORB	E-MORB	OIB	P.M	Uauá	Salvador	Goiás	Uruguay
Rb/Sr	0.11	0.06	0.06	0.01	0.03	0.05	0.03	0.10	0.09	0.10	0.02
min-max	0.08-0.20	0.01-0.09	0.01-0.17								
Zr/Y	2.78	1.71	3.14	2.64	3.32	9.66	2.46	2	3.70	3.8	7.1
min-max	2.07-2.51	0.79-2.63	2.2-4.47								
Ce/Y	0.59	0.28	0.71	0.26	0.68	2.75	0.26	0.50	0.92	0.79	2.3
min-max	0.47-0.67	0.20-0.45	0.49-1.11								
Ce/Zr	0.22	0.19	0.23	0.10	0.21	0.29	0.1	0.25	0.23	0.20	0.22
min-max	0.18-0.29	0.08-0.27	0.15-0.38								
La/Yb	2.43	0.93	2.95	0.82	2.66	17.12	1.39	2.14	5.32	4	9.2
min-max	1.9-2.7	0.6-1.6	1.6-4.9								
Ti/Zr	106.63	164.57	107.37	103	82	61	90	135.3	93	78.7	68.3
min-max	77.98-145.1	101- 279.1	73.2-167.8								
La/Nb	4.46	2.37	2.77	1.07	0.76	0.77	0.96	1.93	1.1	1.92	1.3
min-max	2.54-9.26	1.39-3.54	1.61-3.03								
Ti/Y	278.71	240.99	335.41	271	273	593	285	234	386	284	478
min-max	261.5-300.5	220.5-266	183.1-331.9								
Ba/La	28.48	15.95	23.11	2.52	9.04	9.46	10.17	19.26	17.40	16.90	15.02
min-max	14.35-19.55	8.81-30.19	6.51-24.48								
Th/La	0.16	0.04	0.11	0.05	0.09	0.11	0.12		0.24		
min-max	0.11-0.18	0.01-0.07	0.03-0.16								

Table 4 Measured Rb, Sr, Sm, Nd, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ values; calculated initial $^{87}Sr/^{86}Sr$ (Sr_i) ratios and $\varepsilon_{Sr(T)}$ and $\varepsilon_{Nd(T)}$ values of selected samples from the mafic intrusions. Serra da Providência Intrusive Suite (1.55 Ga), Colorado Complex (1.35 Ga), Nova Brasilândia Sequence (1.10 Ga).

Sample	Age (Ga)	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$	Sr_i	$\varepsilon_{Sr(T)}$	Sm (ppm)	Nd (ppm)	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd(T)}$
RO-01	1.10	21.85	128.36	0.71080(6)	0.70304	-2.4	4.06	12.62	0.512688(12)	1.3
RO-04	1.10	8.71	121.62	0.70693(3)	0.70367	6.5	5.53	18.28	0.512621(15)	1.6
RO-05	1.10	4.45	111.28	0.70745(4)	0.70562	34.2	3.55	11.65	0.512604(14)	1.1
RO-07	1.10	21.79	172.58	0.71063(6)	0.70487	23.6	5.85	21.82	0.512394(9)	0.1
RO-10	1.35	6.56	222.41	0.70337(1)	0.70172	-17.1	0.48	1.51	0.512747(29)	2.7
RO-14	1.35	7.54	105.86	0.70529(7)	0.70130	-23.1	1.67	4.71	0.512798(14)	0.0
RO-18	1.35	2.70	214.74	0.70327(3)	0.70257	-5.0	3.17	7.78	0.513287(13)	4.1
RO-19	1.35	20.26	262.35	0.70509(6)	0.70076	-30.7	3.39	8.41	0.513321(8)	5.2
RO-24	1.55	4.23	159.41	0.70522(6)	0.70373	11.7	3.39	8.41	0.512367(14)	0.2
RO-25A	1.55	4.29	44.51	0.70872(1)	0.70332	-2.4	3.39	8.41	0.512413(13)	-0.6
RO-25B	1.55	1.57	175.03	0.70379(2)	0.70329	7.5	3.39	8.41	0.512359(11)	-0.5
RO-26	1.55	4.34	294.61	0.70340(3)	0.70258	-3.3	3.39	8.41	0.512002(13)	-0.9
RO-33	1.55	12.43	227.72	0.70535(6)	0.70229	-12.1	2.41	7.66	0.512699(10)	2.5
RO-36	1.55	42.76	263.65	0.71229(8)	0.70320	-12.1	8.05	30.74	0.512393(14)	2.8

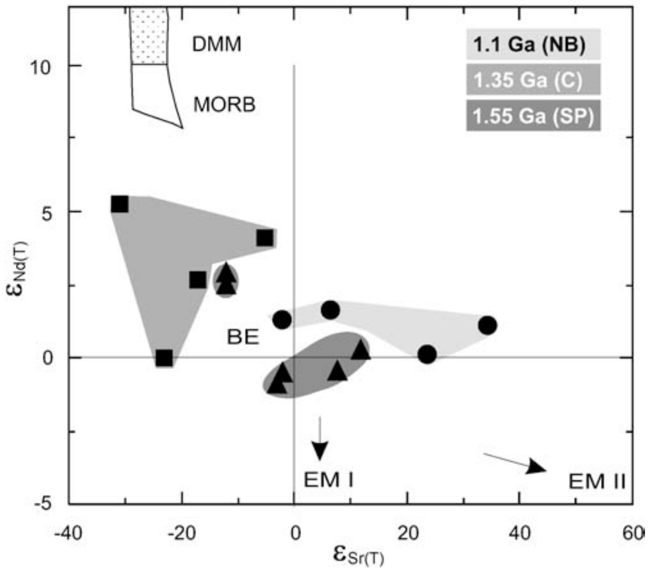

Figure 3 $\varepsilon_{Sr(T)}$ *vs.* $\varepsilon_{Nd(T)}$ ***diagram for samples of the mafic intrusions. Key symbols: Serra da Providência Intrusive Suite – SP (1.55 Ga): triangle; Colorado Complex – C (1.35 Ga): square. Nova Brasilândia Sequence – NB (1.10 Ga): circle. MORB, EMI, EMII after Zindler and Hart (1986) and DMM after Rollinson (1993).***

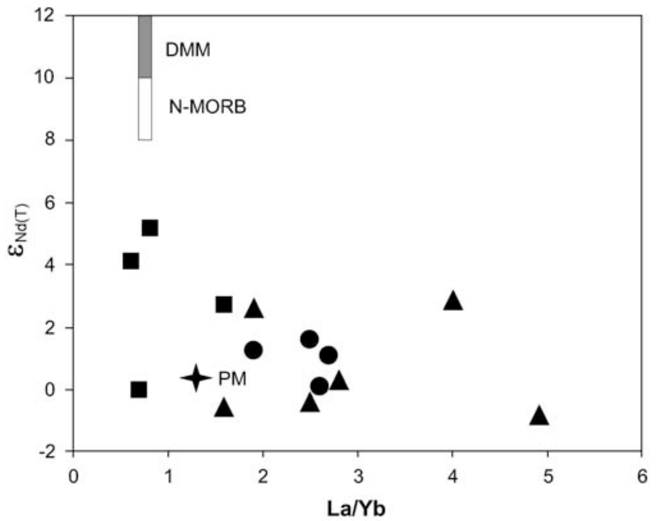

Figure 4 $\varepsilon_{Nd(T)}$ ***vs. La/Yb diagram for selected samples of the mafic intrusions. Symbols, as in Figure 3. PM = primitive mantle, after Sun and McDonough (1989).***

Petrogenetic and tectonic implications

The $\varepsilon_{Nd(T)}$ vs. La/Yb diagram (Figure 4) displays the relationship of trace element and isotopic composition of the investigated units. The Colorado samples have higher $\varepsilon_{Nd(T)}$ and lower La/Yb ratios. Only one sample is slightly displaced to the right of primitive mantle values, thus indicating that the Colorado mafic rocks were the least affected by crustal contamination. The Serra da Providência and Nova Brasilândia units display higher La/Yb ratios, and consequently a larger degree of crustal contamination, as also shown by their respective spidergrams (Figure 2).

One difficult task concerning the petrogenesis of mafic rocks is the determination of whether the contamination occurred within the mantle source, or through assimilation of country-rocks, either in the magma chamber or during the ascent of the magma. In this respect the distinctive correlation between isotopic parameters and element concentration or ratios can be a useful tool.

The Serra da Providência samples do not display either negative correlations between $\varepsilon_{Nd(T)}$ and La/Yb (Figure 4) or positive trends

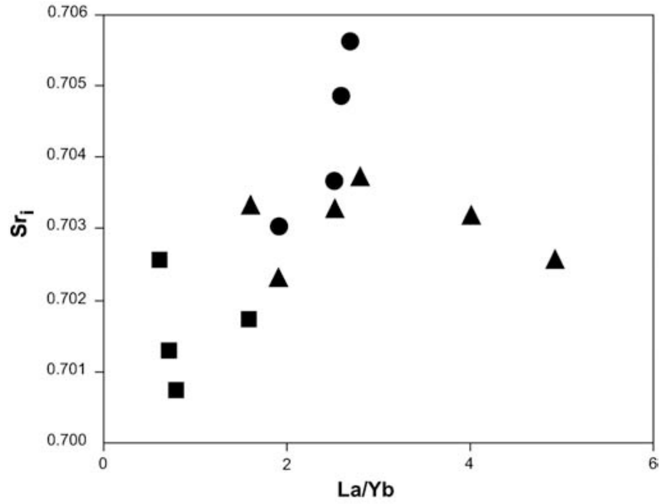

Figure 5 ***Sr_i vs. La/Yb diagram for selected samples of the mafic intrusions. Symbols as in Figure 3.***

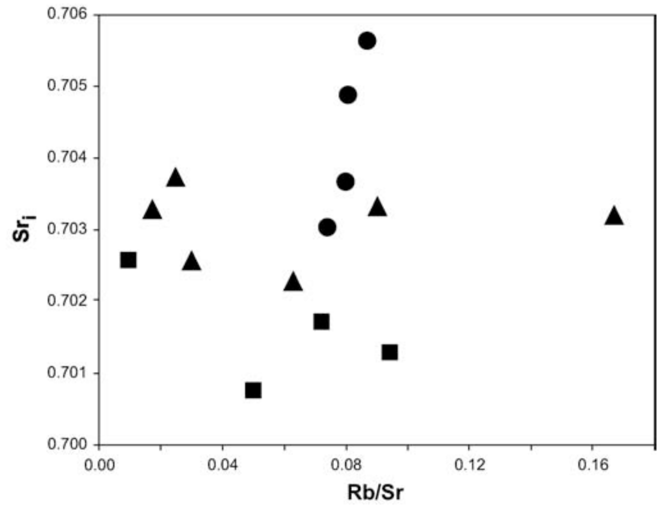

Figure 6 ***Sr_i vs. Rb/Sr diagram for selected samples of the mafic intrusions. Symbols as in Figure 3.***

between Sr_i and La/Yb (Figure 5), and Sr_i and Rb/Sr (Figure 6), as expected during crustal assimilation of older country rocks. However, Rb/Sr variation is quite large (Table 3, Figure 6), in contrast with the virtually constant and low Sri values (Table 4). This likely means that Rb enrichment did not affect Sri values, thus characterizing a decoupling between isotopic parameters, LILE and LREE concentrations. According to Bettencourt et al. (1999a) and Payolla et al. (2002), the Serra da Providência felsic and mafic suites, resulting from bimodal magmatism, are coeval, and their $\varepsilon_{Nd(T)}$ values range from –0.6 to +2.0, and from –0.9 to +2.8 respectively (Table 4). According to Frost (2002), such an isotopic overlap for these mafic and felsic rocks would result from fractional crystallization of mantle-derived magmas.

Alternatively, Haapala et al. (2005) propose that mantle-derived mafic magmas reaching the crust-mantle boundary (underplating) melt part of the lower crust, producing granitic magma. Intrusions of these mafic and felsic melts into higher crustal levels give rise to bimodal magmatism. Bettencourt et al. (1999a) and Payolla et al. (2002) advocate the last model for the origin of the Serra da Providência Intrusive Suite, which would favor a predominance of granitic rocks, as shown by field mapping. The samples lying in the depleted quadrangle ($\varepsilon_{Nd(T)}$ +2.5 and +2.8, Table 4, Figure 3) would represent the least contaminated parental mafic magma. Contamination by acidic to intermediate melts would probably be the main cause for the pronounced Ba, K, Rb, La and Ce positive anomalies of the mafic rocks. Similar $\varepsilon_{Nd(T)}$ ranges of the most contaminated basaltic melts and the granite-charnockite suite suggest a short residence of the melted pre-existent crust, which would account for the decoupling of LREE, LILE and Sri in the basic rocks. As such, the proposed model favors a continental intraplate setting for the Serra da Providência Intrusive Suite.

Coeval mafic and felsic rocks (ca. 1.35Ga) of the Colorado Complex display similar positive $\varepsilon_{Nd(T)}$ values, ranging from zero to +5.2 (Table 4) and from +1.4 to +6.5 (Rizzoto et al., 2002; Teixeira et al., 2006) respectively, which is compatible with derivation in an intra-oceanic environment. Contamination of mafic rocks, although present, is significantly lesser than that observed in the Serra da Providência and Nova Brasilândia samples. These geochemical and isotopic parameters, as well as the contemporaneous sedimentation represented by turbidites with U/Pb zircon detrital ages ranging from approximately 1.35 to 1.42 Ga (Rizzotto and Quadros, 2007), suggest that generation of the Colorado basaltic magma took place after oceanic crust rupture and subsequent rifting. In our view this was followed by oceanic slab subduction below the peridotite wedge (island arc setting), in partial agreement with the original ideas of Rizzotto and Quadros (2007). In this scenario fluids and/or small melt fractions generated from the slab induced metasomatism in the overlying mantle. The observed LILE and LREE enrichment are attributed to overlying sediments (e.g., Weaver, 1991), whereas retention by rutile in the slab eclogites may have produced the observed negative Nb-Ta anomalies (e.g. Cordery et al., 1997; Takahashi et al., 1998; Ayers, 1998; Rivalenti et al., 1998; Leitch and Davis, 2001). Small amounts of rutile (~2%) would be enough to prevent HSFE enrichment in the mantle wedge (Brenan et al., 1994).

The felsic plutonic and coeval mafic rocks of the Nova Brasilândia Sequence intruded metapelitic gneisses and calc-silicate rocks at 1.02–1.10 Ga (Rizzotto et al., 2001; Teixeira et al., 2006). The metasedimentary host rocks display $\varepsilon_{Nd(T)}$ values ranging from -3.8 to -4.3 (Rizzoto, 1999). The $\varepsilon_{Nd(T)}$ data are slightly positive (+0.1 to +0.6 , Table 4, Figure 3), but Rizzoto et al. (2001) report substantial higher values (+3.1 to +5.0) for other Nova Brasilândia mafic rocks. This variation and the large range in $\varepsilon_{Sr(T)}$ values (–2.4 to 34.2, Table 4) indicate significant contamination, which is also supported by trace element data. Sri values correlate positively with La/Yb (Figure 5) and with Rb/Sr ratios (Figure 6), whereas the μNd vs. La/Yb diagram suggests a negative correlation (Figure 4), thus indicating that the mafic melts underwent crustal contamination by older country rocks.

Summarizing, the available isotopic and geochemical data for the Nova Brasilândia Sequence indicate that the original mafic suite is consistent with an oceanic setting with subsequent crustal contamination. These data are compatible with the intrusion of basaltic magmas into metasedimentary rocks including deep-sea and continental sediments during the evolution of a narrow proto-ocean; and are consistent with both models of Rizzoto et al. (2001) and Tohver et al. (2004).

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