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Geochemistry and Sm–Nd isotopic characteristics of bimodal volcanic rocks of Juscelândia, Goiás, Brazil: Mesoproterozoic transition from continental rift to ocean basin

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Abstract

The ca. 1.28 Ga Juscelândia Sequence, in Goiás, Brazil, comprises a unit of bimodal metavolcanic rocks, amphibolite and felsic gneiss, intercalated with metapelite and metachert. The bimodal nature of the magmatism is evident as the metavolcanic rocks have basalt and rhyolite compositions. Bimodality is also shown by the trace elements and Nd isotope data. Amphibolites yield positive $\varepsilon_{Nd}(T)$ values that can be separated into two groups. In the first group, amphibolite samples from lower and middle portion of the sequence are characterized by ε_{Nd} between +2.8 and +5.4. These fairly positive values and enrichment in LREE and LILE suggest they were derived from a depleted mantle source with subsequent assimilation of continental crustal material. The second group is formed by amphibolite of the upper portion of the sequence that have ε_{Nd} around +6.0 and their low LILE and LREE contents resemble normal mid-ocean ridge basalts (N-MORB). Initial $^{143}Nd/^{144}Nd$ ratios represent the composition of the depleted mantle at 1.28 Ga. Felsic rocks yield negative $\varepsilon_{Nd}(T)$ values, between ca. −2.8 and −4.5, and Paleoproterozoic model ages (T_{DM} values in the interval between 1.8 and 2.1 Ga). The original felsic magmas represent the product of melting of older (Paleoproterozoic) continental crust with trace element chemistry indicating that the felsic magmas were the product of continental crustal melts with small mantle contribution. Previous models proposing an oceanic setting for the origin of magmatism of the Juscelândia rocks, within a mid-ocean ridge or back-arc basin are not supported by the data presented here. Transition from a continental rift to an ocean basin represents the most likely tectonic setting for the origin of the Juscelândia rocks.

Keywords: Bimodal volcanism; Juscelândia Sequence; Brazil; Continental rift-ocean basin transition; Mesoproterozoic; Sm–Nd isotope geochemistry

1. Introduction

Bimodal volcanism occurs in associations where two chemically discrete compositional trends are displayed without intermediate compositions, in general, basalt and rhyolite, but lacking andesite. Bimodal volcanism is common in volcano-sedimentary sequences from diverse modern tectonic settings such as intracratonic and intraoceanic basins, continental rifts, continental margins, back-arc basins and in some volcanic arcs. In each of these modern tectonic

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environments, such volcanic activity may give rise to specific features, such as lithological assemblage, geochemical signature and type of associated ore deposits. Nevertheless, for Precambrian volcano-sedimentary sequences characterized by bimodal volcanism, those features may be masked due to the effects of deformation and metamorphism. Such processes can modify the geochemical signatures, and/or the stratigraphic sequence, making the identification of the tectonic setting problematic.

In Central Brazil, the Mesoproterozoic Juscelândia volcano-sedimentary sequence (Fuck et al., 1981; Danni et al., 1984; Moraes, 1992, 1997; Moraes and Fuck, 1994) is characterized by bimodal volcanism. Previous studies have suggested that the Juscelândia amphibolites formed in a mid-ocean ridge environment, largely due to the similarities between the major element geochemistry of these rocks and that of modern normal mid-ocean ridge basalts (N-MORB) (Danni and Kuyumjian, 1984; Winge, 1995). However, minor and trace element concentrations indicate similarity with enriched basalts, such as transitional (T) or plume (P) MORB, suggesting an origin in a back-arc basin (Kuyumjian and Danni, 1991; Moraes, 1992). All previous authors based their studies on the geochemical data of the mafic rocks (amphibolites), and neglected the felsic rocks. The aim of the present study is to investigate the tectonic setting of the Juscelândia Sequence based on geochemical data for both groups of rocks in the bimodal assemblage, with support of new analyses for major, minor and trace elements, as well as Sm–Nd isotopic data.

2. Regional geologic setting

The Juscelândia Sequence is exposed in the central part of a large Neoproterozoic orogen, known as the Brasília Belt, which developed as a consequence of the convergence between the Amazon and São Francisco/Congo cratons at ca. 630 Ma (Fig. 1a and b).

The Brasília Belt largely comprises a thick and extensive supracrustal sequence (mainly metasedimentary) in its eastern part, and a large Neoproterozoic (ca. 900–630 Ma) juvenile arc in the west, which is dominated by calc-alkaline volcano-sedimentary sequences and coeval tonalites and granodiorites (for recent reviews, see Dardenne, 2000; Pimentel et al., 2000).

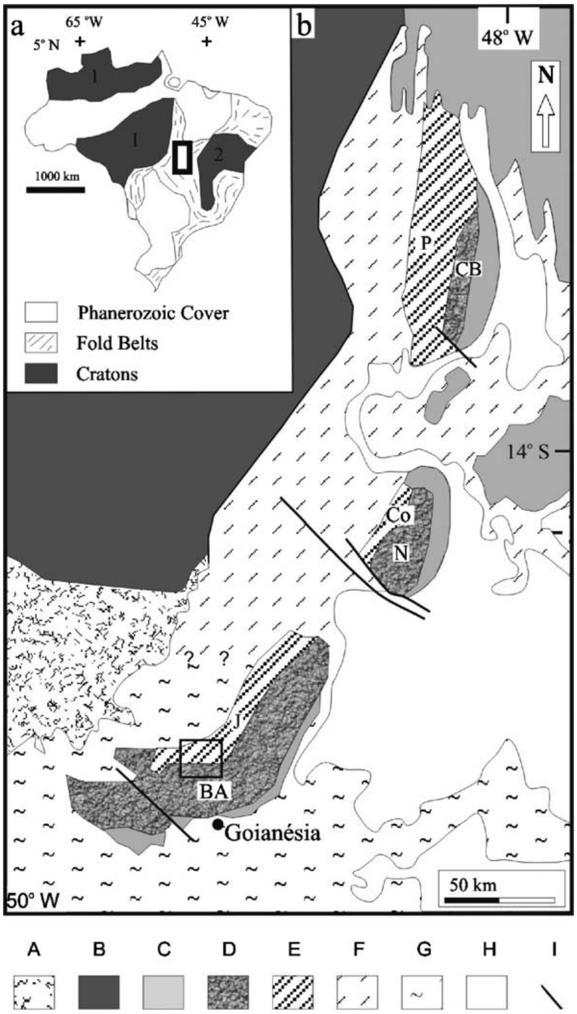

Fig. 1. (a) Main tectonic units of Brazil. 1: Amazon Craton; 2: São Francisco Craton. (b) Northern segment of Brasilia Fold Belt. Modified from Fuck et al. (1994). A: Archean Greenstone Belt and Granite-gneiss terranes. B: Goiás Magmatic Arc. C: Paleoproterozoic granite-gneisses and volcano sedimentary sequences. D: Mafic-ultramafic layered intrusions (BA: Barro Alto Complex; N: Niquelândia Complex; CB: Cana Brava Complex). E: Volcano-sedimentary sequences (J: Juscelândia Sequence; Co: Coitezeiro Sequence; P: Palmeirópolis Sequence). F: Serra da Mesa and Araí Groups. G: Araxá Group. H: Paranoá Group. I: faults.

Exposure of older rocks, such as the Goiás-Crixás Archean Block, the Almas-Cavalcante Paleoproterozoic terrains and three large mafic-ultramafic complexes, is known within the Neoproterozoic orogen (Fig. 1b). One of the most intriguing and debated aspects of the geological evolution of the Brasília Belt is the tectonic significance of the three large mafic-ultramafic complexes and associated bimodal volcano-sedimentary sequences forming a ca. 350 km long NNE trending belt (Fig. 1b). The mafic-ultramafic intrusions are, from south to north, the Barro Alto, Niquelândia and Cana Brava complexes; the corresponding volcano-sedimentary sequences, flanking their western margins, are the Juscelândia, Coitezeiro and Palmeirópolis sequences, respectively (Fig. 1b).

The Barro Alto, Niquelândia and Cana Brava complexes are large layered mafic-ultramafic bodies, which underwent deformation and high-grade metamorphism at ca. 780 Ma (Ferreira Filho et al., 1994; Suita et al., 1994; Correia et al., 1996, 1997). Intrusion ages of these bodies are not well constrained. A Mesoproterozoic age was suggested for the Niquelândia rocks using conventional zircon U–Pb method (Ferreira Filho et al., 1994). More recent SHRIMP and Sm–Nd isochron data for mafic granulites of the three complexes indicate Paleoproterozoic (ca. 2.0 Ga) crystallization ages (Correia et al., 1996, 1997). Observed discrepancies in the ages were thought to be due to the extreme temperatures (>950 °C) reached during regional metamorphism (Ferreira Filho et al., 1998; Moraes and Fuck, 2000), which caused severe Pb loss.

A group of younger layered mafic intrusions occurs at the highest structural level (west) of the Barro Alto and Niquelândia granulitic rocks (Fuck et al., 1981; Danni et al., 1984; Moraes and Fuck, 1994; Moraes, 1997; Ferreira Filho and Pimentel, 2000). Metamorphism in these rocks varies from granulite to amphibolite facies (Moraes, 1997; Ferreira Filho et al., 1998; Ferreira Filho and Pimentel, 2000). In the study area these layered younger rocks are represented by the Cafelândia amphibolite (Fig. 2). U–Pb analyses of zircon indicate that crystallization age for this unit is

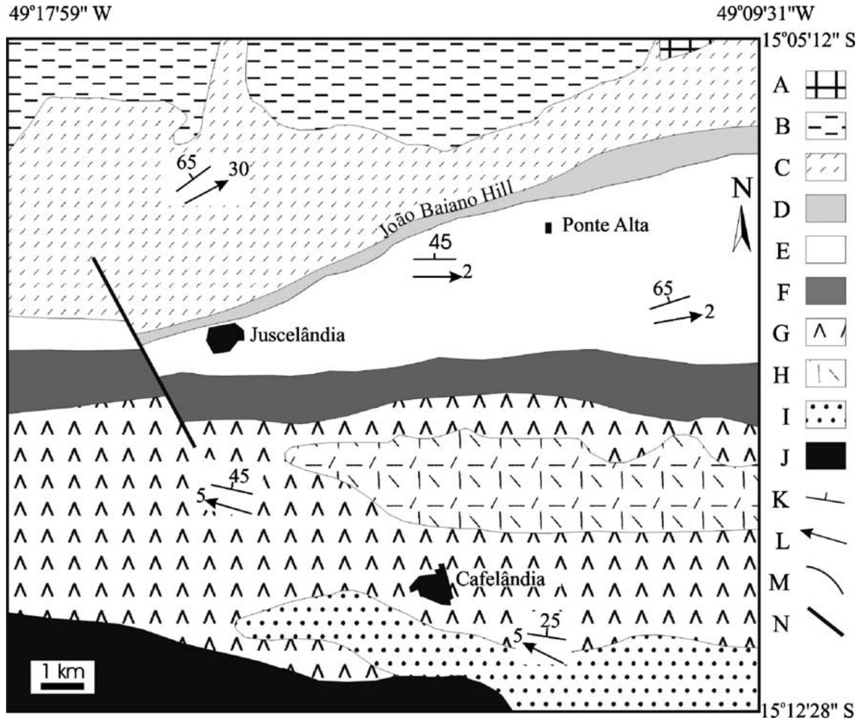

Fig. 2. Geological sketch map of Juscelândia Sequence and part of Barro Alto Complex, including Cafelândia amphibolite. Juscelândia Sequence: A: upper amphibolite; B and C: (sillimanite-kyanite-staurolite) garnet-mica schist; D: biotite-muscovite gneiss with (garnet) amphibolite lenses; E: biotite gneiss with (garnet) amphibolite lenses (probably dikes); F: garnet amphibolite with metachert lenses. Barro Alto Complex: G: banded garnet amphibolite (Cafelândia amphibolite); H: felsic granulite with mafic xenoliths; I: sillimanite-garnet quartzite with lenses of fine-grained mafic granulite and felsic granulites; J: mafic granulites; K: foliation; L: mineral lineation; M: geological contact; N: fault.

ca. 1280 Ma (Suita et al., 1994). In the Niquelândia Complex, correlated rocks known as the Upper Layered Series have Sm–Nd isochron age of ca. 1350 Ma (Ferreira Filho and Pimentel, 2000).

Granitic rocks intruded the layered Barro Alto rocks and these have slightly younger crystallization ages (ca. 1267 Ma) than the Cafelândia amphibolite as indicated by Rb–Sr isochron (Fuck et al., 1989) and zircon ages obtained by conventional and SHRIMP U–Pb determinations (Suita et al., 1994; Correia et al., 1997, 1999). The same ultrahigh temperature metamorphic event that affected the layered mafic-ultramafic body is recorded by the younger layered rocks and granites (Moraes, 1997; Moraes and Fuck, 2000), at ca. 770–820 Ma (Ferreira Filho et al., 1994; Suita et al., 1994; Correia et al., 1997, 1999).

The volcano-sedimentary sequences of Juscelândia, Coitezeiro (Brod, 1988) and Palmeirópolis (Ribeiro Filho and Teixeira, 1980; Araújo, 1986, 1996) form a discontinuous elongated belt of more than 350 km located along the western border of these mafic-ultramafic intrusions Barro Alto, Niquelândia and Cana Brava complexes, respectively (Fig. 1b). All three sequences have a similar stratigraphy, contain bimodal volcanic rocks and were metamorphosed under amphibolite to granulite facies conditions (Moraes and Fuck, 1994, 1999; Brod and Jost, 1991; Araújo, 1996; Ferreira Filho et al., 1999). Rb–Sr isochron data indicate an age of ca. 1330 Ma for the gneisses of the Juscelândia Sequence (Fuck et al., 1989). Pb–Pb isotopic data for galena from a Pb–Zn ore deposit associated with the Palmeirópolis Sequence indicate model ages in the 1170–1270 Ma interval (Araújo et al., 1996). Zircon from a metavolcanic rock from the Coitezeiro Sequence was dated by SHRIMP at 1330 Ma (Correia et al., 1999) and our work in progress on Juscelândia metavolcanics suggests a SHRIMP zircon age of ca. 1.28 Ga. The age of metamorphism seems to be the same as that of the adjacent layered bodies, as zircon grains of Juscelândia gneiss yielded a $^{207}Pb/^{206}Pb$ age of ca. 795 Ma (Sandra Kamo, personal communication).

3. Geology of the Juscelândia Sequence

In the Juscelândia region, the base of the Juscelândia Sequence is in tectonic contact with the Cafelândia amphibolite. This is a metamorphosed layered gabbro, which presents a mineral assemblage constituted of brown hornblende, plagioclase, garnet, clinopyroxene, quartz, and occasional orthopyroxene, attesting to granulite facies conditions during metamorphism (Moraes and Fuck, 1994; Moraes, 1997). The Juscelândia Sequence comprises six lithological units (Moraes, 1997; Moraes and Fuck, 1994, 1999). The lower portion comprises garnet amphibolite with intercalated metachert and calc-silicate rocks, suggesting a subaqueous origin. This is overlain by biotite gneiss, commonly with mylonite texture, and bodies of garnet amphibolite. Some of these amphibolites are narrow tabular bodies with preserved chilled margins and xenoliths of the host biotite gneiss that suggest they represent dikes. Biotite gneiss is homogeneous with respect to its mineralogy and fabric and probably represents metamorphosed felsic volcanic to subvolcanic rocks. In some outcrops, similar biotite gneiss has sodic amphiboles, suggesting derivation from alkaline felsic volcanic rocks; a strong mylonite fabric characterizes this rock. Rare metachert lenses occur within the biotite gneiss. Pelitic schists with kyanite, sillimanite, garnet, staurolite, and mica overly these rocks and contain lenses of amphibolite, biotite-muscovite gneiss and metachert. Feldspathic schist and biotite-muscovite gneiss with bluish elliptical quartz crystals of volcanic origin make up the following unit. Amphibolite intercalations are common. The upper portion of the sequence is dominated by very fine-grained amphibolite (metabasalt) with intercalated metachert lenses.

To highlight differences between their chemical compositions, the amphibolites are separated into three different groups: lower, middle, and upper amphibolites. The following samples were selected to be analyzed: three fine-grained amphibolites from the upper portion (F14-55, F14-77, F14-152); five samples of fine to medium-grained (garnet) amphibolite intercalated with metasedimentary and metavolcanic felsic rocks from the upper-middle portion (RM29e, RM179, RM180, RM184, RM220); five samples of fine to medium-grained (garnet) amphibolite dikes that cut through biotite gneiss (RM40b, RM188, RM191, RM201, RM205) from the lower-middle portion; and two samples of medium-grained amphibolite of the lower portion (RM16b, RM248). Variations in minor and trace elements of Juscelândia felsic metavolcanic rocks were investigated in three samples of biotite gneiss from the lower portion (RM262, RM268, RM293, representing subvolcanic granites), six of biotite-muscovite gneiss and feldspathic schist (metavolcanics, RM22b, RM29a, RM29b, F18-9, F18-32, F18-109) of the lower-middle portion and four of the upper-middle portion (F14-179, F15-56, F15-76, F15-127).

Medium to fine-grained amphibolite from the lower and middle portions is made up of hornblende, plagioclase, quartz, and garnet; ilmenite, titanite, pyrite, apatite, and zircon are accessory phases. Fine-grained amphibolite from the upper portion comprises hornblende, plagioclase, and quartz; ilmenite is an accessory mineral. Feldspathic schist and biotite-muscovite gneiss are medium-grained and contain quartz, plagioclase, microcline, muscovite, and biotite; ilmenite, zircon, and apatite are minor phases and garnet is very rare. The compositional, textural, and modal homogeneity plus the bluish elliptical quartz crystals with corrosion gulfs were features used to suggest a volcanic to subvolcanic origin for these rocks (Moraes, 1992, 1997; Moraes and Fuck, 1994).

4. Analytical procedures

Major and some minor elements were analyzed in the Geochemistry Laboratory of the Universidade de Brasília, using the methodology described by Boaventura and Hirson (1987) and Boaventura (1991). Most of minor and trace elements were analyzed by ICP-AES, Fe was analyzed by volumetry; K and Na by flame emission spectrometry. Rb, Ba, Sr, Y, and Zr were determined by X-ray fluorescence and for some samples (marked with * in Table 1), Sc, Co, Ta, Hf, Th, U and rare earth elements (REE) were determined by instrumental neutron activation. For these analyses, about 100 mg of the sample were accurately weighed in polyethylene vials previously cleaned with a dilute nitric acid solution. Samples and standards were irradiated for 8 h at a thermal neutron flux of $10^{12}\,n\,cm^{-2}\,s^{-1}$ at the IEA-R1 nuclear reactor of the Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN/SP). Geological reference materials GS-N and BE-N (IWG-GIT) were used as standards. Measurements of induced gamma-ray activity were carried out in a GMX20190 hyperpure Ge detector (CANBERRA). The multichannel analyzer is an 8192 channel CANBERRA S-100 plug-in-card in a PC computer. Resolution (FWHM) of the system was 1.90 keV for 1332 keV gamma-ray of ^{60}Co. Two series of counting were performed, the first one 5 days after irradiation, for the determination of La, Sm, Nd, Yb, Lu and U, and the second one 15 days after irradiation for the determination of the other analyzed elements. Counting times varied from 1 to 2.5 h. Gamma-ray spectra were processed using in-house gamma-ray software, which locates peak positions and calculates energies and net areas.

Isotopic analyses were carried out at the Geochronology Laboratory of Universidade de Brasília. Sample dissolution was done in sealed Savillex capsules. Two initial digestions with $HF–HNO_3$ were followed by digestion with HCl 6N. Rare earth elements were separated in cation exchange columns and Sm and Nd were separated by reverse chromatography using columns with HDEHP (di-2-ethyl-hexil phosphoric acid) supported by PTFE Teflon powder. Ln-Spec resin was also used. A mixed tracer solution of $^{149}Sm–^{150}Nd$ was used. Sm and Nd samples were deposited on double Re filaments and isotopic analyses were done in static mode, using a Finnigan MAT 262 mass spectrometer. Uncertainties in Sm/Nd ratios and $^{143}Nd/^{144}Nd$ are considered to be better than $\pm0.01\%$ (1σ) and $\pm0.003\%$ (1σ), respectively. These are based on several analyses of international rock standards BCR-1 and BHVO-1. $^{143}Nd/^{144}Nd$ ratios were normalized to 0.7219 for the $^{146}Nd/^{144}Nd$ ratio. Total laboratory blanks of Nd for all the procedures are lower than 100 pg (Gioia and Pimentel, 2000).

The precision of REE analyses by ICP-AES is between 1 and 2% for elements with concentration five times higher than the detection limits, as observed in the analyzed samples. The accuracy varies between 5 and 15% when values of several international standards are taken into account (as STM-1, BHV01, SCo-1, QLO, SDC-1, RGM-1, BRC-1, SY-2 and SY-3). For instrumental neutron activation accuracy and precision of the results were verified by analysis of reference materials granite GS-N (IWG) and basalt BE-N (IWG). Results agreed with the certified values, showing relative errors between 0 and 7% and good precision (relative standard deviations less than 10%). All samples analyzed by ICP-AES present La/Ce normalized ratio smaller than 1. There seems to be an

Table 1
Major, minor and trace elements for felsic and mafic metavolcanic rocks of Juscelândia Sequence

Amphibolites

	RM16b	RM29e*	RM40b	RM179*	RM180	RM184	RM188*	RM191	RM201	RM205*	RM220	RM248	F29-125	F14-51*	F14-123	F14-41	F14-77*	F14-152*	F14-170
SiO_2	48.82	51.06	46.33	47.03	46.90	46.10	46.01	49.13	45.81	44.99	46.01	44.48	46.45	48.37	48.15	50.10	45.63	49.01	52.91
TiO_2	1.16	2.97	2.74	3.03	2.02	2.47	3.41	2.85	2.23	2.21	2.12	2.83	3.68	2.06	1.35	1.94	2.37	1.16	1.25
Al_2O_3	16.61	10.39	13.22	12.98	15.34	14.25	12.24	12.41	13.66	13.41	14.03	13.30	11.84	13.72	14.50	15.16	15.41	14.87	17.10
Fe_2O_3	1.63	2.14	2.90	0.10	0.85	2.35	4.03	4.07	2.76	3.76	2.04	4.49	6.63	3.92	3.63	1.47	4.17	2.05	0.00
FeO	8.13	13.78	11.95	18.27	12.14	12.47	14.10	13.15	12.82	11.50	13.96	14.37	14.21	10.75	9.78	10.79	12.77	9.32	10.86
MnO	0.13	0.22	0.22	0.24	0.17	0.28	0.20	0.22	0.21	0.20	0.22	0.24	0.31	0.23	0.20	0.15	0.20	0.19	0.06
MgO	5.44	5.43	7.17	4.83	8.52	7.05	5.44	5.06	6.55	7.16	7.24	6.30	6.50	6.57	8.05	7.17	7.10	9.50	3.44
CaO	12.84	8.69	8.76	8.41	10.99	11.91	9.68	8.74	10.26	10.86	9.21	10.25	8.07	9.64	9.81	7.99	9.36	10.37	5.27
Na_2O	2.44	2.28	3.46	2.27	0.80	1.29	2.40	1.97	3.43	3.24	3.01	0.23	0.81	2.74	3.08	3.08	2.41	2.61	1.81
K_2O	0.54	0.42	0.44	0.39	0.45	0.34	0.75	0.62	0.62	0.85	0.41	0.48	0.00	0.10	0.00	1.90	0.13	0.75	3.65
P_2O_5	0.07	0.25	0.22	0.30	0.19	0.20	0.33	0.32	0.18	0.17	0.14	0.21	0.42	0.19	0.12	0.16	0.16	0.13	0.14
LOI	1.29	2.40	2.09	2.39	1.91	1.63	2.02	1.66	1.96	1.60	1.90	2.01	1.58	1.43	1.58	0.39	0.55	0.80	2.56
Total	99.10	100.03	99.50	100.24	100.28	100.34	100.61	100.20	100.49	99.95	100.29	99.19	100.50	99.72	100.25	100.30	100.26	100.76	99.05
#Mg	0.40	0.28	0.38	0.21	0.41	0.36	0.28	0.28	0.34	0.38	0.34	0.30	0.31	0.38	0.45	0.40	0.36	0.50	0.24
Cr	98	39	142	23	250	110	70	36	56	66	96	75				56	44	124	
Ni	55	43	78	35	75	57	39	32	57	55	58	56	59	73		38	48	68	70
Co		46.4		53.6			48.4			55.2				57			69	42.4	
Sc	20	44	37	44	42	42	48	28	23	47	44	44		51			54	48	
V	200	89	360	290	340	480	620	420	240	300	470	580	565	452	357	287	333		
Zn	58	150	100	152	105	147	142	166	137	130	129	160	189	138	109	96	98	98	84
Rb	19	5	11	7	6	8	9	8	7	8	10	10							
Cs																			
Ba	28	35	20	18	17	12	19	22	10	64	16	35	17	53	70	47	112	47	473
Sr	250	110	85	41	190	130	94	110	93	110	44	110	14	138	145	32	141	141	99
Ta							1.8			0.32	0.9			0.35			0.4	0.31	
Nb							16.5				5.3								
Hf		5.23		6.45			5.87			3.05	3.5			2.8			2.9	1.59	
Zr	76	190	160	210	120	120	200	230	120	100	88	110							
Y	23	61	46	50	31	33	53	57	37	33	35	37	61	37	25	32	14	14	13
Th		2.5		4.7			2.3			0.66	0.7			0.53			0.47		
U		0.46		0.91			0.66												
La	3.0	14.2	6.9	18.8	4.9	5.8	16.9	11.9	5.6	5.9	4.4	7.3		6.3			6.3	4.2	
Ce	12.4	36	22.6	45	16.9	20.1	42	33.6	18.2	16.7	12.7	22.2		16.2			17.4	9.5	
Nd	8.45	23.5	18.04	25.7	13.44	14.94	25.8	22.79	14.4	12.1	11.3	15.9		9.8			11	6.4	
Sm	2.47	6.9	5.42	8.4	3.75	4.15	7.9	6.39	4.07	4.4	3.5	4.5		4.1			4.3	2.5	
Eu	0.6	2.1	1.14	2.3	1.0	1.2	2.6	1.5	1.2	1.5	1.3	1.2		1.45			1.6	0.82	
Gd	2.48		5.57		3.91	4.21		6.89	4.34		4.10	5.08							
Tb		1.5		1.4			1.5			1.3				1.1					
Dy	2.6		6.5		4.34	4.5		8.2	4.9		5.0	5.9							
Ho	0.6		1.4		0.94	1.0		1.7	1.1		1.1	1.3							
Er	2.04		4.60		2.90	3.16		5.41	3.31		3.39	4.04							
Yb	1.68	6.1	4.14	5.2	2.39	2.7	7.2	4.88	2.81	3.6	3.07	3.58		4.5			4.44	2.5	
Lu	0.24	0.72	0.55	0.64	0.29	0.34	0.83	0.62	0.35	0.48	0.38	0.45		0.59			0.65	0.34	

Felsic metavolcanic and metasubvolcanic rocks

	F14-179*	F15-56*	F15-76*	F15-127*	F18-9*	F18-32*	F18-74	F18-86	F18-109*	RM29b	RM29a	RM 22b	RM262*	RM268*	RM293*
SiO_2	73.19	73.51	71.25	68.75	58.94	72.50	78.55	75.70	63.77	69.82	71.09	67.39	71.50	73.85	74.31
TiO_2	0.46	0.60	0.66	0.66	1.16	0.75	0.63	0.48	0.90	0.66	0.75	0.66	0.71	0.19	0.60
Al_2O_3	13.08	12.09	12.76	14.07	19.07	13.65	11.07	11.35	17.51	10.72	11.23	12.49	12.85	13.05	13.56
Fe_2O_3	0.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.43	0.59	0.47	0.00	0.00	0.00
FeO	3.02	5.12	5.11	5.49	7.34	4.26	3.16	4.07	5.57	3.97	4.21	3.54	5.51	3.13	3.58
MnO	0.05	0.08	0.07	0.09	0.14	0.08	0.05	0.05	0.13	0.01	0.19	0.08	0.08	0.07	0.05
MgO	1.77	1.68	3.07	3.41	2.28	0.90	0.61	1.02	1.82	1.20	1.36	1.99	1.36	1.39	0.98
CaO	3.49	2.33	0.69	0.72	2.02	1.14	0.50	0.93	1.80	0.98	0.94	2.90	1.13	2.38	1.07
Na_2O	0.35	0.56	0.00	0.00	1.48	0.97	0.46	0.22	2.35	2.96	2.62	1.03	2.30	3.17	2.80
K_2O	3.31	2.24	3.01	3.27	4.76	4.09	3.51	3.41	4.09	4.54	3.54	5.91	3.58	1.53	2.49
P_2O_5	0.09	0.11	0.12	0.14	0.25	0.17	0.14	0.24	0.17	0.08	0.25	0.23	1.15	0.09	0.08
LOI	1.10	0.11	2.85	3.06	2.38	1.59	1.39	2.11	1.52	2.54	2.63	2.49	0.68	0.85	0.65
Total	100.52	98.43	99.59	99.66	99.82	100.10	100.07	99.58	99.63	98.91	99.40	99.18	100.85	99.70	100.17
#Mg	0.37	0.25	0.38	0.38	0.24	0.17	0.16	0.20	0.25	0.23	0.24	0.36	0.20	0.31	0.21
Cr	2	4	3	11	19	14	12	12	16	6	11	10	18	23	22
Ni					5				2	11	19	20			
Co	2.36	5.7	4.9	12.4	4.76	6.3			2.48				7.37	120	83.7
Sc	6.5	16.4	10.8	15.8	23.6	6.3			19	13	12	5	17.2	10.5	10.2
V										89	53	94			
Zn	49	57	178	181	177	213	153	59	237	42	260	41	57	37	44
Rb	167	176	106	181	272	151			212	110	130	150	92	113	107
Cs	6.6	8	3.36	10.4	6.1	3			3.4				0.4	0.36	
Ba	454	455	239	327	763	680	685	595	1209	29	42	80	536	564	547
Sr	18			21	128	77	77	49	81	29	42	80	55	48	61
Ta	1.09	1.1	0.9	0.93	1.42	1.05			1.3				1.2	2.41	2
Nb															
Hf	7.03	8.2	5.9	8.4	13.92	8.17			9.7				12.7	8.7	8.2
Zr										480	580	520			
Y	42	31	16	26	63	48	33	40	51	61	79	140	27	30	36
Th	22.1	13.4	9.79	11.43	20.4	12.1			13.3				19	17.4	17.7
U	5.2	3.2	2.5	2.8	4	2.8			3.6				3.6	3.2	2.8
La	54.5	49	44	13.4	57.8	34.3			27.5	30.9	40.2	38.2	51.9	35.2	46.4
Ce	115	102	90	30	125	78			69	72.3	91.7	75.7	115	95	103
Nd	48	43	40	14.3	58	36			33	39.28	45.09	43.01	50	34	49
Sm	10.1	8.7	8.6	3.7	13.7	8.5			8.2	8.33	9.38	9.95	12.2	7.9	9.3
Eu	1.25	1.5	1.4	0.83	2.6	1.54			1.5	0.8	1.1	1.2	1.9	1.12	1.39
Gd										5.53	6.85	10.25			
Tb	1.31	1.0	1.15	0.68	1.9	1.11			1.38				1.9	0.9	1.3
Dy										2.8	3.7	11.8			
Ho										0.6	0.7	2.51			
Er										1.6	1.9	7.5			
Yb	4.5	4.57	5.05	3.24	7.4	5			6.2	1.85	2.05	6.22	6.3	4.4	4.5
Lu	0.58	0.64	0.67	0.57	0.93	0.63			0.89	0.29	0.31	0.75	0.92	0.57	0.58

Samples marked with (*) have Sc, Co, Ta, Hf, Th, U and REE determined by instrumental neutron activation.

analytical problem with La determination, as samples from other localities analyzed at the same laboratory during the same time presented the same problem.

5. Major elements

The amphibolites have basalt major element compositions except for Na_2O contents; SiO_2 shows a relatively small range throughout the sequence, between 44.5 and 51.1 wt.%. MgO values are between 5.4 and 6.3 wt.% in the lower amphibolites, between 5.7 and 7.5 wt.% in the middle amphibolites and between 6.5 and 8.0 wt.% in the upper amphibolites, although there are some outliers (see Table 1). TiO_2 content is normally higher than 2 wt.%, but varies between 1.1 and 3.4 wt%, with the highest values concentrated in the middle portion and the lowest in the upper portion and Mg # (MgO/(MgO + FeO)) varies between 0.21 and 0.5, with the lowest values being associated with the middle portion and the highest with the upper portion of the sequence (Fig. 3a). In the $SiO_2 \times Na_2O + K_2O$ diagram (Cox et al., 1979) amphibolite samples plot mainly in the basalt field, some in the andesitic basalt field and a few samples plot outside the defined fields (Fig. 3b) due to low alkali contents, probably caused by loss of Na_2O during or before metamorphism. K_2O contents are in the normal range for basaltic rocks (Table 1). Geochemical data suggest that protoliths of amphibolites were sub-alkaline basalts (Fig. 3b) and that crystallization followed a tholeiitic trend (Fig. 3c), as described previously (Danni and Kuyumjian, 1984; Moraes, 1992; Winge, 1995).

As discussed above, petrographic and field features indicate that the felsic gneisses can be divided into

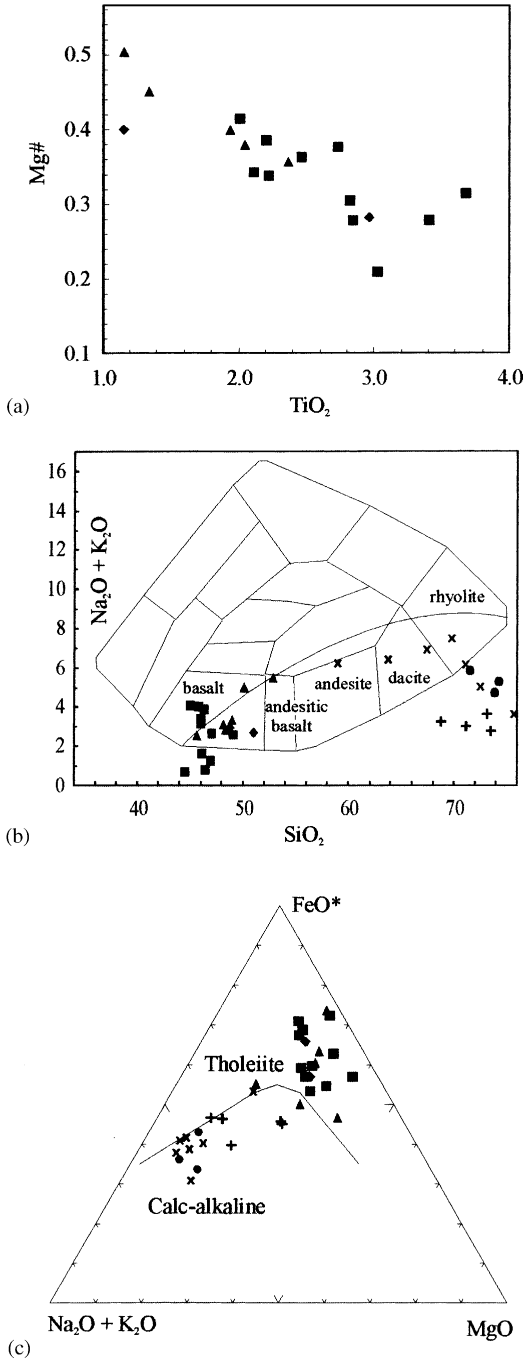

Fig. 3. (a) $TiO_2 \times$ Mg# diagram for amphibolites of Juscelândia Sequence. (b) $SiO_2 \times Na_2O + K_2O$ diagram for volcanic rock classification and subdivision between alkaline and sub-alkaline. The fields were taken from Cox et al. (1979). (c) FeO–MgO–$Na_2O + K_2O$ triagular diagram for definition of tholeiitic and calc-alkaline trends in volcanic rocks; definition of trends as proposed by Miyashiro (1978). ▲, Upper amphibolites; ■, middle amphibolites; ◆, lower amphibolites; +, upper-middle level felsic meta-volcanic; ×, lower-middle level felsic meta-volcanic; ●, lower meta-subvolcanic (biotite gneiss).

metavolcanic and metasubvolcanic groups, but their geochemical characteristics are similar. In the $SiO_2 \times Na_2O+K_2O$ (Fig. 3b) diagram two samples plot in the rhyolite field, one sample plots in the andesite field, while another one plots in the dacite field. Although SiO_2 content is in the range of granitic rocks, between 68.7 and 75 wt.%, some samples have up to 78.55 wt.% SiO_2; most of the samples plot below the rhyolite field (Fig. 3b). This may be due to leaching of alkalis during alteration prior to metamorphism, since many of these rocks are epiclastic deposits, which preferentially lost alkali enriched components during sedimentation. Another possibility is that alkalis were leached during metamorphism.

Intermediate rocks are rare and, in fact, there is no chemical transition between felsic and mafic rocks (Fig 3b). The bimodal character of the volcanic activity in the Juscelândia Sequence is noted by previous workers (Fuck et al., 1981; Danni and Kuyumjian, 1984; Kuyumjian and Danni, 1991; Moraes, 1992; Winge, 1995) and is reinforced here (Fig. 3b).

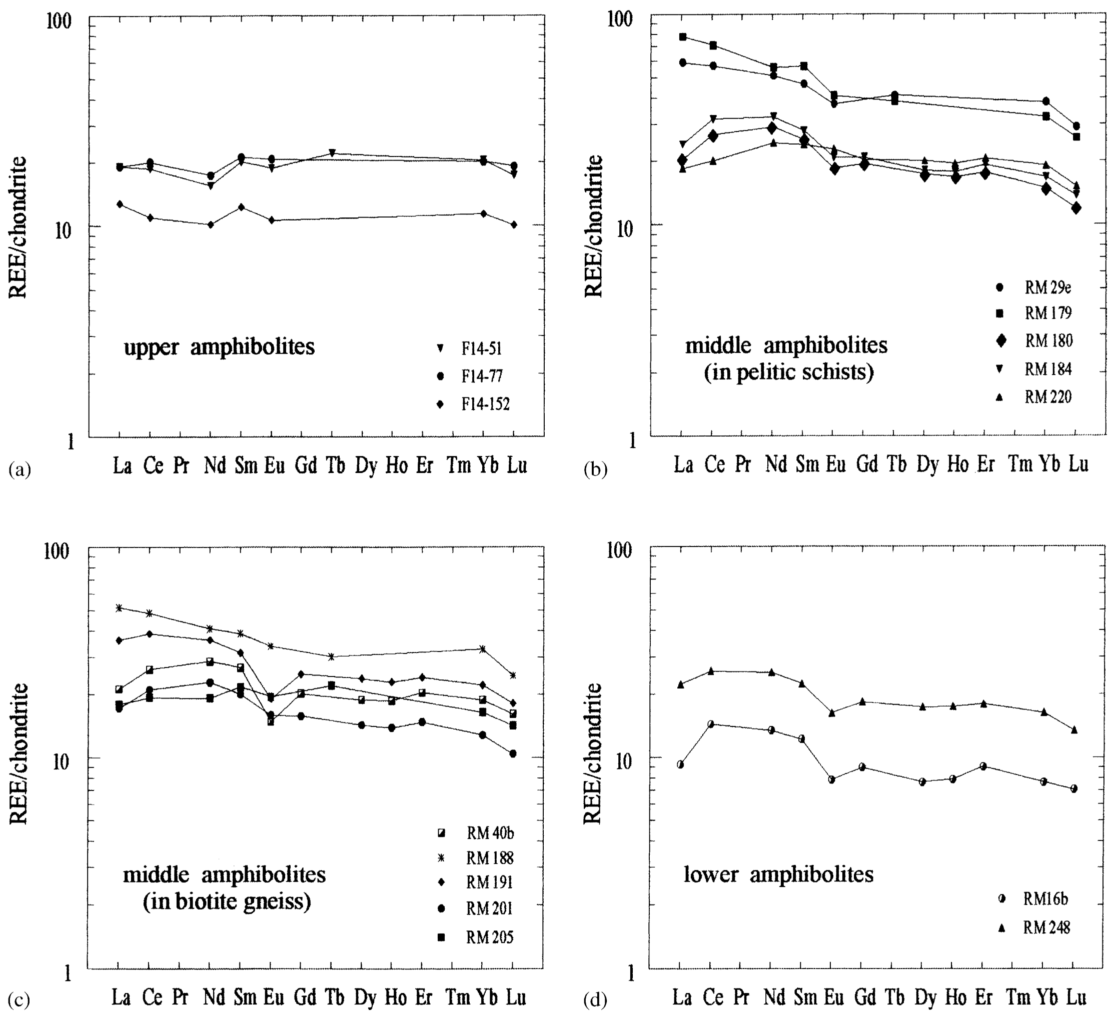

Fig. 4. Chondrite-normalized REE patterns of Juscelândia amphibolites: (a) upper portion amphibolites. Middle portion amphibolites; (b) amphibolite lenses within mica schists; (c) amphibolite lenses within biotite gneiss; (d) lower portion amphibolites. Chondrite normalization values are from Nakamura (1974).

6. Minor and trace elements—amphibolites

Amphibolites of the upper portion are REE-depleted compared to those of the middle and lower portions of the sequence (Fig. 4a–d). Their REE patterns are flat (Fig. 4a), as evidenced by La/Sm_{nc} and La/Yb_{nc} ratios between 0.9 and 1.0. Middle and lower amphibolites are rather similar as a group, with a flat HREE pattern and enrichment in LREE from 10 to 60 times chondrite values. A negative Eu anomaly is present in most samples (Fig. 4b–d). La/Sm_{nc} and La/Yb_{nc} ratios are between 0.7 and 1.2, and 1.1 and 2.4, respectively and show that middle and lower amphibolites are similar to more enriched basalts, like T or P-MORB, as defined by Sun et al. (1979), as La/Sm_{nc} and La/Yb_{nc} ratios for T-MORB are between 0.85 and 1.27 and 1.7 and 4.3, whereas for P-MORB they are between 1.3 and 2.3, and 4.8 and 6.9, respectively (Steinberg et al., 1979; Sun et al., 1979; Hees, 1989; Wilson, 1989).

The flat HREE patterns observed in all samples suggest that melting occurred at shallow depths in the mantle, outside the garnet stability field (Hanson, 1980, 1989; Arndt et al., 1993). The enrichment in LREE recorded in lower and middle amphibolites can be produced by melting of an enriched LREE mantle source, by crystal fractionation or by assimilation of continental crust. The flat REE patterns of upper amphibolites are different when compared to the lower and middle portions, suggesting that a chondritic mantle source was involved in the genesis of upper amphibolites or that no crustal contamination was involved, or both.

The differences between the two groups of amphibolites are also observed in spider diagrams. Large-ion lithophile elements (LILE, such as K, Rb, Th, Na and Ba) exhibit erratic behavior (Fig. 5a–c). Ba is depleted in all samples, whereas Rb and Th are enriched and K shows signs of enrichment in some samples and depletion in others. As some LILE may be mobilized during metamorphism, caution is necessary when trying to trace the original igneous evolution using these elements (Gelinas et al., 1982; Winchester, 1984). High-field-strength elements (HFSE, such as Ti, P, Y, Zr, Ta and Hf), as well as REE, are considered relatively immobile during metamorphism (Knoper and Condie, 1988). Negative Sr, P, Zr, and Y anomalies and positive Ti, Tb, Sm, and Nd anomalies occur in all samples from the lower and middle portions and

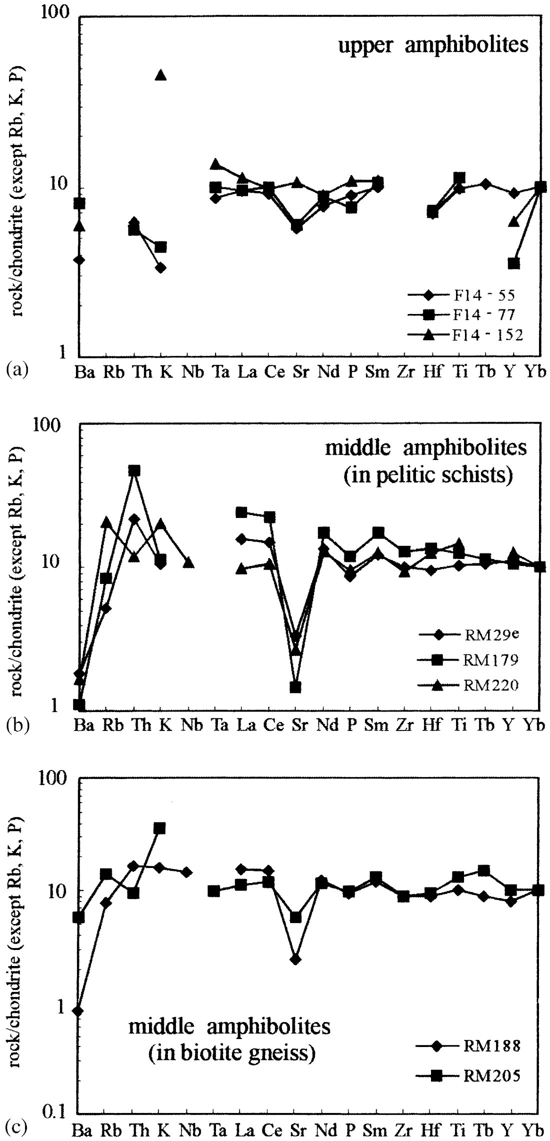

Fig. 5. Double normalized spider diagrams of Juscelândia amphibolites following proposal of Thompson et al. (1984). The elements are normalized first to chondrite (Ba: 6.9, Th: 0.042, Nb: 0.35, Ta: 0.02, La: 0.328, Ce: 0.865, Sr: 11.8, Nd: 0.63, Sm: 0.203, Zr: 6.84, Hf: 0.2, Ti: 620, Tb: 0.052, Y: 2.0, Tm: 0.034, Yb: 0.22, except K, Rb and P, normalized to primitive mantle by Sun (1980); K: 120, Rb: 0.35, P: 46) and a second normalization is done to equal Yb to 10 and the other elements in the same proportion. (a) Upper portion amphibolites. (b) Middle portion amphibolites. (c) Lower portion amphibolites.

a negative Hf anomaly is present in some (Fig. 5b and c). Common crustal rocks that are easily melted have much higher concentrations of LILE and LREE than MORB and ocean island basalt (OIB), although their contents of Nb, Ta, P, Zr, Hf, Ti, Y and middle and HREE are similar to or even lower than these rocks. Assimilation of continental crust can lead to a significant number of negative anomalies in continental basalts, in elements such as Th, Nb, Ta, Sr, and Ti (Thompson et al., 1984). This is observed in tholeiitic basalts of the Paraná Basin, Brazil (Piccirillo and Melfi, 1988), Campos, Santos and Espírito Santo coastal basins, Brazil (Fodor and Vetter, 1984), of the Rio Grande rift, USA (Dungan et al., 1986) and of Deccan, India (Dupuy and Dostal, 1984). Previous studies on Juscelândia amphibolites from the Nova Glória region, to the west of the study area, have demonstrated that spidergrams present negative Ta and Nb anomalies relative to La and Ce, and this feature was used to suggest a back-arc basin setting (Kuyumjian and Danni, 1991), since this is considered to be a typical signature of basalts from convergent settings (Davidson et al., 1991; López-Escobar et al., 1991; Mahlburg-Kay et al., 1991). However, depletion in Ta and Nb is not exclusive to this tectonic environment, being common in continental flood and rift basalts (Thompson et al., 1984; Wilson, 1989; Arndt et al., 1993). Although incomplete, the variation diagrams for the upper amphibolites reveal a flat pattern with LILE depletion and negative Sr, Hf, Y, and P anomalies (Fig 5a). Depletion of LILE and the flat pattern resemble N-MORB.

In the spider diagrams normalized to N-MORB, the upper amphibolites show little fractionation between LILE and HFSE (Fig. 6a). Concentrations of most elements are similar to those of N-MORB's, except for Ba, Th, Ta and Ce, which are slightly enriched. Amphibolites of the middle portion are enriched in K, Rb, Th, Ta, Nb, Ce, and Th in relation to N-MORB (Fig. 6b). HFSE concentrations are two to three times higher than N-MORB and a pattern with a gentle slope between P and Yb is also observed. A large Ba depletion is observed in all samples of lower and middle amphibolites. Cr and Ni are depleted in all samples. Despite the negative Ba anomaly, the N-MORB normalized spidergrams of middle amphibolites are very similar to the patterns of various continental flood and

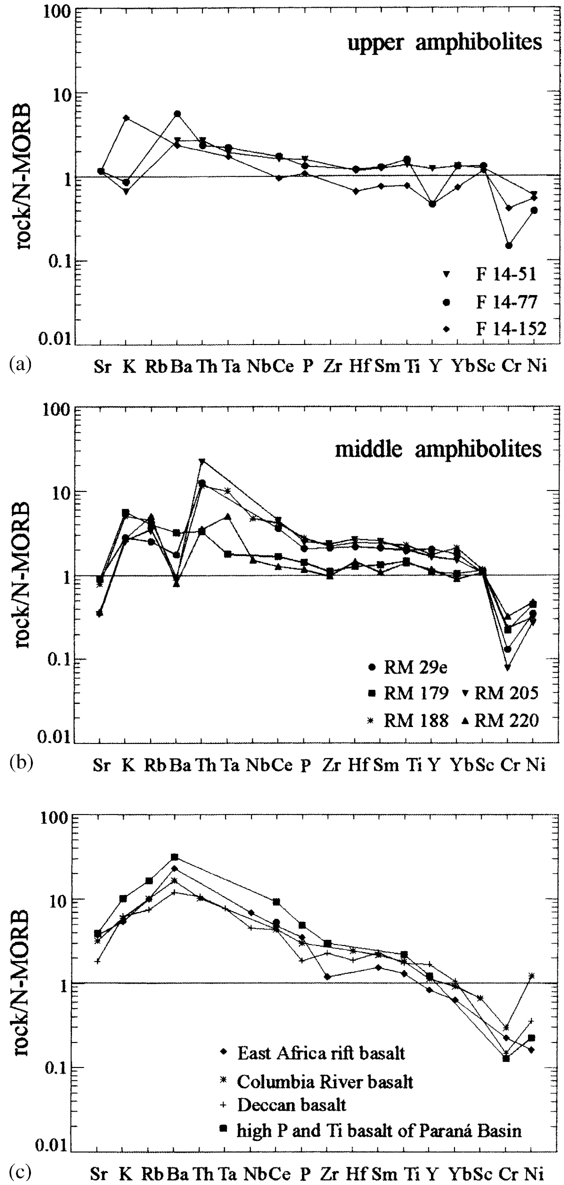

Fig. 6. N-MORB normalized spider diagrams (Sr: 120, K: 1245, Rb: 2, Ba: 20, Th: 0.2, Ta: 0.18), Nb: 3.5, Ce: 10, P: 524, Zr: 90, Hf: 2.4, Sm: 3.3, Ti: 8992, Y: 30, Yb: 3.4, Sc: 40.6, Cr: 296 and Ni: 123) of Juscelândia amphibolites and continental flood basalts following proposal of Pearce (1983). (a) Upper portion amphibolites. (b) Lower and middle portion amphibolites. (c) Continental flood basalts—compositions compiled from Wilson (1989).

rift basalts such as Paraná, Deccan, Columbia River, and East African Rift (Fig. 6c). In summary, the spider diagrams normalized to N-MORB also indicate that lower and middle amphibolites came from an enriched mantle source or their precursor melts were involved with continental material, whereas upper amphibolites were generated by the melting of a depleted mantle source similar to the source of modern N-MORB.

7. Minor and trace elements—felsic metavolcanic rocks

REE patterns of felsic metavolcanic and metasubvolcanic rocks are similar (Fig. 7a–c), except for samples RM29a and RM29b, which are comparatively more depleted in HREE and sample F15-127, which has a lower content of all REE. The REE pattern is fractionated (Ce/Yb_{nc} between 3.9 and 6.5), with concentrations varying between 100 (La–Nd) and 40 (Nd–Sm) times the chondrite value, with a marked negative Eu anomaly and flat HREE pattern, around 10 and 20 times richer than chondrite. Ce/Sm_{nc} ratios vary between 1.9 and 2.8, whereas Ce/Yb_{nc} vary between 3.9 and 6.5, reflecting the steep inclination and enrichment in LREE in the felsic rocks of the Juscelândia Sequence. REE indicate that the protolith of these felsic rocks was generated from a LREE-rich HREE-poor crustal source.

Juscelândia felsic metavolcanics have high LILE/HFSE ratios (Fig. 8a–c). Among the LILE, Rb, K and Th are enriched, Ba is depleted, La and Ce are enriched in relation to Ta; negative Sr, P, and Ti anomalies are prominent. These features are typical of leucocratic continental magmas formed by mixing between continental and mantle melts (Thompson et al., 1984).

Normalization of felsic rocks to ORG, a hypothetical mid-ocean ridge granite (Pearce et al., 1984) is shown in Fig. 9a–c. As a general trend, from K_2O to Yb there is a decrease in normalized values of the elements, with enrichment in Rb and Th in relation to K_2O and Ba. There is a negative break between Th and Ta and a shallower slope until Y, finishing with a negative Yb anomaly. This pattern of the Juscelândia felsic rocks is similar to that of granites formed in thinned continental lithosphere, such as Mull and Skaergaard granites, which were derived from melting of crustal material with some contribution of mantle liquids (Pearce et al., 1984, Fig. 9d).

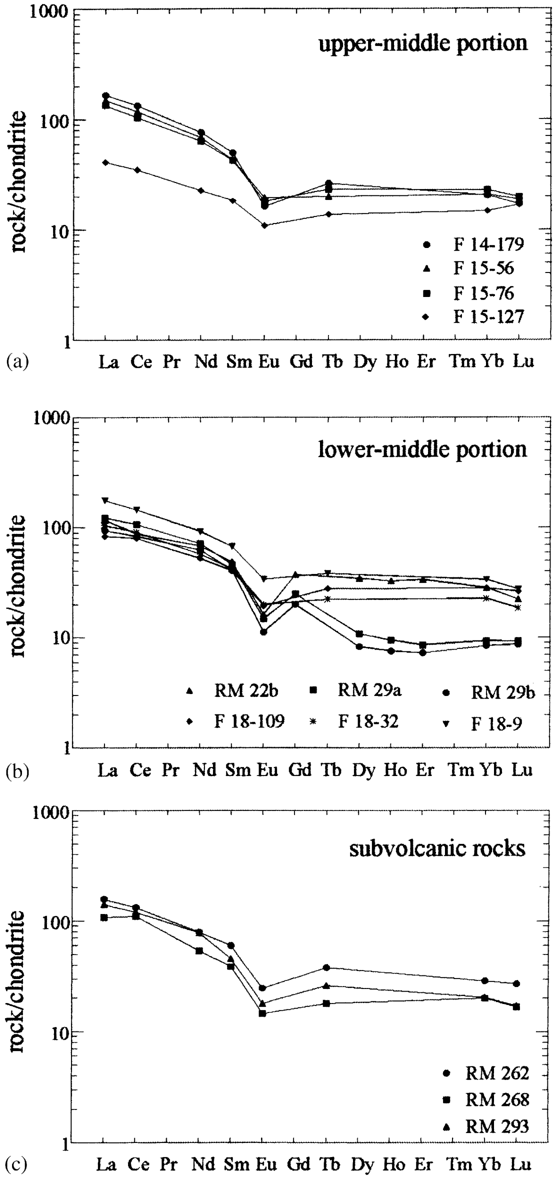

Fig. 7. Chondrite-normalized REE patterns of Juscelândia felsic volcanics: (a) (garnet) muscovite feldspathic schist of upper-middle potion, (b) (garnet) muscovite feldspathic schist of lower-middle portion, (c) biotite gneiss. Chondrite normalization values are from Nakamura (1974).

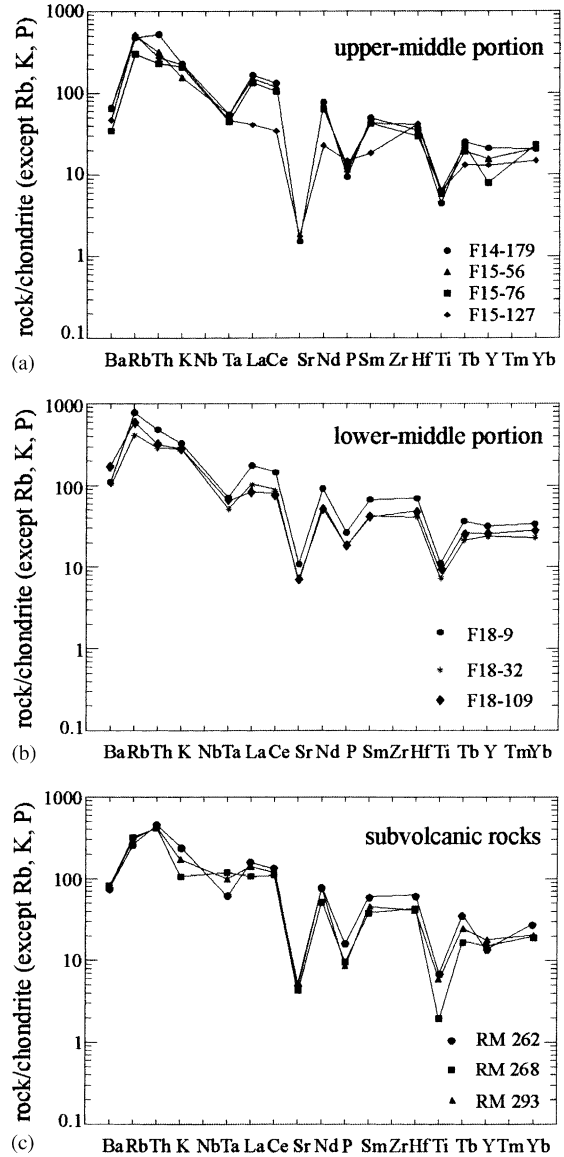

Fig. 8. Chondrite-normalized spider diagrams of Juscelândia volcanics following proposal of Thompson et al. (1984): (a) (garnet) muscovite feldspathic schist of upper-middle portion, (b) (garnet) muscovite feldspathic schist of lower-middle portion, (c) biotite gneiss. Normalization values as Fig. 5.

8. Nd isotopes

Seven samples of amphibolite and six of felsic metavolcanic rocks (including one granulite facies granite) were analyzed for Nd isotopes. For comparison, one sample of kyanite-staurolite-garnet-biotite schist of the Juscelândia Sequence and one sample of the Cafelândia amphibolite were also investigated (Table 2). Initial isotopic compositions for the individual samples are listed in the form of the $\varepsilon_{Nd}(T)$ for the age of 1.28 Ga, the best available crystallization age for these rocks, as discussed previously.

The bimodal nature of the magmatism is clear from the data (Table 2). Felsic rocks yield negative $\varepsilon_{Nd}(T)$ values, between ca. −2.8 and −4.5, and Paleoproterozoic model ages (T_{DM} values in the interval between 1.8 and 2.1 Ga—all calculations based on model of De Paolo, 1981), and, therefore, the original felsic magma may be interpreted as the product of melting of older (Paleoproterozoic) continental crust. $\varepsilon_{Nd}(T)$ values for the mafic rocks range from +2.8 to +5.5, indicating derivation from a depleted mantle reservoir (Fig. 10). The highest $\varepsilon_{Nd}(T)$ values (+6.0 and +5.7) correspond to amphibolite samples of the upper portion of the sequence (Fig. 10), which are compatible with their more primitive geochemical nature. Amphibolites from the lower and middle portions of the sequence display $\varepsilon_{Nd}(T)$ between +2.8 and +4.5. The isotopic composition of the Cafelândia amphibolite ($\varepsilon_{Nd}(T) = +4.2$) also falls within this interval. These values are similar to those found for equivalent leucotroctolite and amphibolite of the Niquelândia Complex, +4.8 and +4.1, respectively (Ferreira Filho and Pimentel, 2000).

The large spread in $\varepsilon_{Nd}(T)$ values for the Juscelândia amphibolites is interpreted here as the product of varying degrees of contamination with Paleoproterozoic crust (Fig. 10). Amphibolites of the upper portion of the sequence have high Sm/Nd ratios and the highest $\varepsilon_{Nd}(T)$ values, whereas amphibolites of the lower and middle portions define a trend towards lower $\varepsilon_{Nd}(T)$ values accompanied by a decrease of the Sm/Nd ratios. Such a pattern is compatible with greater degrees of crustal contamination of the mafic magmas during the early stages of magmatism of the Juscelândia Sequence.

Variation in the T_{DM} ages of the felsic metavolcanics is accompanied by an increase in Sm/Nd ratios, in the way that younger T_{DM} values correspond to lower Sm/Nd ratios (Fig. 11), what is compatible with fractionation of the Sm/Nd ratio during crystallization. In the $\varepsilon_{Nd}(T) \times$ time diagram (Fig. 12), it is shown that there is a cross-over of most of the felsic samples near $\varepsilon_{Nd}(T) = -3.5$ and 1.3 Ga (Fig. 12). This is, in fact,

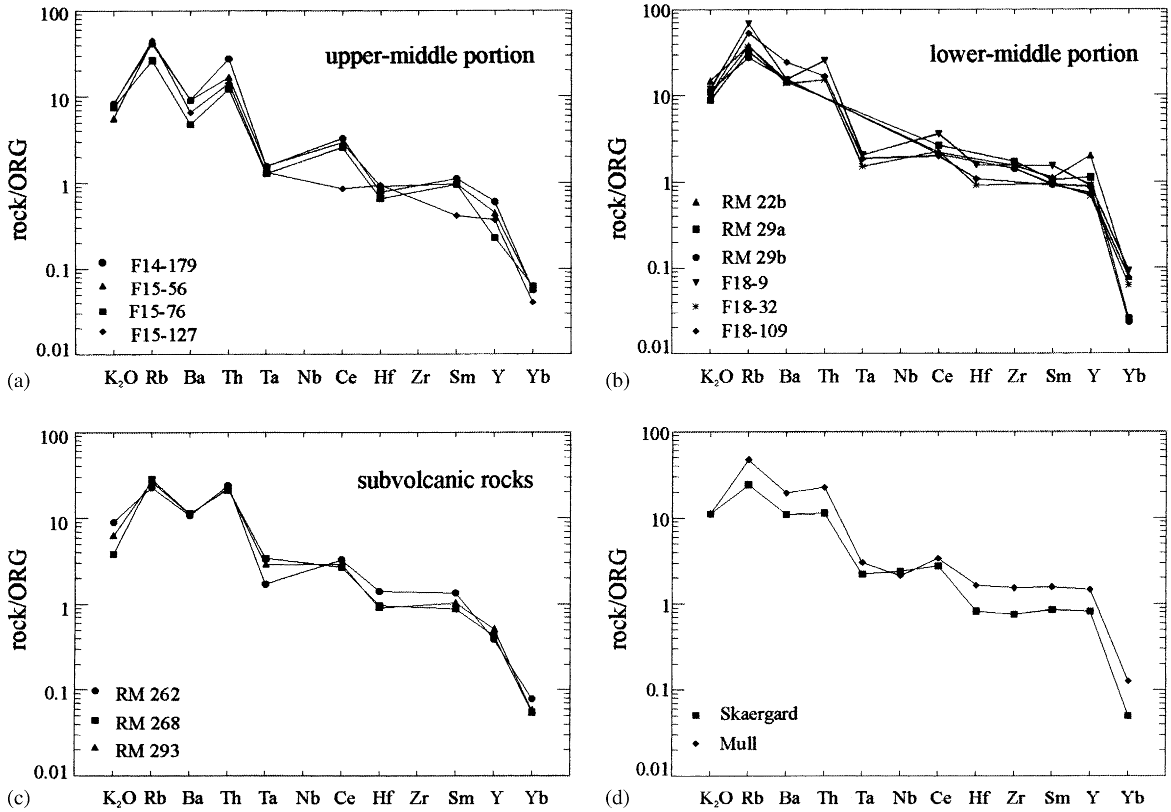

Fig. 9. ORG-normalized spider diagrams (K_2O: 0.4, Rb: 4, Ba: 50, Th: 0.8, Ta: 0.7, Nb: 10, Ce: 35, Hf: 9, Zr: 340, Sm: 9, Y: 70 and Yb: 80) of Juscelândia felsic volcanics following proposal of Pearce et al. (1984): (a) (garnet) muscovite feldspathic schist of upper-middle portion, (b) (garnet) muscovite feldspathic schist of lower-middle portion, (c) biotite gneiss, (d) Skaeergard and Mull granites—compositions compiled from Pearce et al. (1984).

a result of the near isochronous relationship among the felsic samples and reaffirms the common initial Nd for the felsic gneiss. It means that each sample is probably related to the others through magmatic fractionation producing variable $^{147}Sm/^{144}Nd$ ratios with the same initial value. In this context, it is interesting to note that sample F15-56 would represent the most fractionated magma with a $^{147}Sm/^{144}Nd$ ratio of 0.10, whereas F15-127 would be representative of the least fractionated magma with a ratio of 0.14.

Although there is a good spread of Sm/Nd ratios for the data set of the Juscelândia mafic volcanic rocks (amphibolites), the contamination process hampers the determination of a reliable Sm–Nd isochronic age for these rocks. However, when the data set of the Juscelândia meta-felsic volcanic rocks plus the felsic granulite of Barro Alto Complex are taken into account, the slope of a poorly constrained regression line (MSWD = 5.0) indicates the age of 1.28 ± 0.15 Ga (1σ), with $\varepsilon_{Nd}(T)$ of -3.5 (Fig. 13). This age is similar to a Rb–Sr isochronic age previously determined for these rocks (Fuck et al., 1989), as well as the negative value for the initial Nd isotopic composition that is consistent with the high initial $^{87}Sr/^{86}Sr$ ratio (0.70819) observed for these rocks (Fuck et al., 1989).

The isotopic composition of the metasediment sample is similar to the less fractionated felsic volcanic rocks (initial $^{147}Sm/^{144}Nd$ ratio $\approx$0.14). It has a Paleoproterozoic model age (2.13 Ga), most probably indicating erosion of the same or similar Paleoproterozoic rocks which melted to give rise to the siliceous magmas of the Juscelândia rhyolites. The similarity of the initial $^{147}Sm/^{144}Nd$ ratios between metasedimentary and less fractionated felsic volcanic

Table 2
Sm and Nd concentrations Nd isotopic composition and depleted mantle model ages for Juscelândia and related rocks

Sample	Rock type	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{144}Nd/^{143}Nd$	ε_{Nd}(1.28 Ga)	T_{DM} (Ga)
Felsic rocks							
F15-56	Metavolcanic	9.369	57.565	0.0989	0.511660	−2.81	1.80
F15-127	Metavolcanic	6.038	36.592	0.1373	0.511931	−3.92	2.12
F18-9	Metavolcanic	11.984	54.950	0.1318	0.511924	−3.14	2.00
F18-109	Metavolcanic	9.695	49.179	0.1192	0.511836	−2.75	1.89
RM268	Meta subvolcanic	7.641	35.160	0.1314	0.511921	−3.73	2.00
RM293	Meta subvolcanic	9.203	42.740	0.1302	0.511894	−3.46	2.02
RM75	Pelitic schist	7.061	30.311	0.1408	0.511982	−3.51	2.12
Amphibolites							
F14-51	Upper portion	4.009	12.147	0.1995	0.512969	+6.00	
F14-77	Upper portion	4.695	14.809	0.1916	0.512887	+5.72	
RM220	Middle portion	3.924	11.717	0.2024	0.512964	+5.42	
RM188	Middle portion	7.842	27.254	0.1749	0.512597	+2.83	
RM29e	Middle portion	7.071	24.498	0.1745	0.512660	+4.13	
RM16b	Lower portion	2.778	9.150	0.1835	0.512800	+5.37	
RM2OS	Lower portion	4.794	15.018	0.1940	0.512894	+5.45	
Other units							
RM 570	Barro Alto felsic granulite	4.051	22.940	0.1066	0.511642	−4.45	1.94
803-135	Cafelândia amphibolite	4.720	14.797	0.1931	0.512824	+4.23	
Standards							
La Jolla					0.511853		
JM					0.512255		

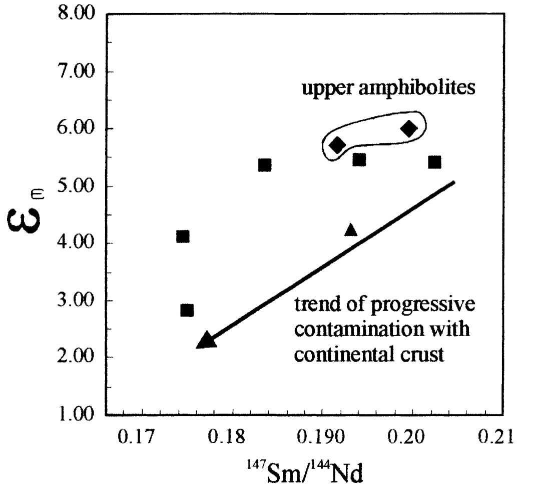

Fig. 10. $\varepsilon(T) \times {}^{147}Sm/^{144}Nd$ ratio in Juscelândia and Cafelândia amphibolites. Contamination by continental crust leads to lower values for $\varepsilon(T)$ and $^{147}Sm/^{144}Nd$ ratio. ◆, Upper amphibolites; ■, middle amphibolites; ▲, Cafelândia amphibolite.

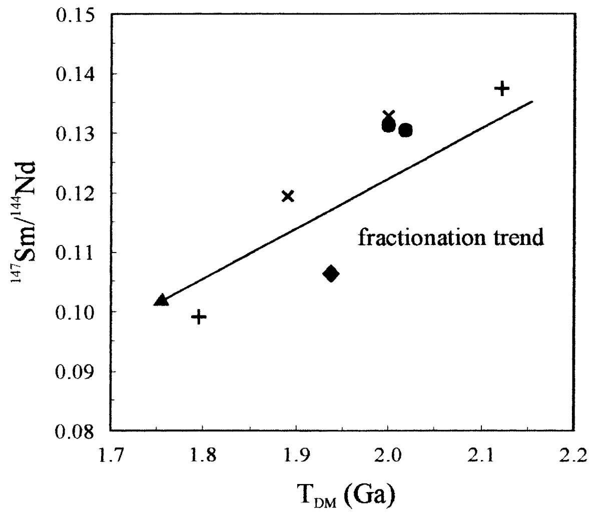

Fig. 11. $^{147}Sm/^{144}Nd \times$ model ages ($T_{(DM)}$ in Ga) for Juscelândia felsic metavolcanic rocks interpreted as derived from melting of a Paleoproterozoic continental crust. More fractionated rocks present higher $^{147}Sm/^{144}Nd$ and older models ages. +, Upper-middle portion felsic volcanic; ×, lower-middle portion felsic volcanic; ●, felsic subvolcanic rocks; ◆, Barro Alto felsic granulite.

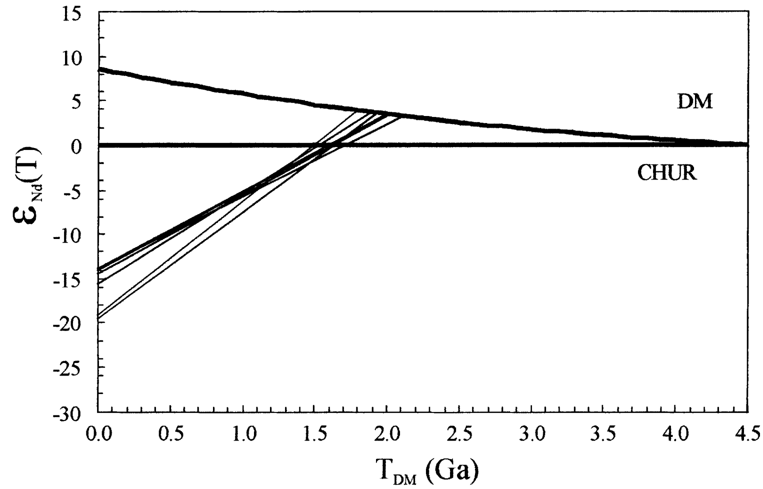

Fig. 12. Nd evolution diagram for Juscelândia felsic volcanics. Model ages indicate that source was Paleoproterozoic. All evolution lines cross each other at ≈ 1.3 Ga, showing their near isochronous relationship.

rocks may be explained by the character of the Paleoproterozoic basement observed regionally, which is mainly composed of granitic rocks and smaller amounts of sedimentary and volcanic rocks.

The isotopic data suggest that the mafic volcanic rocks of the Juscelândia Sequence formed in the Mesoproterozoic in response to melting of depleted mantle. The mafic magma invaded the Paleoproterozoic

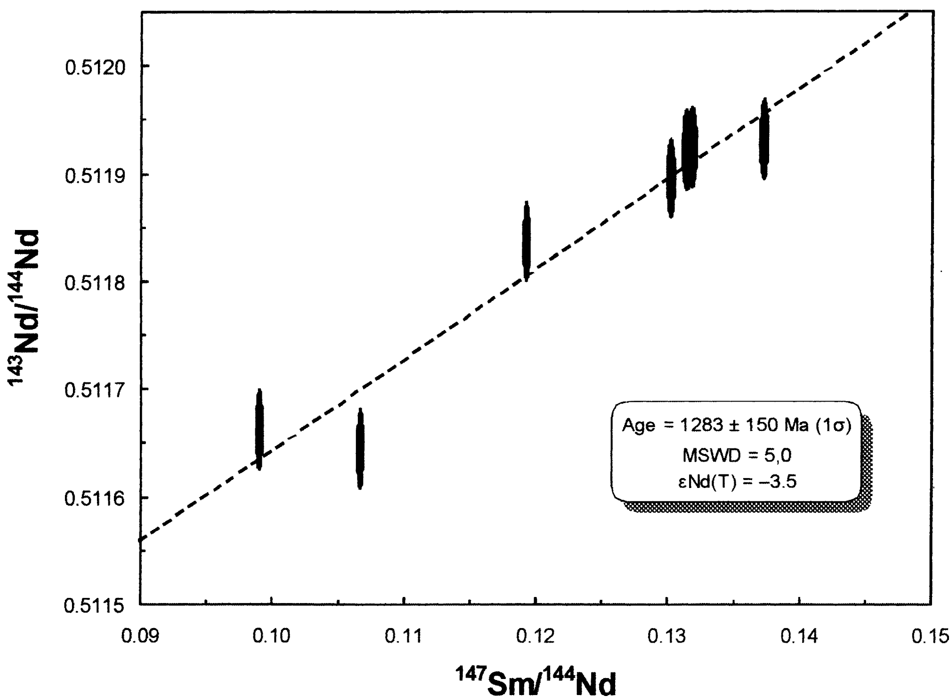

Fig. 13. Errorchron made with felsic metavolcanic rocks of Juscelândia sequence plus a sample of felsic granulite of Barro Alto Complex yielded an age of ca. 1.28 Ga.

continental crust and the advective heat transfer promoted extensive crustal melting and formation of the felsic end member of the Juscelândia Sequence.

9. Tectonic setting

In summary, the Juscelândia Sequence consists of a bimodal volcanic association, with pelitic and chemical sediments. Coarse-grained detrital rocks have not been recognized; felsic metavolcanic and subvolcanic rocks have geochemical characteristics typical of granites formed in thin continental crust, by mixing of melts derived mainly from continental crust material with small contribution of mantle material. T_{DM} model ages indicate that the continental source of melting and sedimentation was predominantly Paleoproterozoic. Juscelândia amphibolites can be divided into two distinct geochemical groups: lower and middle amphibolites are the product of metamorphism of tholeiitic basalts originated by melting of a less depleted mantle source or by melting of depleted mantle but incorporating some continental crust contamination, resembling modern continental flood and continental rift basalts. The protoliths of upper amphibolites were generated by melting of a strongly depleted mantle source, similar to that of modern N-MORBs.

Previous studies on the geochemistry of Juscelândia and Palmeirópolis amphibolites proposed that the protoliths of amphibolites were extruded in a mid-ocean ridge environment (Danni and Kuyumjian, 1984; Araújo, 1986, 1996; Winge, 1995; Araújo et al., 1996) or in a back-arc basin (Kuyumjian and Danni, 1991; Moraes, 1992). A mid-ocean ridge was also suggested as the most likely environment for plutonic mafic rocks of the Upper-Layered Series (equivalent to Cafelândia amphibolite) in the Niquelândia Complex (Ferreira Filho and Pimentel, 2000). However, the volcano-sedimentary sequences and their possible plutonic counterparts of Goiás have geological features that are inconsistent with mid-ocean ridge or back-arc basin settings. Bimodal volcanism is not common in mid-ocean ridges, although it can occur in some back-arc basins. Felsic volcanic rocks, as well as abundant anorthosites and leucotroctolites are not common in mid-ocean ridges either. The late crustal granites that cut almost all the rocks in the area and seem to be coeval with or slightly younger than mafic rocks (Cafelândia amphibolite and correlated rocks) are also inconsistent with a mid-oceanic ridge setting. All proposed mid-ocean ridge or back-arc basin models were based exclusively on the geochemical signature of the amphibolites or plutonic equivalents, and no data from the felsic rocks were considered. The back-arc basin model is based on negative Ta and Nb anomalies in relation to La and Ce (Kuyumjian and Danni, 1991), but this feature is not exclusive of back-arc basin settings, being also common in continental tholeiitic basalts (Thompson et al., 1984; Arndt et al., 1993). Therefore, an alternative tectonic setting that explains all the observed characteristics must be considered.

A continental rift is the geological setting that provides appropriate conditions for the origin of the Juscelândia Sequence and related plutonic rocks. During opening of the rift system, the hot underlying mantle melted due to decompression. The mafic magma intruded into the continental crust. Its crystallization formed the protolith of Cafelândia amphibolite and related rocks (anorthosites, coronitic gabbros, leucogabbros, etc). Batches of melt that reached the surface erupted as the Juscelândia basalts. The heat from the mafic magma induced melting of surrounding lower continental crust, resulting in granitic intrusions and felsic volcanism, and giving rise to the bimodal volcanic association. The continental rift system evolved until opening of an ocean basin, where N-MORB-like magma was extruded.

The observed sedimentary record, however, represents an important problem for the continental rift model. Metasedimentary rocks of Juscelândia are schists, calcsilicate rocks or metachert, basically products of metamorphism of pelite and chemical sediments, which are not typical of rifts. Conglomerates and sandstones should be expected, at least at the base of the sedimentary pile, but they are absent from the Juscelândia Sequence. These rocks might have been tectonically suppressed during the exhumation stage, since it has been demonstrated that the contact between the base of Juscelândia Sequence and the Cafelândia amphibolite is a fault zone, across which a metamorphic gap of at least 2 kbar (equivalent to ca. 7 km of crust) occurs (Moraes, 1997; Moraes and Fuck, 1994, 1999). South of Cafelândia (Fig. 2), there is a lens composed of sillimanite-garnet quartzite, fine-grained mafic granulite and meta-granite, which was interpreted as roof-pendant of the Barro Alto layered rocks (Fuck et al., 1981). An alternative explanation for these rocks is that they could represent a dismembered part of the Juscelândia Sequence and, at least, some of these quartzites could be part of the coarse-grained rift phase sedimentation. As the quartzite was severely recrystallized, its possible detrital character was erased. This possibility needs to be assessed through more field and isotopic data. On the other hand, there are modern rift examples which also lack coarse-grained sediments. For instance, geological structure of the Iberian and Newfoundland coasts (Whitmarsh et al., 2001), formed during the opening of the Atlantic Ocean, is marked by gabbros and associated rocks pre-dating the extrusion of voluminous amounts of MORB, which are, in turn, covered by deep-sea sediments. This situation seems very similar to the Juscelândia Sequence geology and correlated plutonic rocks.

10. Conclusions

Previous Rb–Sr and U–Pb geochronological data and, to a certain extent, the Sm–Nd data presented here, suggest that the metavolcanic rocks of the Juscelândia Sequence and their plutonic correlatives (small granite intrusions and the Cafelândia amphibolite) crystallized at ca. 1.3 Ga (Fuck et al., 1989; Suita et al., 1994; Correia et al., 1996, 1997, 1999; Ferreira Filho and Pimentel, 2000). The Sr isotopic data of Fuck et al. (1989) have also pointed out the high initial $^{87}Sr/^{86}Sr$ ratio of the felsic metavolcanics (i.r. ≈0.70819), which is compatible with their negative $\varepsilon_{Nd}(T)$ (averaging −3.5) and Paleoproterozoic Nd model ages. The data indicate that the original magma of the felsic rocks, therefore, represents reworking of older continental crust with small contribution of mantle melts in their genesis. On the other hand, $\varepsilon_{Nd}(T)$ values for the mafic rocks are positive, varying between +2.8 and +6.0. The large spread of $\varepsilon_{Nd}(T)$ is interpreted as the product of varying degrees of contamination with crustal material. Amphibolites of the lower and middle sections of the sequence have been contaminated, with $\varepsilon_{Nd}(T)$ values between +2.8 and +4.5, whereas mafic rocks of the upper part of the sequence are the most primitive ($\varepsilon_{Nd}(T) = +5.7$ and +6.0) and represent the best estimate for the isotopic composition of the depleted mantle at 1.3 Ga. Similar conclusions can be drawn from REE and other trace element features of the Juscelândia rocks.

Nd isotopic composition of the Cafelândia amphibolite ($\varepsilon_{Nd}(T)$ of ca. +4.2) falls within the interval defined by the lower and middle amphibolites, and suggests that it represents the layered plutonic equivalent of the basal volcanic rocks. This value is also similar to those found for equivalent leucotroctolite and amphibolite (metagabbro) of the Upper Layered Series in the Niquelândia Complex, +4.8 and +4.1, respectively (Ferreira Filho and Pimentel, 2000).

Magmatic activity that produced the Juscelândia Sequence and associated plutonic counterparts occurred most probably in a continental rift setting, which started to be active at ca. 1.3 Ga. It is possible that the rift system evolved until the opening of a narrow and long oceanic basin. Whether this progressed into the development of a large ocean basin with formation of a passive margin sedimentary sequence (Paranoá and Canastra groups, for example) is, at this stage, a matter for further investigation.

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