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The 1590-1520 Ma Cachoeirinha magmatic arc and its tectonic implications for the Mesoproterozoic SW Amazonian craton crustal evolution

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ABSTRACT

Isotopic and chemical data of rocks from the Cachoeirinha suite provide new insights on the Proterozoic evolution of the Rio Negro/Juruena Province in SW Amazonian craton. Six U-Pb and Sm-Nd analyses in granitoid rocks of the Cachoeirinha suite yielded ages of 1587-1522 Ma and T_{DM} model ages of 1.88-1.75 Ga (Epsilon$_{Nd}$ values of –0.8 to +1.0). In addition, three post-tectonic plutonic rocks yielded U-Pb ages from 1485-1389 Ma (T_{DM} of 1.77-1.74 Ga and Epsilon$_{Nd}$ values from –1.3 to +1.7). Variations in major and trace elements of the Cachoeirinha suite rocks indicate fractional crystallization process and magmatic arc geologic setting. These results suggest the following interpretations: (1) The interval of 1590-1520 Ma represents an important magmatic activity in SW Amazonian craton. (2) T_{DM} and arc-related chemical affinity support the hypothesis that the rocks are genetically associated with an east-dipping subduction zone under the older (1.79-1.74 Ga) continental margin. (3) The 1590-1520 Ma age of intrusive rocks adjacent to an older crust represents similar geological framework along the southern margin of Baltica, corroborating the hypothesis of tectonic relationship at that time.

Key words: Amazonian craton, U-Pb and Sm-Nd geochronology, Mesoproterozoic, juvenile magmatism.

INTRODUCTION

The Amazonian craton represents a key region for reconstruction of Meso- and Paleoproterozoic continents. To understand its geological framework and crustal evolution is, therefore, essential for such reconstruction models. Hoffman (1991) and Dalziel (1992, 1997) suggested that Amazonia amalgamated with Laurentia-Baltica to form Rodinia supercontinent as a result of the worldwide 1.1 to 1.0 Ga melting event. Others authors have also interpreted Amazonia as the continent which collided with Laurentia-Baltica (e.g. Moores 1991, Unrug 1996) at that time.

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Alternatively, Sadowsky and Bettencourt (1996) suggested that Amazonia was already joined to Laurentia-Baltica at 1.6 Ga. However, Amazonia became an isolated continental mass during the Mesoproterozoic rifting (probably correlated to the break-up of the Columbia supercontinent, according to Rogers (1996). This extensional event is probably coeval with the Pinwarian orogeny (1.51-1.45 Ga), reported by Gower and Tucker (1994) in the Grenville Province, followed by a complete Wilson cycle which led to further agglutination to Laurentia-Baltica and formation of Rodinia. There is a lack of paleomagnetic information in Amazonia between 1.6 Ga and 1.4 Ga. However, recent paleomagnetic data (Tohver et al. 2002) support juxtaposition of SW Amazonia with Laurentia-Baltica at ca. 1200 Ma and D´Agrella et al. (2000) reported paleomagnetic data indicating another collision at 1000 Ma.

The ages, structures, and compositions of the rock units and orogenic events within Amazonia are not well known, in spite of significant recent studies (Bettencourt et al. 1999, Tassinari et al. 2000, Geraldes et al. 2001). In order to improve the knowledge of the SW portion of the Amazonian craton, this paper presents new U-Pb ages, Sm-Nd isotopic results and chemical data on granitoids constraining the nature of the Mesoproterozoic plutonic rocks that crop out in SW Mato Grosso State (Brazil). Furthermore, the implications for the Mesoproterozoic crustal formation in SW Amazonian craton are discussed providing potential tectonic correlation between Amazonia and Laurentia-Baltica at 1.59-1.52 Ga.

THE AMAZONIAN CRATON

The Amazonian craton consists of five NW-SE trending Proterozoic provinces that developed adjacent to an Archean core (Teixeira et al. 1989, Tassinari and Macambira 1999, Santos et al. 2000). Recent U-Pb geochronology supported by Nd isotopic mapping defined the 2.25-2.00 Ga Maroni-Itacaiúnas Province (MIP) and the 2.00-1.80 Ga Ventuari-Tapajós Province (VTP) (Tassinari et al. 1997, 2000, Tassinari and Macambira 1999). The slightly younger Rio Negro-Juruena Province (RNJP) is dominated by granitic, granodioritic, tonalitic gneisses and migmatites with crystallization ages varying from 1.80 Ga to 1.63 Ga and Pb, Nd and Sr isotopic data also indicate that it is a juvenile accretionary province (Tassinari et al. 1997, 2000, Tassinari and Macambira 1999, Geraldes et al. 2001). VTP rocks are locally overlain by ca. 1.8-1.7 Ga felsic to intermediate volcanic rocks (Neder et al. 2002).

The Rondonian-San Ignácio Province (RSIP) is parallel to and outboard of the RNJP and consists of accretionary juvenile material formed from 1.58 Ga to 1.36 Ga (Tassinari et al. 2000, Tassinari and Macambira 1999, Geraldes et al. 2001) strongly affected and reworked by metamorphic events at about 1.34 Ga (Tassinari et al. 2000), 1.20 Ga (Tohver et al. 2002), and 1.11 Ga (Rizzotto, personal communication). Several suites of 1.6 to 1.0 Ga undeformed plutons with rapakivi characteristics intrude the RNJP. This spectrum could be grouped in 6 periods: 1.61-1.53 Ga, 1.41 Ga, 1.39 Ga, 1.35-1.31 Ga, 1.31-1.30 Ga, 1.0-1.08 Ga (Bettencourt et al. 1999).

Alternatively, Santos et al. (2000) suggested a new configuration for the geochronological provinces of SW Amazonian craton. In this proposition, Santos et al. (2000) renamed the Rio Negro-Juruena, suggesting the name Rio Negro for the rocks above the Amazonas river, and Juruena-Rondonian for the Rio Negro-Juruena sensu Tassinari and Macambira (1999). In this paper we use the SW Amazonian craton division according to Tassinari and Macambira (1999).

The ca. 1.0 Ga Sunsás Province occurs west of the Rondonian/San Ignacio Province in Bolivia (Litherland et al. 1989) and includes the Sunsás and Aguapeí groups, comprised of low-grade to undeformed supracrustal sequences, and the high grade metamorphic rocks of the Nova Brasilândia Group (Rizzotto, personal communication). These sedimentary rocks locally overlie the basement of the Rio Negro/Juruena and Rondônia-San Ignacio Pro-

TABLE I

A time-correlation table showing the synthesis of the major juvenile accretionary events, anorogenic plutonism and sedimentation of the SW Amazonian craton in Mato Grosso state.

Rio Negro/Juruena Province		Rondonian/San Ignácio Province		Sunsás Province
Alto Jauru orogen	Cachoeirinha orogen	Rio Alegre orogen	Santa Helena orogen	Aguapeí Thrust
Tonalites and granites formed between 1.79-1.75 Ga, in arc-related tectonic setting				
	Tonalites and granites formed between 1.59-1.52 Ga, in arc-related tectonic setting			
		MORB, BIF and cherts (1.51 Ga). Tonalites and granites formed between 1.79-1.75 Ga, in island arc tectonic setting		
Intracontinental magmatism, (rapakivi granites and related mafic roks) 1.47-1.43 Ga			Granodiorites and granites formaded between 1.45-1.42 Ga, in arc-related tectonic setting	
Aguapeí Group deposition (< 1.1 Ga)	Aguapeí Group deposition (< 1.1 Ga)	Aguapeí Group deposition (< 1.1 Ga)	Aguapeí Group deposition (< 1.1 Ga)	Aguapeí Group deposition (< 1.1 Ga)

vinces (Table I). The tectonic event between 970-840 Ma in the Aguapeí thrust belt in SW Mato Grosso (Geraldes et al. 1997) is apparently coeval with that identified in the Sunsás Province, and some authors (Tassinari and Macambira 1999) have interpreted the Aguapeí thrust belt as a branch of the Sunsás deformation front reported in Bolivia (Litherland et al. 1986).

GEOLOGY OF SW MATO GROSSO STATE

Three major geochronological and tectonic provinces (Teixeira et. al. 1989, Tassinari and Macambira 1999) are traditionally considered and represented in the western part of the Amazonian craton in Mato Grosso state: Rio Negro-Juruena Province, Rondonian-San Ignacio Province, and Sunsás Province.

Recent advances in understanding the evolution of these provinces, based on newly achieved geochronological and geological data (Tassinari et al. 1997, 2000, Sato and Tassinari 1997, Pinho et al. 1997, Bettencourt et al. 1999) among others, provide the basis to the better understanding of these provinces. In this way the geochronological provinces can be subdivided in various orogenies and terranes, which have evolved within the time-period established for each province.

The Proterozoic basement in SW Mato Grosso (Figure 1) consists of igneous and metamorphic rocks interpreted as belonging to the RNJP. This province includes distinct rock associations, such as the oldest Alto Jauru orogenic rocks (Pinho et al. 1997) encompassing acid metavolcanics associated to BIF's and metasedimentary rocks and tonalitic to granitic gneisses. U-Pb ages (volcanic and plutonic rocks) vary from 1790 to 1740 Ma ($\varepsilon_{\mathrm{Nd}}$ from +2.6 to +2.2 and T_{DM} from 2.00 to 1.80 Ga) interpreted as originated in a volcanic arc due to their juvenile isotopic signatures and chemical characteristics (Pinho et al. 1997, Geraldes et al. 2001).

The geological map presented in Figure 1 is compiled from (unpublished data) and Carneiro et al. (1992) and shows intrusive rocks in the Alto Jauru greenstone belt rocks. These intrusive rocks are here named Cachoeirinha suite and petrologic, field evidences, U-Pb and Sm-Nd geochronology of these rocks are the objectives of this work.

In the eastern sector of the studied area occurs the Rio Branco suite, composed of bimodal intrusive rocks (rapakivi granites and alkaline basalts) dated about 1.47-1.42 Ga (unpublished data). The youngest unit in the studied area (Figure 1) is represented by the Aguapeí Group, which is composed by slightly metamorphosed claystones, sandstones and conglomerates. These sedimentary rocks were probably deposited between 1.3 Ga to 1.0 Ga, and cover all the units previously described. In addition, the rocks in the western boundary of the RNJP are ascribed to the Rondonian-San Ignácio Province, where three orogenic belts have been described. These are the Santa Helena, Rio Alegre (in Brazil) and San Ignácio (in Bolivia). Several granites occur in the west of the studied area such as the large batholith defined as 1.45-1.42 Ga Santa Helena orogen (Geraldes et al. 2001). The 1.42-1.36 Ga San Ignacio orogen (Geraldes et al. 2002) and the 1.50-1.48 Ga Rio Alegre orogen (Matos et al. 2004) may be interpreted as accretionary arcs related of the SW Amazonian craton crust formation during the Mesoproterozoic.

ANALYTICAL PROCEDURES

Major element analyses were carried out at the Geochemistry Laboratory, Department of Mineralogy and Geotectonics of the University of São Paulo, using an ICO-ES according to the procedures described in Janasi et al. (1996). Trace element including REE were analyzed at the ACTLAB (Toronto, Canada) using ICP-MS routine.

For the U-Pb analyses 20 to 30 kg of sample were crushed, milled and heavy minerals were concentrated in wiffley table at University of São Paulo (Brazil). Heavy liquids were used for separation of zircon. U-Pb zircon analyses were carried out in the Isotope Geochemistry Laboratory (IGL), Department of Geology, University of Kansas (USA). The less magnetic fraction was abraded and hand-picked single grains were spiked with ^{205}Pb-^{235}U mixed tracer. Zircons were dissolved and Pb and U were separated using procedures modified after Krogh (1973, 1982) and Parrish (1987). Zircon weight varied from 0.001 to 0.005 mg. Isotopic ratios were measured using a VG Sector multi-collector mass spectrometer in a single collector mode using Daly detector.

Pb isotope compositions were analyzed on single Re filaments using silica gel and phosphoric acid. Uranium was loaded with Pb on the same filament and analyzed as UO_2^+. Radiogenic ^{208}Pb, ^{207}Pb, and ^{206}Pb were calculated by correcting for laboratory Pb blank (from 55 to 17 pg of total Pb during the analyses) and for nonradiogenic common Pb corresponding to Stacey and Kramers (1975) model for approximate age of the sample. Decay con-

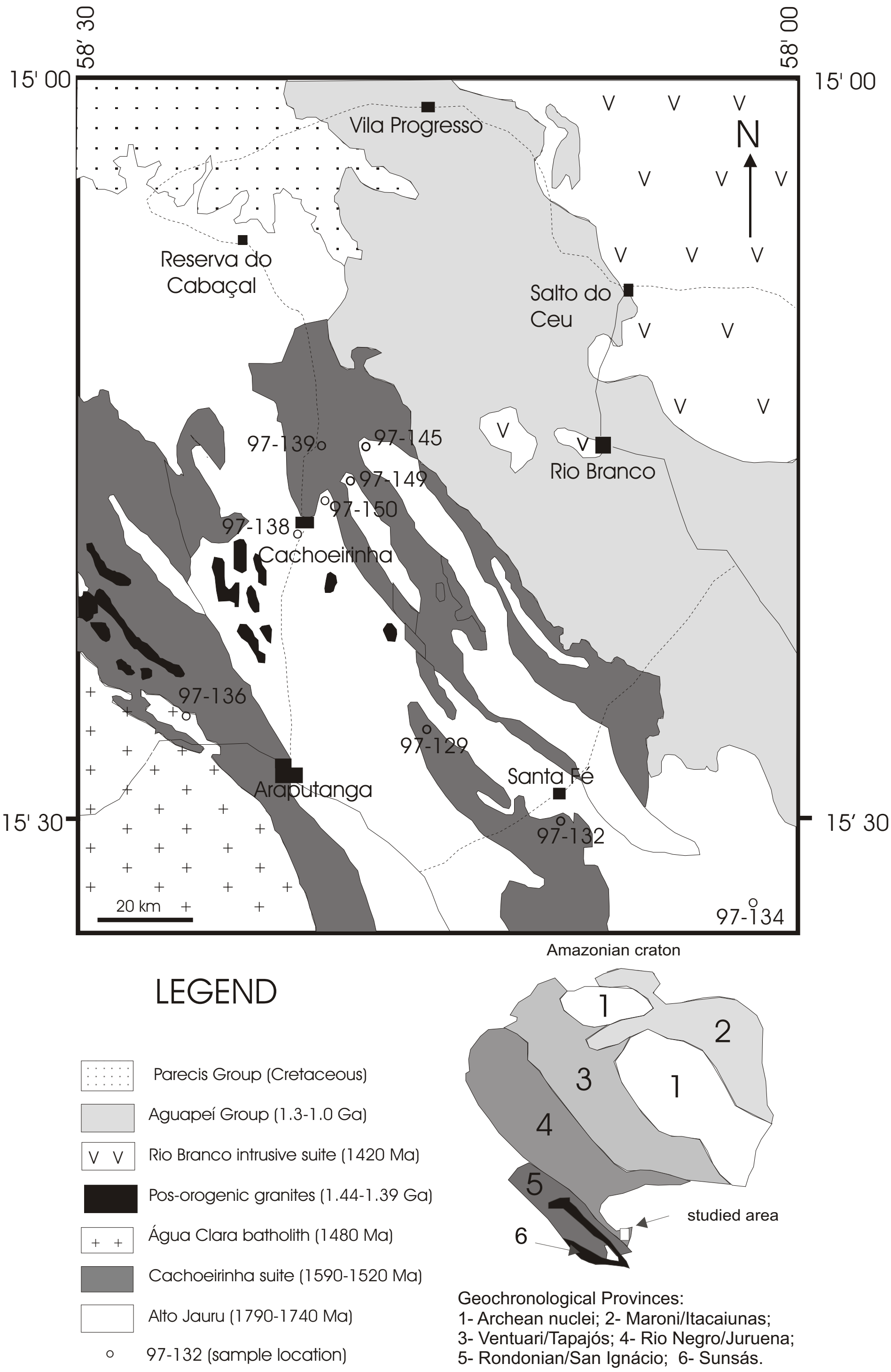

Fig. 1 – Geological map of the studied area, SW Amazon Craton, Mato Grosso State, Brazil. (samples 97-130, 97-134, 97-145, 97-149 and 97-150 are too small bodies within Alto Jauru terrane to be displayed at the map scale).

stants used were 0.155125 × 10^{-9} $year^{-1}$ for ^{238}U and 0.98485 × 10^{-9} $year^{-1}$ for ^{235}U (Steiger and Jäger 1977). Zircon data were regressed using the ISOPLOT program of Ludwig (1998). Uncertainties on concordia intercept ages are given at the 2 sigma (σ) level.

For the Sm-Nd analyses, rock powders were dissolved in bombs at ca. 180°C and spiked with ^{145}Nd and ^{144}Sm. REE were extracted using the methodology of Patchett and Ruiz (1987). Isotopic compositions were measured in a VG Sector 5-collectors mass spectrometer. Sm was loaded with H_3PO_4 on a single Ta filament and typically analyzed as Sm^+ in a static multicolector mode. Nd was loaded with phosphoric acid on a single Re filament having a thin layer of AGW-50 resin beads and analyzed as Nd^+ using static mode. Analyses of BCR-1 during the period when unknown samples were analyzed yielded Nd = 29.44 ± 0.70 ppm, Sm = 6.77 ± 0.21 ppm, $^{147}Sm/^{144}Nd$ = 0.13931 ± 0.00071, and $^{143}Nd/^{144}Nd$ = 0.512641 ± 0.000007, yielding ε_{Nd} = 0.07 ± 0.12 (all at 1σ). Sm-Nd model ages (T_{DM}) were calculated according to DePaolo (1988). During the course of these analyses Nd blanks ranged from 500 to 150 pg, with corresponding Sm blanks of 100 to 50 pg. Correction for blanks was insignificant for Nd isotopic composition and insignificant for Sm-Nd concentrations and ratios. Sm-Nd ratios are corrected to within ±0.5 percent based on analytical uncertainties.

U-Pb AND Sm-Nd RESULTS

Nine rocks of the studied area (Figure 1) were analyzed for U-Pb and Sm-Nd (summarized in Table II). Complete U-Pb results are presented in Table III and Sm-Nd results in Table IV. Chemical results from 9 samples of studied area are presented in Table V.

The Cachoeirinha suite rocks show compositional variations from tonalites, granodiorites to granites. These rocks are leucocratic, gray to green in color and medium-grained size (0.1 to 1 cm), presenting isotropic, slightly foliated and banded fabrics. The essential mineralogy includes plagioclase, amphibole, biotite, quartz and K-feldspar. Zircon, apatite, allanite and oxides are the accessory minerals.

Several plutonic bodies were individualized from the gneissic basement in the Cachoeirinha region according to the geologic mapping published by Saes et al. (personal communication), (unpublished data) and Carneiro et al. (1992). The authors above cited worked in different locations, what hampered the temporal relationship between the granitoid intrusions observed in the respective studied areas. However, the nomenclature described by these authors was used during the sampling work and include the following granitoids: Quatro Marcos, Cachoeirinha, Santa Cruz, Alvorada and Água Clara. The new units sampled and analyzed in this paper without previous studies were described using new denominations as Santa Fé, São Domingos and Araputanga.

Quatro Marcos Tonalite

Two tonalitic rocks were sampled for U-Pb dating. The first one (sample 97-134) was collected in the southeastern region of the Santa Fé town. In this region Carneiro et al. (1992) identified Paleoproterozoic (1.9-1.7 Ga) Rb-Sr ages on a gray gneiss. Four zircons were analyzed for U-Pb from a gray tonalitic gneiss and yielded an upper intercept age of 1536 ± 11 Ma with T_{DM} = 1.77 and ε_{Nd} = +0.5 (Figure 2A; Table II).

Chachoeirinha Tonalite

The second tonalitic sample (97-150) was collected 2 km to the west of Cachoeirinha town (Figure 1). Zircons obtained from this rock yielded upper intercept U-Pb age (Figure 2B; Table II) of 1549 ± 10 Ma and whole rock Sm-Nd analysis yielded T_{DM} = 1.83 and ε_{Nd} = +1.0.

São Domingos Gneiss

This sample (97-149) presents a compositional banding of quartz and feldspar, in felsic layers, and biotite and amphibole-enriched in mafic layers. The São Domingos gneiss yielded an U-Pb zircon

TABLE II
U-Pb ages and Sm-Nd isotopic properties of rocks from Cachoeirinha suite.

Sample	Lithotype	U-Pb (Ma)	$\varepsilon_{Nd(0)}$	$\varepsilon_{Nd(t)}$	T_{DM}	f
97-134	Quatro Marcos Tonalite	1536 ± 11	–14.2	+0.5	1.77	–0.38
97-159	Cachoeirinha Tonalite	1549 ± 10	–14.7	+1.0	1.83	–0.40
97-149	São Domingos Gneiss	1587 ± 04	–15.0	–0.8	2.05	–0.36
97-138	Granite Cachoeirinha	1522 ± 12	–19.6	+0.9	1.78	–0.54
97-132	Santa Fé Granite	1537 ± 06	–22.2	+0.5	1.75	–0.60
97-145	Santa Cruz Gneiss	1562 ± 36	–20.2	+0.9	1.79	–0.53
97-136	Água Clara Granodiorite	1485 ± 04	–5.0	+1.7	1.77	–0.50
97-139	Araputanga Granite	1440 ± 06	–20.2	–0.2	1.74	–0.56
97-129	Alvorada Granite	1389 ± 03	–20.3	–1.3	1.77	–0.54

age (Figure 2C; Table II) in the range of 1587 to 1489 Ma and T_{DM} = 2.05 Ga and $\varepsilon_{Nd(1489)}$ = –0.8. The widespread distribution of the results when plotted in the concordia diagram also suggest the presence of inherited zircons which upper intercept indicate the age about 1.7 Ga.

Santa Cruz Gneiss

This granodioritic rock (sample 97-145) is surrounded by the São Domingos gneiss and may comprise lateral variations (unpublished data) of the last unit. The Santa Cruz sample yielded U-Pb zircon age (Figure 2D; Table II) of 1562 ± 36, and T_{DM} age of 1.79 Ga and $\varepsilon_{Nd(1562)}$ = +0.9.

Cachoeirinha Granite

The analyzed sample (97-138) was collected from a plutonic body intruded in the São Domingos Gneiss (sample 97-149). The upper intercept yielded U-Pb zircon age of 1522 ± 11 Ma, T_{DM} = 1.78 Ga and $\varepsilon_{Nd(1522)}$ = +0.9 (Figure 2E; Table II).

Santa Fé Granite

Isotropic granitic rocks related to the Cachoeirinha suite are widespread within the Santa Fé-Araputanga region (Figure 1). The Santa Fé granite (sample 97-132) yielded U-Pb zircon ages of 1546 ± 15 Ma and T_{DM} = 1.78 Ga and $\varepsilon_{Nd(1537)}$ = +0.9 (Figure 2F; Table II).

In addition, three post-orogenic plutons of granitic and granodioritic compositions reported in previous studies (Saes, Monteiro and Matos personal communication) were analyzed. The Água Clara is described as a large anorogenic batholith in the Jauru region (600 km^2) and comprises mainly granodiorites with subordinate granites. The Alvorada granite comprises several isotropic granitic bodies widespread within the Jauru-Araptanga region. Araputanga granite is a small body intrusive in banded gneisses in Araputanga region.

Água Clara Granodiorite

U-Pb zircon analysis yielded 1468 ± 35 Ma (sample 97-136, Figure 3A; Table II), with the T_{DM} age is 1.77 Ga and $\varepsilon_{Nd(1485)}$ = +1.7.

Alvorada Granite

The 97-129 sample yielded two discordia lines, indicating U-Pb zircon ages (Figure 3B; Table II) of 1483 ± 10 Ma and 1440 ± 06 Ma (T_{DM} = 1.74 Ga and $\varepsilon_{Nd(1440)}$ = –0.2).

Araputanga Granite

These granitic bodies are interpreted (Pinho et al. 1997 among others) as the youngest magmatic event in the region. The 97-139 sample yielded U-Pb zircon age (Figure 3C; Table II) of 1394 ± 37 Ma (T_{DM} = 1.77 Ga and $\varepsilon_{Nd(1440)}$ = –1.3).

TABLE III

U-Pb isotope data from Cachoeirinha suite rocks.

Fraction	Size	U	Pb	Observed #			Radiogenic		Calculated Ages ± 2SE (Ma)‡		
	(mg)	(ppm)	(ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	Ratios† $^{207}Pb/^{206}Pb$	(Rho)	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	207/206
97-129											
Alvorada Granite											
NM(3) [1]	0.003	866	240	431	2.93909	0.24140	0.088302	0.976	1393 ± 10	1394 ± 09	1389 ± 2.9
M(3) [1]a	0.005	2860	403	1355	1.52602	0.13619	0.081255	0.985	941 ± 05	823 ± 04	1228 ± 1.7
M(4) [1]	0.004	2219	267	1111	1.27879	0.11257	0.082391	0.981	836 ± 05	688 ± 03	1255 ± 2.1
NM(3) b	0.002	1356	261	624	2.16566	0.17780	0.088336	0.965	1170 ± 09	1055 ± 07	1390 ± 3.8
NM(3) b	0.002	594	148	194	2.24644	0.18656	0.087329	0.917	119 ± 16	1103 ± 13	1368 ± 11
97-132											
Santa Fé Granite											
NM(5) [1]	0.001	1327	239	602	1.92455	0.16038	0.087030	0.982	1090 ± 10	959 ± 10	1361 ± 3.2
M(6) [1]	0.002	1553	318	1516	2.38753	0.19195	0.090209	0.984	1239 ± 09	1132 ± 08	1430 ± 2.5
NM(5) "O"	0.002	1348	323	3873	3.24699	0.24842	0.094794	0.985	1469 ± 12	1430 ± 11	1524 ± 2.6
97-134											
Quatro Marcos Tonalite											
NM(-1) [1]	0.007	1013	256	3749	3.09600	0.23424	0.095860	0.992	1432 ± 07	1357 ± 07	1545 ± 12
M(1) [1]	0.006	802	184	2667	2.80773	0.21244	0.095855	0.991	1358 ± 07	1242 ± 07	1545 ± 1.4
M(-1) [1]	0.009	977	276	3601	3.44264	0.26153	0.095469	0.993	1514 ± 08	1498 ± 08	1537 ± 1.1
M(0) [1]	0.002	688	148	1595	2.61705	0.19701	0.096344	0.991	1305 ± 07	1159 ± 06	1555 ± 1.2
97-136											
Agua Clara Granodiorite											
NM(0) [1]	0.007	632	139	1099	2.73623	0.21152	0.093818	0.979	1338 ± 07	1237 ± 06	1505 ± 1.8
M(0) [1]	0.004	395	85	1824	3.00620	0.21321	0.096798	0.965	1368 ± 08	1246 ± 07	1563 ± 2.7
M(1) [1]	0.007	479	83	3144	2.29866	0.17573	0.094871	0.962	1212 ± 07	1044 ± 06	1526 ± 3.0
NM (0)	0.004	799	192	674	2.95776	0.30399	0.093310	0.953	1396 ± 12	1337 ± 11	1490 ± 5.0
NM (0)	0.004	62	22	106	3.06905	0.242033	0.091966	0.969	1425 ± 57	1397 ± 54	1467 ± 19
97-138											
Cachoeirinha Granite											
NM(0) [2]	0.008	161	51	411	3.50167	0.26626	0.095379	0.970	1528 ± 13	1522 ± 13	1536 ± 3.9
M(0) [2]	0.011	668	150	702	2.01803	0.17121	0.085486	0.961	1121 ± 06	1019 ± 08	1327 ± 2.8
M(1) [2]	0.004	1156	284	1316	2.90693	0.22359	0.094290	0.956	1384 ± 07	1301 ± 07	1514 ± 03
M(2) [2]	0.004	2103	430	1191	2.27294	0.18208	0.090533	0.865	1204 ± 12	1078 ± 12	1437 ± 13
97-139											
Araputanga Granite											
NM(5)"M" [1]	0.002	139	39	294	3.10414	0.23967	0.093934	0.989	1434 ± 28	1385 ± 27	1507 ± 5.6
NM(5) "N" [1]	0.006	2118	504	417	2.43338	0.19804	0.089116	0.969	1253 ± 06	1165 ± 06	1407 ± 2.4
NM(5) "O" [1]	0.005	1035	283	514	2.93237	0.23548	0.090315	0.970	1390 ± 11	1363 ± 10	1432 ± 3.7
NM (5) "F"	0.010	7664	1655	1945	2.83983	0.21508	0.095758	0.991	1366 ± 07	1256 ± 07	1543 ± 1.4
97-145											
Santa Cruz Gneiss											
M(-1) [1]	0.004	1262	329	322	2.83861	0.21308	0.096619	0.869	1366 ± 15	1245 ± 12	1560 ± 10
M(1) [1]	0.013	262	74	956	3.44136	0.25935	0.096236	0.991	1514 ± 13	1487 ± 13	1552 ± 2.3
M(2) [1]	0.004	807	180	855	2.74331	0.20886	0.095260	0.984	1340 ± 14	1223 ± 12	1533 ± 3.4

GEOCHEMISTRY

The major and trace elements analyses (n = 9, Table V) of tonalites, granodiorites and granites of Cachoeirinha suite show variation content in compatible elements related to a calc-alkaline fractional differentiation. The SiO_2 amount ranges from 44% to 55% in the more primitive rocks, 67% to 68% in the intermediate rocks, and reaches 70 to 73% in the more fractionated rocks. CaO ranges from 7% to 8%, 4% to 5%, and 2% to 3%, and MgO ranges from 4.7% to 7.2%, 1% to 1.2%, and 0.3% to 0.8%, respectively in the tonalitic (more primitive), granodioritic (intermediated) and granitic (evolved) rocks. Trace element results plot within the field of volcanic arc granites (VAG), following the Pearce et al. (1984) tectonic discrimination diagram (Figure 4A) for both orogenic and post-orogenic rocks. In

TABLE III (continuation)

Fraction	Size (mg)	U (ppm)	Pb (ppm)	Observed #			Radiogenic Ratios†	(Rho)	Calculated Ages ± 2SE (Ma)‡		
				$^{206}Pb/^{204}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$		$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	207/206
97-149											
São Domingos Gneiss											
NM(-1) [4]	0.006	557	164	544	3.69373	0.25591	0.104681	0.970	1570 ± 29	1469 ± 26	1709 ± 8.3
M(-1) [4]	0.009	469	151	807	4.17118	0.28545	0.105978	0.922	1668 ± 20	1619 ± 18	1731 ± 8.6
M(1) [4]	0.008	740	249	439	4.07927	0.28429	0.104067	0.903	1650 ± 10	1613 ± 08	1698 ± 5.1
M(0) [3]	0.003	2134	540	767	2.9358	0.22339	0.095312	0.941	1391 ± 11	1300 ± 10	1534 ± 5.3
NM(-1) J [1]	0.001	982	130	354	0.881317	0.10496	0.060896	0.978	642 ± 09	643 ± 10	636 ± 7.2
NM(-1) "K" [1]	0.001	268	81	337	3.81267	0.27129	0.101927	0.964	1595 ± 28	1547 ± 27	1660 ± 09
NM(-1) "L" [1]	0.001	298	83	510	3.68764	0.26099	0.102474	0.990	1569 ± 25	1495 ± 23	1669 ± 4.3
NM(-1) "M " [1]	0.001	339	94	466	3.55433	0.25638	0.100232	0.899	153 ± 29	1471 ± 24	1628 ± 15
NM(-1) "N" [1]	0.001	244	87	234	4.28069	0.29589	0.104923	0.992	1690 ± 33	1671 ± 33	1713 ± 4.8
97-159											
Cachoeirinha Tonalite											
M(-1) [1]	0.004	223	76	195	3.51349	0.26562	0.095931	0.894	1530 ± 21	1519 ± 18	1546 ± 12
M(0) [1]	0.002	244	73	262	3.46200	0.26129	0.096093	0.981	1519 ± 25	1497 ± 256	1550 ± 6.3
M(1) [1]	0.001	1312	380	618	3.37969	0.25395	0.096519	0.968	1500 ± 12	1459 ± 12	1558 ± 4.1
M(0) "b" [1]	0.002	592	168	1247	3.48712	0.26401	0.095792	0.993	1524 ± 12	1510 ± 12	1544 ± 1.8

M, NM refer to magnetic fractions at Franz (at 5 amp). [m] = multigrain; [1] = monocrystal. #: Not corrected for blank and comum Pb. †: Corrected for blank and comum lead. ‡: Based on constants according to Steiger and Jäger (1977).

TABLE IV

Sm-Nd isotopic results from Cachoeirinha suite rocks.

Sample	Lythotype	Age U/Pb	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	E(Nd) t=0	E(Nd) t(U/Pb)	T(DM) Ma	*f*
97-129	granite	1394	64.21	9.55	0.08993	0.511595	–20.34	–1.27	1773	–0.54
97-132	granite	1546	38.65	5.96	0.09336	0.511632	–19.62	0.87	1777	–0.53
97-134	tonalite	1536	25.88	5.24	0.12247	0.511913	–14.14	0.48	1876	–0.38
97-136	granodiorite	1468	21.61	3.48	0.09751	0.511758	–17.16	1.73	1675	–0.50
97-138	granite	1521	67.67	9.01	0.0805	0.511501	–22.17	0.49	1754	–0.60
97-139	granite	1440	35.82	5.23	0.08834	0.511602	–20.21	–0.21	1743	–0.56
97-145	granodiorite	1562	38.91	5.89	0.09165	0.511605	–20.16	0.89	1786	–0.53
97-147	granod. gneiss	1586	40.40	6.72	0.10064	0.511639	–19.48	0.06	1882	–0.49
97-150	tonalite	1549	28.41	5.53	0.11774	0.511884	–14.70	0.98	1829	–0.40

the Figure 4B (alumina index; Maniar and Piccoli 1989), the studied samples vary from peraluminous (granitic and granodioritic rocks) to metaluminous (tonalitic rocks).

The hypothesis of fractionation is confirmed by Rb/Sr *versus* Sr diagram (Figure 5) which analytical data plot indicates an increasing Rb/Sr ratio and decreasing Sr content. The post-tectonic plutonic rocks (U-Pb ages from 1.48 to 1.39 Ga) show SiO_2 variation from 73% to 70%, with low Ca_2O content (from 3% to 1.37%) and high Na_2O and K_2O values (4.3% to 3.7% and 4.6% to 2.6%), indicating that this group of rocks present highly fractionated signature.

The REE patterns indicate a higher fractionation between LREE and HREE for the felsic rocks (97-138, 97-132, 97-129 and 97-139), compared with the intermediate (97-147, 97-145 and 97-136) and primitive rocks (97-134 and 97-150). The REE distribution between the rocks is also characterized by slightly positive Eu anomaly in the most primitive rocks, a slightly negative Eu anomaly in the inter-

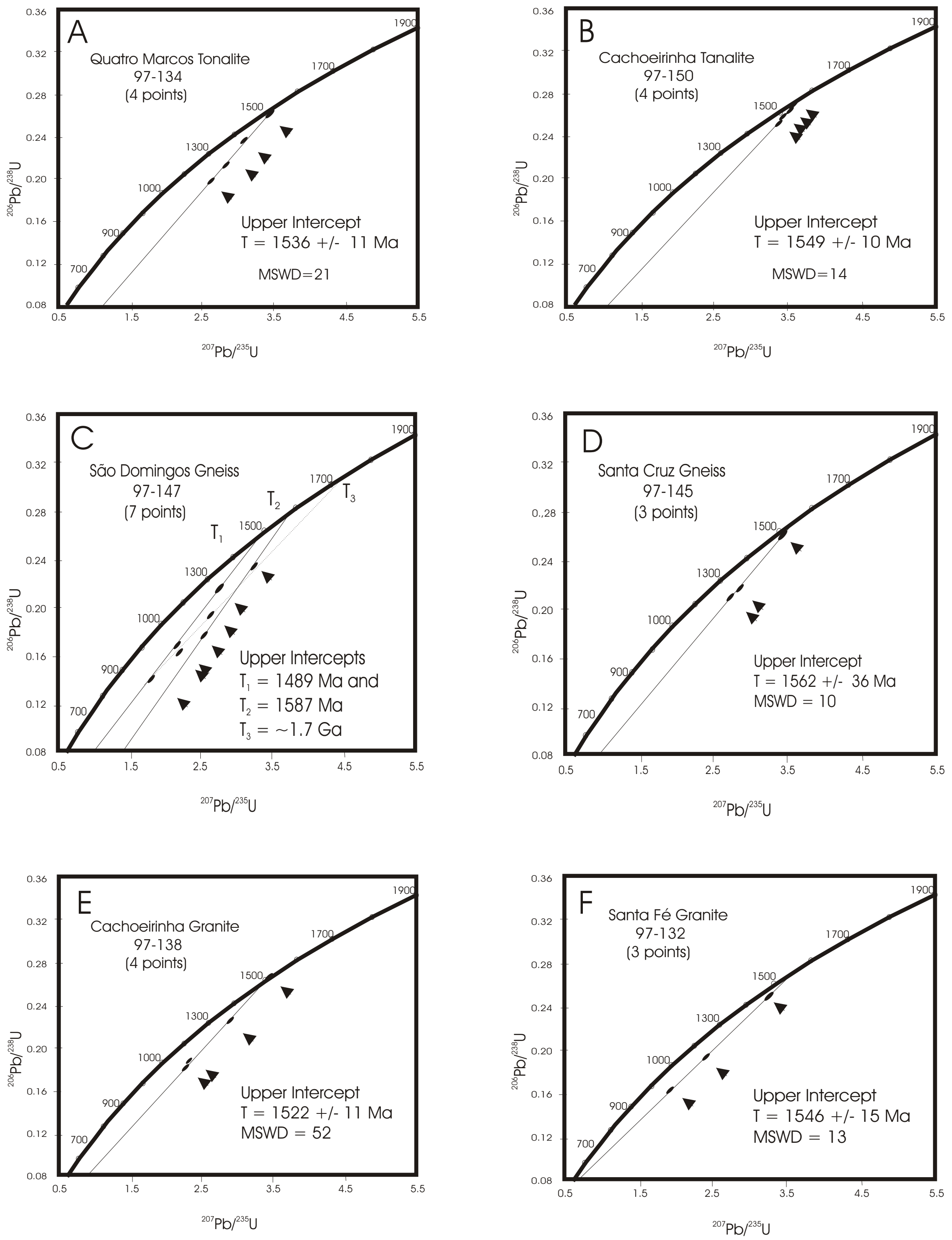

Fig. 2 – Concordia diagrams for the tonalitic (samples 97-134 and 97-150), granodioritic (samples 97-149 and 97-145) and granitic rocks (samples 97-138 and 97-132) of the Cachoeirinha suite.

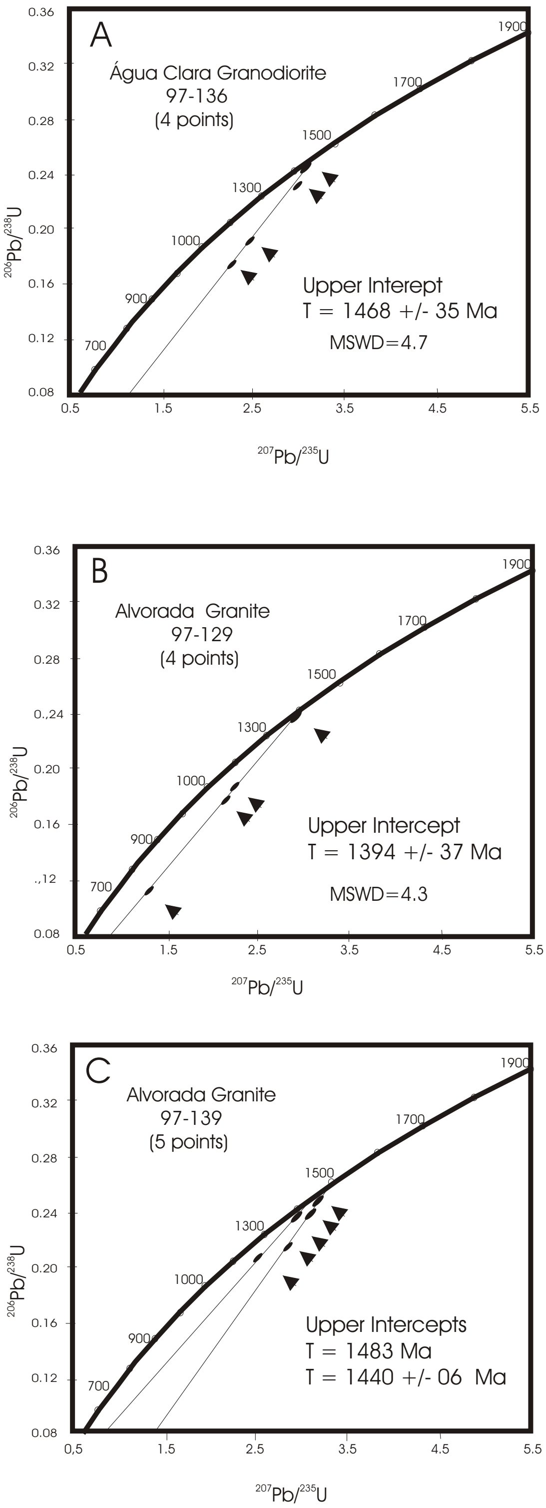

Fig. 3 – Concordia diagrams for the post-tectonic granodioritic (sample 96-136) and granitic (samples 97-129 and 97-139) intrusive rocks of the Cachoeirinha suite.

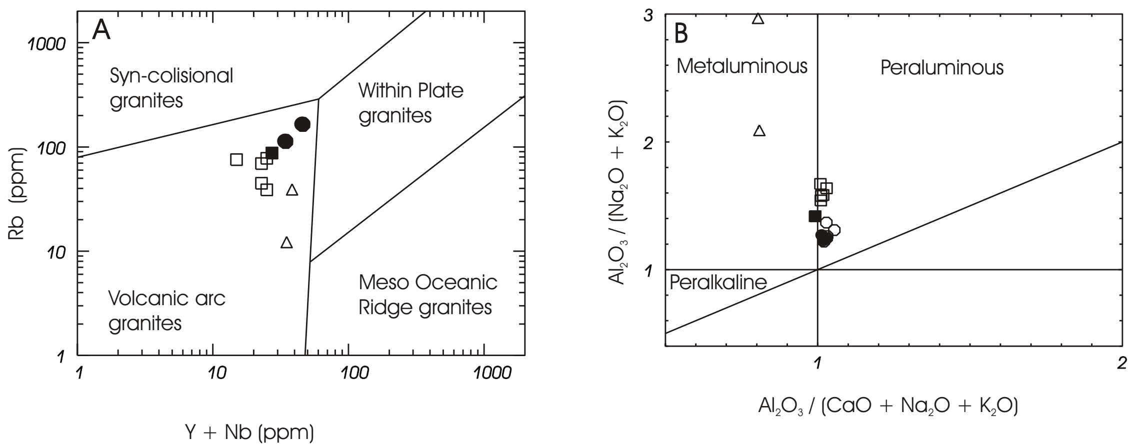

Fig. 4 – (A) Tectonic discrimination diagram (Pearce et al. 1984) and (B) Shandy Index (Maniar and Piccoli 1989) for Cachoeirinha suite rocks. Open symbols = post-orogenic rocks; and filled symbols = orogenic rocks.

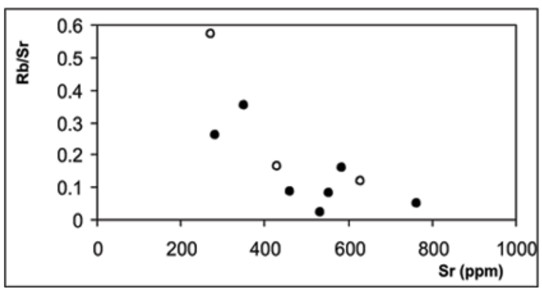

Fig. 5 – Rb/Sr *versus* Sr diagram. The rapidly increasing Rb/Sr ratio with decreasing Sr content can be explained by removal of plagioclase. See text for discussion. Open symbols = post-orogenic rocks; and filled symbols = orogenic rocks.

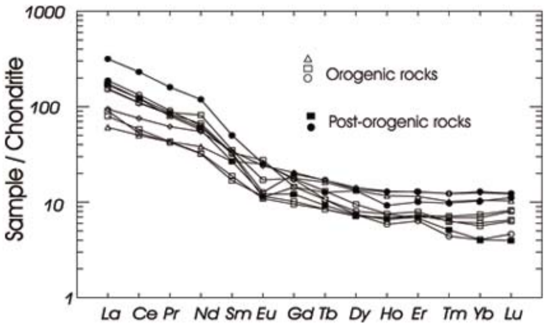

Fig. 6 – REE patterns for samples of Cachoeirinha suite rocks. Chondrite normalized according to Taylor and McLennan (1985). Triangle: tonalites; Square: granodiorites; and Circle: granites.

mediate ones, and moderate Eu negative anomaly in the felsic rocks (Figure 6).

The post-orogenic granites show two distinctive REE patterns (Figure 6). The Agua Clara granodiorite (sample 97-136) presents REE distribution similar to the primitive rocks of the Cachoeirinha suite rocks, and the other two samples (97-129 and 97139) show REE patterns similar to the felsic rocks of the Cachoeirinha suite rocks.

DISCUSSION

Geochronological, isotopic and chemical data provide informations about the nature and tectonic setting of the Cachoeirinha suite, which have important bearing for the understanding of the crustal evolution of the SW Amazonian craton at Mesoproterozoic time. U-Pb zircon ages indicate that the Cachoeirinha granitoids comprise a voluminous rock suite formed during a short period of time (1590 Ma to 1520 Ma), implying that a regional tectonic magmatic event took place succeeding the generation of the Alto Jauru volcanic-plutonic accretionary complex (Geraldes et al. 2001). The T_{DM} between 1.88 Ga and 1.75 Ga and the $\varepsilon_{Nd(t)}$ values varying from slightly negative (–0.8) to positive (+1.0) for the investigated Cachoeirinha rocks together with their calc-alkaline affinity is consistent with an arc-

TABLE V

U-Pb isotopic results from Cachoeirinha suite rocks.

Sample	97-129	97-130	97-132	97-136	97-138	97-139	97-145	97-149	97-150
SiO_2	73.38	44.07	73.26	70.74	73.37	70.77	68.26	71.12	55.38
Al_2O_3	14.05	16.63	14.21	15.55	14.04	15.34	15.73	14.77	16.21
Fe_2O_3	1.94	16.98	2.06	2.61	2.05	2.93	3.94	3.84	9.06
MnO	0.05	0.19	0.05	0.04	0.03	0.05	0.05	0.08	0.14
MgO	0.32	7.17	0.47	0.78	0.40	0.83	1.02	0.91	4.76
CaO	1.37	8.29	1.89	2.92	1.30	2.99	2.62	3.19	7.04
Na_2O	3.70	2.86	3.62	4.34	3.48	4.19	4.61	4.21	3.39
K_2O	4.66	0.83	4.09	2.72	5.14	2.62	2.79	1.77	1.91
TiO_2	0.21	2.26	0.23	0.33	0.22	0.33	0.52	0.28	1.10
P_2O_5	0.08	0.30	0.08	0.11	0.09	0.11	0.21	0.12	0.48
LOI	0.23	0.31	0.21	0.34	0.24	0.25	0.21	0.32	0.42
total	99.76	99.58	99.96	100.14	100.12	100.16	99.75	100.29	99.47
Be	3	2	2	2	1	2	1	2	2
V	17	358	9	32	8	26	52	33	169
Cr	0	59	0	0	0	0	0	0	89
Co	1.9	76	2.6	5.4	2.5	5	6.8	6.6	27
Ni	0	147	24	0	0	0	0	0	44
Cu	0	42	0	0	0	0	0	0	42
Zn	40	138	46	65	37	68	60	51	102
Ga	18	24	17	19	14	19	16	14	20
Ge	1.3	1.5	1.2	1	1.1	1	0.8	1.3	1.3
As	0	0	0	0	0	0	0	0	0
Rb	154	13	123	76	74	71	46	39	40
Sr	270	532	350	628	282	429	552	459	763
Y	30	26	23	22	14	16	19	17	30
Zr	175	137	163	122	187	172	236	90	133
Nb	17	7.4	9.2	4.3	2.6	7.5	3.7	6	6.7
Mo	0.4	0.8	0.3	0.7	0.4	0.7	0.6	0.7	0.7
Ag	0	0	0	0	0	0	0	0	0
In	0	0	0	0	0	0	0	0	0
Sn	1.5	1.6	1.5	1.9	0.7	1.5	0.7	0.6	1.2
Sb	0.13	0.09	0.18	0.07	0.21	0.1	0.09	0.07	0.09
Cs	1	0.4	0.9	2.3	0.4	0.6	0.4	0.4	0.5
Ba	1160	432	1505	999	2376	1210	2134	840	1002
Hf	5.3	3.5	4.8	3.2	4.7	4.6	5.8	2.6	3.7
Ta	1.18	0.39	0.61	0.29	0.22	0.52	0.17	0.52	0.22
W	0.6	1	0	0.4	3	0	0.2	0.3	0.5
Tl	0.92	-0.05	0.95	0.86	0.4	0.71	0.26	0.19	0.32
Pb	35	7	38	14	32	28	19	11	12

TABLE V (continuation)

Sample	97-129	97-130	97-132	97-136	97-138	97-139	97-145	97-149	97-150
Bi	05	0	0	0	0	0	0	0	0.08
Th	24.1	1.52	23.4	3.67	16.3	19.6	5.75	5.14	3.78
U	8.64	0.32	3.33	1.13	2.07	3.06	1.11	1.11	0.75
La	50.3	20	61.9	29.7	104	57.8	50.9	26.2	31
Ce	94.3	43.4	115	45.7	200	105	95.6	50.1	65.4
Pr	10.77	5.566	11.83	5.511	20.79	10.39	10.93	5.595	8.027
Nd	37.9	24.1	39.7	20.2	75	36.1	41.7	20.5	34.5
Sm	6.86	5.42	6.5	3.43	10.2	5.46	6.67	3.8	6.95
Eu	0.977	1.941	0.862	0.889	1.948	0.934	2.12	0.837	1.845
Gd	5.42	4.9	3.97	2.8	4.8	3.35	4.01	2.63	5.65
Tb	0.85	0.81	0.63	0.42	0.53	0.46	0.53	0.42	0.84
Dy	4.67	4.53	3.52	2.45	2.54	2.55	2.75	2.49	4.87
Ho	0.99	0.9	0.71	0.53	0.45	0.51	0.58	0.51	1
Er	2.89	2.58	2.26	1.64	1.43	1.57	1.78	1.64	2.88
Tm	0.433	0.358	0.344	0.224	0.155	0.242	0.219	0.25	0.433
Yb	2.82	2.3	2.26	1.24	0.89	1.51	1.33	1.63	2.75
Lu	0.418	0.351	0.378	0.215	0.157	0.272	0.221	0.278	0.415

related setting for this unit. Moreover, the Nd evidence (Figure 7) suggests crustal contribution in the genesis of the Cachoeirinha suite. This is corroborated by the U-Pb results of sample 97-149, with several inherited zircon populations, probably due to contribution of Alto Jauru crust in the source for this rock. If this interpretation is correct, the sample 97-149 grains of zircon may have retained isotopic signature of ancient rocks, and the magmatic event responsible for the Cachoeirinha suite formation kept part of these zircon within the analyzed sample. The alignment of four U-Pb analytical results of this sample yielded an age of about 1.7 Ga (Figure 2C), suggesting that the older protholith may be the Alto Jauru country rocks.

Post-orogenic magmatism represented by samples 97-129, 97-136 and 97-139 shows crystallization U-Pb zircon ages (Figures 3A, 3B and 3C) varying from 1485 Ma to 1389 Ma, with correspondent Sm-Nd results ($\varepsilon_{Nd(t)}$ values between –1.3 and +1.7) indicating a probable participation of the Alto Jauru rocks in their sources.

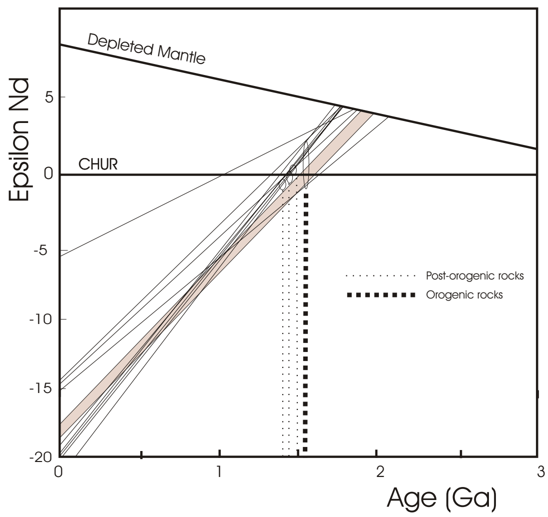

Fig. 7 – Nd isotopic evolution of Cachoeirinha rocks. The Nd isotopic evolution curves of Alto Jauru rocks (basement) are plotted in gray (according to Geraldes et al. 2001).

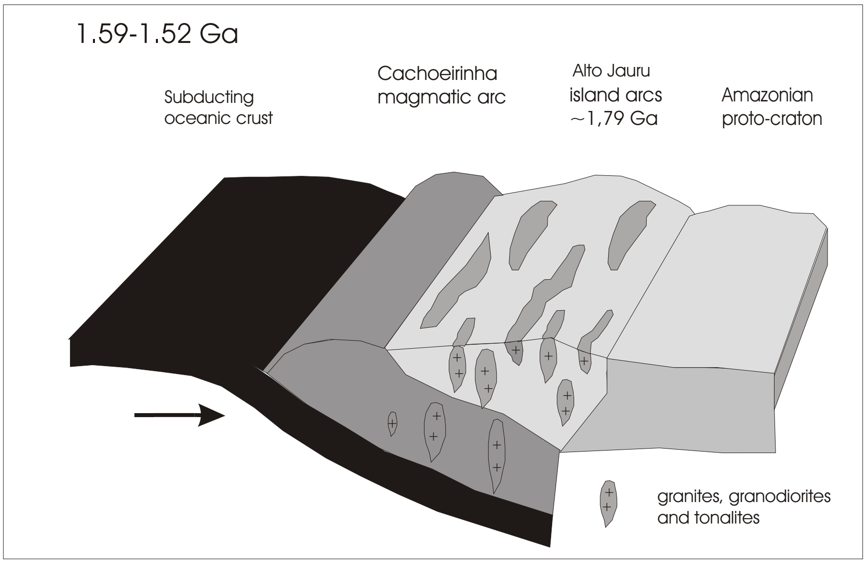

Fig. 8 – Crustal evolution model for the Cachoeirinha arc at about 1.59-1.52 Ga.

The Cachoeirinha suite rocks SiO_2 contents range from about 68% to 73%, contains primitive (high-Ca), and highly evolved (high-K, Rb) phases. The post-tectonic rocks (samples 97-136, 97-139 and 97-129) are the highest evolved rocks and they show SiO_2 contents from 70% to 73%. The Cachoeirinha granitoids show I-type affinities for the primitive and intermediate rocks and A-type affinities for the pos-tectonic more evolved rocks (Figure 4A) and chemical results plot near the peraluminous-metaluminous boundary on the A/CNK *versus* ZNCY diagram (Figure 4B). REE data for the Cachoeirinha suite have steep LREE patterns and relatively flat HREE patterns with moderately negative to absent Eu anomalies. Both major and trace elements in the analyzed samples show distributions characteristic of fractional crystallization. As example, the increasing Rb/Sr ratio with decreasing Sr content (Figure 5) can be explained by removal of plagioclase, K-feldspar, and biotite in the approximate proportions that they occur in the rocks.

The Cachoeirinha suite presents isotopic and chemical signatures that define their juvenile character. Consequently we propose that the rock association here reported was formed in a magmatic arc setting, (e.g., Cachoeirinha magmatic arc) close to an older continental crust (as speculated in Figure 8) during an orogenic event that occurred in the SW (actual) margin of the Amazonian craton which magmatism source had an important contribution of the older crust comprised by the 1790-1740 Ma Alto Jauru volcano-plutonic rocks.

Cachoeirinha rocks may be correlated to rocks formed in coeval magmatic arcs described in Baltica, where continent-continent collision occurred at ca. 1.58 Ga and eastward subduction was renewed (Åhäll and Gower 1997). Evidence is given by calc-alkaline ca. 1.55 Ga mafic-ultramafic tonalitic intrusions (northern Telemark) and ca. 1.53-1.50 Ga rapakivi magmatism in central Sweden. These events are coeval and consistent with the onset of the Cachoeirinha orogen in SW Mato Grosso, and in Finland, by the Aland Riga Group (1.58-1.54 Ga) and ca. 1.56-1.54 Ga Salmi Group rapakivi plutons (Rämö and Haapala 1995). Similarly, the 1.59-1.52 Ga age pattern of the Cachoeirinha suite is partially coeval with the 1.61-1.53 Ga Serra da Providência suite, described as a bimodal (rapakivi granites and gabbros) intrusive suite, according to Bettencourt et al. (1999).

Åhäll et al. (2000) reported more detailed U-Pb studies in the Baltica Mesoproterozoic granites and defined two accretionary events: The first event coined Stage 2 formed crust from 1.62 to 1.58 Ga and Stage 3 formed crust from 1.56 to 1.55 Ga. These authors concluded that the rapakivi suites to the east are inboard manifestations of coeval accretionary process in the west. The data reported by Åhäll et al. (2000) added to data here reported suggest that Amazonia and Baltica had coeval juvenil accretionary events, indicating that both continental masses could be connected as a laterally continuous continental margin at 1.6 to 1.5 Ga.

CONCLUSIONS

U-Pb and Sm-Nd major, trace and REE data provide time and tectonic setting constraints for the rocks here studied and allow to suggest tectonic implications on the Mesoproterozoic crustal evolution of the SW Amazonian craton, as the following:

1) Tonalites, granodiorites and granites ascribed to the Cachoeirinha suite represent juvenile magmatic activity that occurred between 1590 and 1520 Ma. Thereby slightly younger than the Santa Helena arc (1.45-1.42 Ga), the improved chronological resolution obtained using U-Pb and Sm-Nd methods, added to integrated geochemical data, allows to conclude that the rock association are components of a ca. 1550 Ma NW-trending plutonic arc (Cachoeirinha arc).

2) The T_{DM} model ages for rocks of the Cachoeirinha suite, mostly between 1.83-1.75 Ga, suggest some participation of an older crust, in concordance with the development of such arc complex along the western margin (actual) of a Mesoproterozoic continental crust composed by the 1.79-1.74 Ga Alto Jauru volcano-plutonic rocks. However T_{DM} of 2.05 Ga observed in sample 97-149 may indicate a component with age older than Alto Jauru crust.

3) The age pattern of 1.59-1.52 Ga rocks intruded into or adjacent to an older continental crust is similar to geologic framework described along the eastern and southern margins of Baltica prior to 1500 Ma, and would be compatible with tectonic models which propose proximity between Laurentia, Baltica and Amazonia at about 1.6 Ga to 1.5 Ga.

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RESUMO

Estudos isotópicos e químicos foram realizados em rochas da Suíte Cachoeirinha, SW do craton Amazônico. Idades U-Pb e Sm-Nd em rochas granitóides desta suíte forneceram idades de cristalização entre 1587-1522 Ma e idades modelo T_{DM} entre 1,88-1,75 Ga (ε_{Nd} entre –0,8 a +1,0). Em adição, rochas intrusivas apresentam idades U-Pb entre 1485-1389 Ma e apresentam T_{DM} entre 1,77-1,74 Ga e valores de ε_{Nd} entre –1,3 e +1.7. Variações químicas da suíte Cachoeirinha sugerem a existência de processo de cristalização fracionada em ambiente de arco magmático. Os resultados aqui reportados permitem as seguintes conclusões: (1) no período de tempo entre 1590-1520 Ma ocorreu um importante magmatismo no SW do craton Amazônico; (2) as assinaturas isotópicas de Nd e dados químicos suportam a hipótese de que as rochas plutônicas foram geradas em ambiente de arco magmático relacionado a uma subducção sob a margem continental representada pelas rochas do Alto Jauru com idades de 1,79-1,74 Ga; (3) Idades entre 1590-1520 Ma de rochas intrusivas adjacente a uma crosta mais antiga sugerem um contexto geológico semelhante ao longo da margem sul da Laurentia-Báltica no período de tempo aqui estudado.

Palavras-chave: Craton Amazônico, geocronologia U-Pb e Sm-Nd, Mesoproterozóico, magmatismo de arco.

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