Geologic evolution of the Serrinha nucleus granite–greenstone terrane (NE Bahia, Brazil) constrained by U–Pb single zircon geochronology

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ABSTRACT

U–Pb single zircon crystallization ages were determined using TIMS and sensitive high resolution ion microprobe (SHRIMP) on samples of granitoid rocks exposed in the Serrinha nucleus granite–greenstone terrane, in NE Brazil. Our data show that the granitoid plutons can be divided into three distinct groups. Group 1 consists of Mesoarchaeal (3.2–2.9 Ga) gneisses and N–S elongated TTG (Tonalite–Trondhjemite–Granodiorite) plutons with gneissic borders. Group 2 is represented by ca. 2.15 Ga pre-tectonic calc-alkaline plutons that are less deformed than group 1. Group 3 is ca. 2.11–2.07 Ga, late to post-tectonic plutons (shoshonite, syenite, K-rich granite and lamprophyre). Groups 2 and 3 are associated with the Transamazonian orogeny. Xenocryst ages of 3.6 Ga, the oldest zircon yet recorded within the São Francisco craton, are found in the group 3 Euclides shoshonite within the Uauá complex and in the group 2 Quijingue trondhjemite, indicating the presence of Paleoarchaeal sialic basement.

Group 1 gneiss–migmatitic rocks (ca. 3200 Ma) of the Uauá complex constitute the oldest known unit. Shortly afterwards, partial melting of mafic material produced a medium-K calc-alkaline melt, the younger Santa Luz complex (ca. 3100 Ma) to the south. Subsequent TTG melts intruded in different phases now exposed as N–S elongated plutons such as Ambrósio (3162 ± 26 Ma), Araci (3072 ± 2 Ma), Requeijão (2989 ± 11 Ma) and others, which together form a major part of the Archaean nucleus. Some of these plutons have what appear to be intrusive, but are probably remobilized, contacts with the Transamazonian Itapicuru greenstone belt. The older gneissic rocks occur as enclaves within younger Archaean plutons. Thus, serial additions of juvenile material over a period of several hundred m.y. led to the formation of a stable micro-continent by 2.9 Ga. Evidence for Neoproterozoic activity is found in the inheritance pattern of only one sample, the group 2 Euclides pluton.

Group 2 granitoid plutons were emplaced at 2.16–2.13 Ga in a continental arc environment floored by Mesoarchaeal crust. These plutons were subsequently deformed and intruded by late to post-tectonic group 3 alkaline plutons. This period of Transamazonian orogeny can be explained as a consequence of ocean closure followed by collision and slab break-off. The only subsequent magmatism was kimberlitic, probably emplaced during the Neoproterozoic Brazilian event, which sampled older zircon from the basement.

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1. Introduction

The São Francisco craton, the largest preserved remnant of Archaean and Palaeoproterozoic terranes of the Brazilian shield (Fig. 1A), is well exposed in Bahia State and extends to the southwest into Minas Gerais State (Fig. 1). It has been divided into three crustal blocks: (i) the northern Serrinha nucleus (also called Serrinha block,

Barbosa and Sabaté, 2004); (ii) the southern Guanambi nucleus; and (iii) the Remanso nucleus, in the central area of the craton (Mascarenhas et al., 1979) (Fig. 1B). These contain a large number of greenstone belts, which have been affected by greenschist to lower amphibolite metamorphism (Cordani et al., 2000). This craton has been regionally stable since the 2.1 Ga Transamazonian orogeny.

The Transamazonian orogeny is characterized by the emplacement of large volumes of granitoid rocks. Lithostratigraphic features, as well as the context of crustal accretion, are still subject to contrasting interpretations. The overall tectonic regime is ascribed

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Fig. 1. (A) South America regional geologic-tectonic schematic map, showing the locations of Brazil and Bahia State, U-Pb zircon ages of the oldest rocks (after Hartmann et al., 2006). (B) Schematic map of the São Francisco Craton (gray shadow) at Bahia State, showing the distribution of the three main Archaean nuclei (slightly modified from Mascarenhas et al., 1979). (C) Geotectonic division of São Francisco Craton at the Bahia State (modified from Barbosa and Dominguez, 1996). The white rectangle represents Serrinha nucleus area (Fig. 2) and dashed lines represent the Neoproterozoic mobile belts. [1] Gaviao Block, [2] Paramirim Block, [3] Urundi-Paratinga Mobile Belt, [4] Volcano-sedimentary sequences, [5] Contendas-Mirantes Belt, [6] Mundo Novo Greenstone, [7] Jeiquê Block, [8] Itabuna Belt, [9] Serrinha Block, [10] Mairi Block, [11] Salvador-Curaçá Mobile Belt, [12] Salvador-Esplanada Belt, [13] Itapicuru Greenstone, [14] Sobradinho, [15] Macurure, [16] Contendas-Mirantes, [17] Espinhaco Setentrional, [18] Chapada Diamantina, [19] Irece-Utinga basins, [20] São Francisco-Urucuia basin, [21] Formosa do Rio Preto, [22] Sergipana, [23] Aracuai-Piripa, [24] Reconcavo-Tucano-Jatoba Mesozoic basins, [25] Tercio-Quaternary basins.

Fig. 2. Simplified map outlining the main geological units of the Serrinha Nucleus granite–greenstone terrane (slightly modified from Rios, 2002), also showing the location of studied samples and a summary of geochronological data currently available. Superscript numbers are for references (see Table 1 for references). The system of coordinates is UTM (SAD 69) and the values are divided by 1000.

either to actualistic plate tectonic conditions, with dominant collision and thrusting, or to Archaean-type tectonics, with dominant transcurrent shearing and diapirism. One major problem in this debate has been the limited amount of reliable geochronological constraints on these models and, up to now, there were no systematic regional studies of granitoid plutons in the Serrinha nucleus.

This study utilizes sensitive high resolution ion microprobe (SHRIMP) and isotope dilution thermal ionization mass spectrom-

etry (ID-TIMS) U–Pb dating methods on granitoid rocks, in order to furnish both high spatial resolution dating of imaged zircon and high age precision where necessary. The aim of this paper is to show the diversity of plutonism in the Serrinha nucleus through the geochronological study of different granitoid groups, to understand the tectonic context in which these rocks formed, and to compare these granitoid suites with similar granite–greenstone terranes worldwide.

2. Geological outline

The Serrinha nucleus represents the northeastern area of the São Francisco craton, Brazil (Mascarenhas et al., 1979). It underlies an area of >21,000 km², up to 250 km long and 70 km at its widest part, which remained rigid during the Transamazonian orogeny, when it collided with the Salvador-Curaçá mobile belt to the west (Fig. 1C). In the east, it is covered by Neoproterozoic carbonate sedimentary rocks, as well as by the Mesozoic–Cenozoic Tucano-Reconcavo rift basin. In northeast Bahia, the Serrinha nucleus hosts the major concentration of granites of the São Francisco craton and includes the Capim and Itapicuru greenstone belts, as well the Archaean Uauá and Santa Luz granitoid complexes (Fig. 2).

The main lithological units in the Serrinha nucleus granite–greenstone terrane are shown in Fig. 2, on which our dated samples are also located. Table 1 provides a summary of published ages and their interpretation. The terrane consists dominantly of well exposed: (i) Archaean basement, including medium- to high-grade amphibolite facies gneiss-migmatitic rocks and calc-alkaline to Tonalite-Trondhjemite-Granodiorite (TTG) plutons, that are assumed to surround, or enclose, greenstone sequences; (ii) volcano-sedimentary sequences, including the Itapicuru greenstone belt (the most important gold producer of the Bahia State; Silva et al., 2001; Davison et al., 1988), and the Capim greenstone belt (Winge, 1984; Oliveira et al., 1998, 1999); and (iii) Palaeoproterozoic intrusions, which either cut the greenstones or cut both the greenstones and granitoids, and the gneiss-migmatitic basement (Rios et al., 1998, 2000, 2003).

The Itapicuru and Capim greenstone belts (Fig. 2) include from base to top: (i) mafic-ultramafic lava flows, interpreted as E-MORB (enriched mid-ocean ridge basalt) sea floor, and dated at 2.2 Ga (Table 1), consisting of tholeiitic basalt and mafic tuff with associated banded iron formation, chert, and graphitic phyllite; (ii) a bimodal sequence (silica gap between 55% and 60% SiO₂) of andesitic to dacitic flows in the upper units, similar to those of modern active continental margins, and dated at 2080–2178 Ma (Table 1). Both sequences are cut by tonalite-trondhjemite suites (Fig. 2). Intrusive sub-volcanic bodies are represented by rhyodacite, quartz diorite, gabbro and subordinate alkali-feldspar syenite and lamprophyre dykes (formerly mapped as sheared diorite), which occur locally along shear zones with some spatially related to mineralized ore bodies (Xavier, 1991; Barrueto, 1997; Xavier and Foster, 1999). The Itapicuru belt supracrustal pile, which is estimated to be 9.5 km thick (Davison et al., 1988), shows a number of distinctive features from the Capim belt, including the occurrence of an upper, thick meta-sedimentary unit (conglomerate, sandstone, siltstone and shale, as well as minor carbonate, marble, and banded iron formations).

Most authors recognize three distinct metamorphic events within the Itapicuru greenstone belt (Silva, 1987; Davison et al., 1988; Jardim de Sá, 1982; Chauvet et al., 1997a). An M1 event is related to ocean sea-floor hydrothermal activity and is responsible for spilitization. M2 developed at greenschist (350 °C at 2 kbar) to amphibolite (650 °C at 4 kbar) facies conditions and is considered to have been coeval with the emplacement of the main granitic plutons, as the M2 amphibolite facies is restricted to the margins and thermal aureoles developed around intrusions. M3 is a minor event related to contact metamorphism around late-tectonic bodies. All of these events are thought to be Palaeoproterozoic.

Granitoid plutons constitute ca. 30% of the exposed area and show a wide range of petrographic and geochemical compositions. Previous workers (Matos and Conceição, 1993; Rios et al., 1998) divided the granitoid plutons into five groups; one pre-tectonic, two syntectonic and two late-tectonic groups within the Transamazonian orogeny. The petrological characteristics and U–Pb ages

previously available for these rocks are outlined in Table 1 and their locations are shown in Fig. 2.

3. Sampling and analytical procedures

The samples were crushed with a jaw crusher followed by a disc mill or shatter box. Mineral separation followed standard procedures using the Wilfley table, the Frantz isodynamic separator and heavy liquids. Zircon grains were hand picked from the least specific magnetic susceptibility fraction available and examined under a binocular microscope. Single zircon grains were selected for analysis based on grouping into populations according to color, transparency, magmatic habit, and absence of cracks and inclusions.

3.1. U–Pb single zircon geochronology by ID-TIMS

Natural grain surfaces were removed by air abrasion (Krogh, 1982) in order to improve concordance. Analyses were carried out at the Jack Satterly Geochronological Laboratory, in Toronto, Canada. Dissolution was performed in small Teflon bombs with HF mixed with a ²⁰⁵Pb–²³⁵U spike (Krogh, 1973). Dissolved samples were dried, dissolved in 3N HCl, and either passed through anion exchange columns with 50 µl of resin, or loaded directly onto Re filaments with Si-gel and H₃PO₄. Samples weighing <5 µg were generally not passed through columns to remove Zr. Isotopic measurements were carried out using a VG354 mass spectrometer equipped with a Daly collector. All common Pb is assumed to have the isotopic composition of the laboratory blank (²⁰⁶Pb/²⁰⁴Pb=18.221; ²⁰⁷Pb/²⁰⁴Pb=15.612; ²⁰⁸Pb/²⁰⁴Pb=39.36; errors of 2%). All age calculations and statistical assessments of the data have been done utilizing the geochronological software package ISOPLLOT/EX (version 2.00) of Ludwig (2001) and ROMAGE (Davis, 1982).

3.2. U–Pb geochronology by ion microprobe

U–Pb SHRIMP analysis were performed at the J.C. Roddick Ion Microprobe Laboratory, of the Geological Survey of Canada (GSC), Ottawa, Canada, using a Sensitive Resolution Ion Microprobe (SHRIMP II). This technique was used to date zircons from rocks that demonstrated complicated histories, in order to distinguish the different periods of zircon growth. The analytical methods of zircon U–Pb–Th age determinations using the SHRIMP of GSC are reported in Stern (1997). The zircon grains were mounted in epoxy together with the zircon standard and grains were then sectioned, polished and photographed. Scanning electron microscope cathodoluminescence imaging was carried out to detect cores, rims and other complexities, which might be present, and to ensure that no areas of mixed age were analyzed. Analyses were performed using a 3-nA primary ion beam and a 30 µm spot (70 µm Kohler aperture), except for a few cases of thin overgrowths where the beam size was reduced to 10 × 13 µm. Pb/U ratios were determined relative to standard BR266 (559 Ma and 910 ppm U). Standards were analyzed after every five or six unknowns to monitor the stability of calibration. All age calculations and statistical assessments of the data have been done utilizing the geochronological software package ISOPLLOT/EX (version 2.00) of Ludwig (1999). Data reduction used the SQUID software (Ludwig, 2001).

3.3. Nd and Sr isotope analysis

In selected samples, neodymium and samarium were separated for isotopic analysis by standard cation exchange procedures following HF–HNO₃–HCl dissolution of whole-rock powders and

Table 1
Geochronological overview of the available data for Serrinha nucleus rocks. Anf = amphibole, Bt = biotite, Sph = sphene, Zr = zircon, Mc = muscovite, Hb = hornblende, Ep = epidote, Ap = apatite, X = xenotime, Fc = fuchsite, Cl = chlorite, WR = whole rock, Inh = inheritance, M = metamorphism, D = deformation, S = sedimentation, H = hydrothermal zone, O = overgrowth. When nothing else is specified, U–Pb and Pb–Pb analysis are for single zircon crystals.

Unit	Pluton								
	U–Pb (Ma)	Pb–Pb (Ma)	Rb–Sr (Ma)	Sr	K–Ar (Ma)	Ar–Ar (Ma)	Sm–Nd _{WR} (Ma)	<i>T</i> _{DM} (Ga)	εNd
Gneiss-migmatitic basement: UAUA (UC) and Santa Luz (SLC) complex									
Caldeirao Quartzite (UC)	2076 ± 10 ^(M) , 2687 ± 16 ^(S) , 3051 ± 13 to 3204 ± 9 ^(Inh) (a,i)							3.18 ^(a)	
Uaua Granodioritic ortho-gneiss (UC)	2991 ± 22 to 3152 ± 5 ^(a,i)				1800–2200 ^{Anf, Bt} (b)			3.05 ^(e)	1.61 ^(e)
Enderbite Granulite (UC)	2933 ± 3 ^(a)							3.13 ^(e)	–0.69 ^(e)
TTG Retirolandia	3085 ^(g)							3.12 ^(g)	1.16 ^(g)
Enderbite Orthogranulite Rio das Vargens/Lagoa da Vaca (UC)		3072 ^(M) (f,h)						3.28–3.37 ^(e)	–2.22 to –0.57 ^(e)
Gneiss TTG UC	2077 ± 11 ^(O) , 2956 ± 39 to 3070 ± 3 ^(ah)		2700–3100 ^(c)	0.7010–0.7040 ^(c)				2.96–3.26 ^(e,ah)	–1.81 to +1.69 ^(e,ah)
Gneiss SLC Amphibolite Dykes UC		2049 ± 2 ^{Sph} , 2600–2780 ^{Zr} (i)	2500–3000 ^(d) 2033 ± 64 ^(d)	0.7020 ^(d)	2144–1933 ^{Anf} (c)		2895 ± 170 ^(e)		
Noritic Dykes UC							2744 ± 65 ^(e)		
Toleitic Dykes UC	2039 ± 2 ^(M) , 2778 ± 7 ^(ah)						2586 ± 66 ^(e)	2.79 ^(ah)	
Group 1 granitoids									
Ambrosio Gneiss	2930 ± 32 ^(m) ; 3094 ± 21, 3159 ± 18 ⁽ⁱ⁾	1948 ± 28 ^(ab)	2597 ± 272 ^(l)	0.7084 ^(l)					
Ambrosio Massive Granodiorite	2077 ± 2 ^(O, M) , 2937 ± 16, 3111 ± 13, 3162 ± 13 ⁽ⁱ⁾								
Ambrosio Porphyritic Granodiorite	2063 ± 55 ^(O, M) , 2975 ± 7, 3126 ± 5 ⁽ⁱ⁾								
Lagoa das Vacas Anorthosite Complex		3161 ± 65 ^(h)							
Rio Capim Tonalite	2050–3130 Ma ^(g)	2650, 2900, 3000 ^(e)	3120 ^(e)						
Pedra Alta Curral	2650–3000 ^(o)	2076 ± 19 ^(M) , 2468 ± 3 ^(Inh) , 2862 ± 5 ^(ab)	1961 ± 32 ^(d)	0.7110 ^(d)					
Poco Grande	2079 ± 47 ^{Mz} (13), 2645 ± 70 ⁽ⁿ⁾					2023 ± 13 ^{Mc} (k)			
Araci			2002 ± 55, 2234 ± 84 ^(d)	0.7049, 0.7025 ⁽⁴⁾					
Greenstone belts Itapicuru and CAPIM									
Felsic Dyke Rio Capim		2293 ± 114 ^(u)							
Volcanic Felsic Unit Rio Capim		2153 ± 79 ^(u)							
Rio Capim Metapelite								2.52 ^(a)	
Leucogabbre Rio Capim	2143 ± 21 ^(u)								

Table 1 (Continued)

Unit	Pluton								
	U–Pb (Ma)	Pb–Pb (Ma)	Rb–Sr (Ma)	Sr	K–Ar (Ma)	Ar–Ar (Ma)	Sm–Nd _{WR} (Ma)	T _{DM} (Ga)	εNd
Diorite Rio Capim	2148 ± 23 ^(u)								
Mafic-Basal Unit Itapicuru	2107 ± 23 ^{WR} ⁽ⁿ⁾	2178 ± 12 ^{Ep, Ap, Zr} ^(m) ; 2209 ± 60 ^{WR} ^(r,s)		0.7027 ^(a,s)		2080 ± 5 ^{Hb} , 2108 ± 5 ^{Hb} ^(r,s)		2.20 ^(s)	−1.12 ^(h) , +4.0 ^(s)
Felsic-Intermediate Unit Itapicuru		2109 ± 80 ^{WR} ^(r)	2080 ± 90, 2000 ± 200 ^(q)	0.7017 ^(q)	2110 ± 30 ^{Mc} , 2124 ± 37 ^{Bt} ^(s)			2.12 ^(s)	2.0 ^(s)
Sedimentary Unit Itapicuru			2089 ± 85 ⁽ⁿ⁾	0.7016 ⁽ⁿ⁾				2.44–2.49 ^(a)	
Metagabbro sill and associated hydrothermal rocks/Itapicuru							2142 ± 47 ^(ae)		1.2 ^(ae)
Group 2 granitoids									
Trilhado Undeformed Granodiorite	2152 ± 6 ^{Mz} , 2155 ± 9 ⁽ⁱ⁾			0.7017 ⁽ⁱ⁾				2.20, 2.22 ⁽ⁱ⁾	2.41, 2.65 ⁽ⁱ⁾
Nordestina Trondhjemite		2100 ± 10 ^{Zr} ^(k) ; 2155 ± 9 ^(w)	2000 ^(m) ; 2114 ± 103 ^(q)	0.7030 ^(m) ; 0.7050 ^(q)				2.24 ^(w)	1.12 ^(w)
Teofilandia Tonalite	2071 ± 10 ⁰ and 2130 ± 7 ⁽ⁱ⁾			0.7025 ⁽ⁱ⁾				2.21 ^(h)	2.14 ⁽ⁱ⁾
Barrocas Tonalite		2127 ± 5 ^{Zr} ^(k)				2029 ± 13 ^{Bt} ^(k) 2030 ± 100 ^{Bt} ^(v)			
Lagoa dos Bois Granodiorite	2107 ± 23 ^(m)								
Group 3 granitoids									
Morro do Afonso	2111 ± 10 ^(z)	2098 ± 9 Zr and 2641 ± 4 ^(lnh) Zr ^(z)		0.7033–0.7042 ^(z)				2.56–2.58 ^(z)	−2.36 to −2.80 ^(z)
Cansancao Serra do Pintado	2098 ± 2 ^(aa)	2105 ± 3 ^(ab)	2025 ± 47 ^{WR} ^(y)	0.7033 ^(y) 0.7022 ^(aa)				2.40 ^(y) 2.69 ^(aa)	−3.00 ^(y) −4.17 ^(aa)
Morro das Agulhas-Bananas		2086 ± 17 ^{Zr} ^(aa)							
Morro do Lopes Type (MLG) Granodiorite					1791 ± 53 ^{Bt} ^(q)				
Barroquinhas (MLT)			1962 ^{WR} ^(x)	0.7466 ^(x)					
Maravilhas (MLT)	2071 ± 1 ^(af)			0.8081 ^(af)				3.13 ^(af)	
Santa Luz (MLT)			2064 ± 25 ^{WR} ^(q)	0.7031 ^(q)					

Late intrusions and mineralization					
Gold: Scheelita			0.7024 to 0.7060 ⁽ⁱ⁾	2050 ± 4 ^{Fc} , 2054 ± 2 ^{Cl} , 2040 to 2065 ^{Bt} ⁽ⁱ⁾ ; 2031 ± 4 to 2083 ± 4 ^{Bt} , 2049 ± 4 ^{Mc} ^(ac) 2080 ± 5 ^M ⁽ⁱ⁾	1.97 to 2.14 ⁽ⁱ⁾ 1.68 to 6.61 ⁽ⁱ⁾
Fazenda Brasileiro Mine					
Amphibolites, pegmatites and granodioritic dykes cutting Ambrosio Quartz-Feldspar	2080 ± 2 ^X ⁽ⁱ⁾ ; 2079 ± 47 ^(m)	1900 ^(l) ; 2000 ± 60 ^(q) ; 2015 ± 59 and 2031 ± 59 ^(ad)	0.7080 ^(l,m) , 0.7099 ⁽ⁿ⁾		
Porphyry Dyke cutting Teofilândia	2071 ± 9 ^o , 2128 ± 8 ⁽ⁱ⁾				2.18 ⁽ⁱ⁾ 2.45 ⁽ⁱ⁾

^jMascarenhas and Sa (1982); ^pOliveira et al. (2004); ^{ag}Rios et al. (submitted for publication); ^{ai}Chauvet et al. (1997b).

^a Oliveira et al. (2002).

^b Bastos Leal (1992).

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^{ac} Vasconcelos and Becker (1992).

^{ad} Teixeira (1993).

^{ae} Pimentel and Silva (2003).

^{af} Rios (2002).

^{ah} Oliveira et al. (2000).

Table 2

SHRIMP data for Serrinha nucleus rocks. Analyzed zircon crystals are colorless, euhedral and inclusion free, except as described above. Pb_{Com} = common Pb, considering that they all have the isotopic composition of the lab blank. Ab = abraded, zr = zircon crystal, clr = clear, brk = broked, elong = elongated, transp = transparent, Hf = Hf collected, spr = short prism, lpr = long prism, incl = inclusions, no chem = no chemistry/collumns, irr = irregular shape, round = rounded shape. The system of coordinates is UTM (SAD 69).

Analysis no.	U (ppm)	Th (ppm)	²³² Th/ ²³⁸ U ^a	²⁰⁴ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	2σ	²⁰⁷ Pb/ ²³⁵ U	2σ	²⁰⁶ Pb/ ²³⁸ U (Ma)	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb (Ma)	1σ	Disc. (%) ^b	Corr. coeff.
NS 2830: Maracana basement gneiss-migmatite (UTM 447628 and 8892989) (ca. 3166 e 2079 Ma) ^c														
9053-8.1	72	48	0.69	0.000184	.5758	.0119	18.13	0.41	2931	49	3041	14	4	.926
9053-15.1	111	13	0.12	0.000034	.5798	.0148	18.08	0.48	2948	60	3025	10	3	.970
9053-35.1	117	58	0.51	0.000045	.5779	.0108	17.86	0.36	2940	44	3011	12	2	.925
9053-17.1	161	89	0.57	0.000012	.5516	.0114	16.41	0.35	2832	47	2949	9	4	.964
9053-10.1	579	26	0.05	0.000016	.3938	.0070	7.01	0.13	2140	33	2087	7	–3	.977
9053-29.1	427	55	0.13	0.000059	.3656	.0060	6.50	0.11	2009	28	2084	10	4	.948
9053-37.1	340	32	0.10	0.000053	.3717	.0063	6.52	0.12	2037	30	2059	10	1	.947
NS 1351: Ambrosio pluton (UTM 476160 and 8759943) (3162 ± 26 Ma) ^d														
9060-25.1	61	26	0.45	0.000225	.6054	.0143	20.87	0.53	3051	57	3185	15	4	.927
9060-29.1	306	203	0.69	0.000028	.6338	.0107	21.63	0.38	3164	42	3169	8	0	.957
9060-1.1	51	20	0.41	0.000010	.6235	.0141	21.18	0.52	3124	56	3161	15	1	.923
9060-19.1	64	32	0.52	0.000085	.6082	.0132	20.61	0.48	3063	53	3157	14	3	.930
9060-18.1	88	33	0.39	0.000058	.6452	.0173	21.72	0.60	3210	68	3147	12	–2	.963
9060-30.1	53	24	0.47	0.000176	.6479	.0147	21.77	0.57	3220	58	3144	20	–2	.875
9060-1.2	1435	313	0.23	0.001076	.2930	.0028	7.87	0.13	1657	14	2783	22	68	.593
9060-9.1	1301	14	0.01	0.006270	.1377	.0019	2.16	0.18	832	11	1861	150	124	.167
NS 1599: Araci pluton (UTM 499063 and 8782049) ^d														
9061-4.1	55	70	1.32	0.000375	.3759	.0095	6.49	0.22	2057	45	2032	39	–1	.757
NS 1602: Araci pluton (UTM 494382 and 8784504) ^d														
9055-2.1	379	26	0.07	0.000034	.3746	.0063	6.58	0.12	2051	29	2063	11	1	.941
9055-3.1	220	32	0.15	0.000067	.3721	.0066	6.53	0.13	2039	31	2061	13	1	.920
NS 1555: Requeijao (UTM 433371 and 8779131) (2989 ± 11 Ma) ^d														
9057-30.1	104	59	0.59	0.000124	.6051	.0122	18.46	0.40	3050	49	2990	12	–2	.939
9057-12.1	110	69	0.64	0.000000	.5701	.0111	17.38	0.36	2908	46	2989	11	3	.942
9057-29.1	228	55	0.25	0.000118	.5495	.0096	16.59	0.30	2823	40	2973	8	5	.958
9057-9.1	210	18	0.09	0.000141	.5526	.0100	16.46	0.31	2836	41	2951	10	4	.945
9057-24.1	413	86	0.22	0.000026	.5370	.0092	15.45	0.27	2771	39	2895	7	4	.973
9057-5.1	749	170	0.23	0.000372	.4067	.0067	10.21	0.19	2200	31	2672	13	21	.908
9057-28.1	619	114	0.19	0.000559	.2708	.0045	6.74	0.13	1545	23	2658	17	72	.857
9057-39.1	55	70	1.32	0.000375	.1899	.0033	3.28	0.09	1121	18	2032	39	81	.618
NS 1399: Efaceas pluton (UTM 456913 and 8781230) (2163 ± 8 Ma) ^e														
9062-3.1	60	15	0.25	0.000264	.3606	.0114	6.79	0.24	1985	54	2184	30	10	.879
9062-13.1	85	22	0.27	0.000327	.3849	.0080	7.22	0.19	2099	37	2178	30	4	.774
9062-1.1	241	67	0.29	0.000098	.4062	.0071	7.56	0.15	2198	32	2165	15	–1	.891
9062-9.1	123	32	0.27	0.000183	.3937	.0075	7.19	0.16	2140	35	2132	21	0	.844
NS 1543: Cipo pluton (UTM 434504 and 8758260) (2160 e 2080 Ma) ^e														
9056-1.1	139	24	0.18	0.000046	.3841	.0073	7.19	0.15	2095	34	2175	17	4	.885
9056-5.1	139	24	0.18	0.000046	.3705	.0072	6.94	0.15	2032	34	2175	17	7	.891
9056-4.1	265	120	0.47	0.000035	.3975	.0069	7.41	0.14	2158	32	2166	11	0	.941
9056-7.1	486	210	0.45	0.000045	.3743	.0063	6.75	0.12	2050	29	2107	8	3	.963

9056–11.1	383	218	0.59	0.000006	.3675	.0061	6.58	0.12	2018	29	2096	11	4	.934
9056–5.2	300	135	0.47	0.000057	.3817	.0065	6.82	0.12	2084	30	2092	11	0	.939
9056–15.1	725	508	0.72	0.000319	.1976	.0032	2.95	0.08	1163	17	1772	41	52	.588
NS 2595: Itareru Lamprophyre (UTM 469701 and 8749159) (2113 ± 5 Ma) ^f														
9063–4.1	300	242	0.83	–0.000013	.4002	.0068	7.31	0.13	2170	31	2131	10	–2	.947
9063–51.1	317	193	0.63	0.000007	.3763	.0064	6.84	0.12	2059	30	2123	11	3	.942
9063–53.1	361	343	0.98	0.000004	.3945	.0066	7.17	0.13	2144	30	2122	10	–1	.943
9063–51.2	182	143	0.81	0.000041	.3704	.0067	6.71	0.13	2031	31	2117	15	4	.905
9063–25.1	297	293	1.02	0.000035	.3955	.0067	7.13	0.13	2148	31	2109	10	–2	.950
9063–49.1	360	349	1.00	0.000071	.3885	.0066	6.99	0.13	2116	31	2106	13	0	.921
9063–18.1	238	162	0.70	0.000140	.3831	.0067	6.89	0.13	2091	31	2103	15	1	.903
9063–38.1	243	159	0.68	0.000035	.3898	.0077	6.98	0.14	2122	36	2097	11	–1	.951

^a Th/U calculated from radiogenic ²⁰⁸Pb/²⁰⁶Pb ratio and ²⁰⁷Pb/²⁰⁶Pb age assuming concordance.

^b Disc., percent discordance for the given ²⁰⁷Pb/²⁰⁶Pb age.

^c Basement units: UAU complex.

^d Group 1 granitoids.

^e Group 2 granitoids.

^f Group 3 granitoids.

subsequently analyzed on a mass spectrometer at McMaster Isotope Geochronology Laboratory using a VG 354 automated thermal ionization mass spectrometer following established procedures (Holmden and Dickin, 1995). Rb/Sr ratios were determined by ICP-MS at Activation Laboratories, Ancaster, Ontario, Canada, using a calibration against international standards. Some data were also checked against “blind” standards previously analyzed by isotope dilution at McMaster. Detection limits are 0.01 ppm for Sm and 0.05 ppm for Nd. The notations of ϵ_{Nd} and $f_{\text{Sm}/\text{Nd}}$ are defined according to common equations (Faure, 1986). The Nd and Sr isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$ and $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$, respectively. During the course of this work, the mean value obtained for $^{143}\text{Nd}/^{144}\text{Nd}$ from La Jolla was 0.51185 ± 0.00002 (2σ) and for $^{87}\text{Sr}/^{86}\text{Sr}$ from NBS 987 was 0.71030 ± 0.00004 (2σ), in agreement with recommended values for these standards. The Sm/Nd spike has been calibrated against several rock standards from different isotope labs, and gives a Sm/Nd ratio of 0.2280 ± 0.0002 for the USGS standard BCR-1. The decay constant for ^{87}Rb ($1.42 \times 10^{-11}/\text{yr}$) is taken from Davis et al. (1977) and for ^{147}Sm ($6.54 \times 10^{-12}/\text{yr}$), from Lugmair and Marti (1978).

4. Results

Isotopic analysis are given in Table 2 for SHRIMP and in Table 3 for ID-TIMS. Rb–Sr and Sm–Nd data are presented in Table 4. Uncertainties in the isotopic ratios and ages in the data tables (and in the error ellipses in the plotted data) are reported at the 2σ level. Where ages are calculated from combined data or from regression analysis, errors are quoted at 95% confidence limits. Results are presented in chronological order from oldest to youngest. Detailed descriptions of the units sampled are given in Rios (2002).

4.1. Pre-tectonic Mesoarchean granitoid rocks

The lithologies of the Serrinha nucleus basement are represented by the Uauá complex in the north, which has been correlated with the Congo craton (Bellieni et al., 1995), and by the Santa Luz complex in the south. These complexes are composed of gneissic migmatite with amphibolitic layers and banded gneiss and gneiss with garnet and sillimanite, which seems to surround the gneissic migmatite. These rocks were metamorphosed to amphibolite-facies, have tonalitic-granodioritic and quartz-feldspathic compositions, and include subordinate amphibolite and meta-ultramafic rock types (Bellieni et al., 1995). They were partially remobilized during the Transamazonian orogeny (Beurlen, 1970; Winge, 1984; Bastos Leal, 1992). Numerous less eroded granitic plutons cut the gneissic lithologies.

The general orientation of the gneissic fabric is 315° – 330° dipping steeply SW. Aerial photography and Landsat images reveal complex structural relationships, suggesting the existence of several deformational events. Amphibolite rocks occur as enclaves, or as concordant and discordant layers. There are many hypotheses to explain the genesis of these mafic rocks, from marginal sediments (Inda et al., 1976) to mafic meta-volcanic rocks from the greenstone belts (Mascarenhas et al., 1979; Melo et al., 1995). The greenschist facies metamorphism affects both the gneiss and amphibolite and is here interpreted as an effect of Palaeoproterozoic regional metamorphism.

Based on whole-rock litho-geochemical studies (see Rios, 2002 for details), there are no significant differences between the gneisses of the Santa Luz and Uauá complexes. All the gneissic rocks show a small range of silica contents ($69.9\% < \text{SiO}_2 < 75.8\%$), being predominantly potassic ($0.3 > \text{K}_2\text{O}/\text{Na}_2\text{O} > 3.1$, ratios from 0.9 to 3.8

Table 3
 ID-TIMS data for Serrinha nucleus rocks. Ab = abraded, zr = zircon, cl = clear, incl = inclusion, no chem = no chemistry, brk = broked, elong = elongated, frag = fragment, col = collected, rnd = rounded, lpr = long prism, irreg = irregular. Th/U calculated from the radiogenic $^{208}\text{Pb}/^{206}\text{Pb}$ ratios and $^{207}\text{Pb}/^{206}\text{Pb}$ ages, considering concordance. % Disc: percentual of discordance for the $^{207}\text{Pb}/^{206}\text{Pb}$ presented age; decay constants from Jaffey et al. (1971). The system of coordinates is UTM (SAD 69).

Zr. no.	Analyzed fraction description	Weight (mg)	U (ppm)	Th/U	Pb _{com} (pg)	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	2 σ	$^{207}\text{Pb}/^{235}\text{U}$	2 σ	$^{207}\text{Pb}/^{206}\text{Pb}$ age (Ma)	2 σ	% Disc.	Corr. coeff.
NS 1552: Valente basement gneiss (UTM 457994 and 8739173) (3102 ± 5 Ma) ^a														
3	1 ab zr, pink, clr, brk, seems to have core, no chem	0.0030	87.5	0.54	1.07	2289.8	0.6136	0.0071	20.001	0.233	3096	2	0.5	0.99541
1	1 clr, ab zr, black incl, no chem	0.0030	49.3	0.39	0.67	2075.0	0.6124	0.0023	19.931	0.080	3094	2	0.6	0.96537
2	1 small, clr, ab zr, no chem	0.0005	142.4	0.27	1.68	284.8	0.4901	0.0018	13.667	0.061	2845	3	11.6	0.89223
4	1 ab brown zr, elong, clr, no chem	0.0010	141.4	0.61	0.74	617.2	0.3775	0.0018	6.748	0.032	2093	4	1.6	0.90631
NS 1662: Amphibolite layer (443339 and 8858224) (2078 ± 2 Ma) ^a														
2	1 ab zr fragment, shiny, pale pink, clr, transp, Hf	0.0050	54.1	0.28	1.88	466.5	0.3788	0.0009	6.716	0.020	2079	3	0.5	0.87253
3	1 ab zr, core?, anedric, round, pale pink, clr, Hf	0.0150	27.8	0.28	1.37	965.6	0.3792	0.0010	6.723	0.019	2079	2	0.4	0.91452
1	1 ab zr, frosted fragment, cloudy	0.0080	25.8	0.28	3.24	214.6	0.3797	0.0018	6.729	0.040	2078	6	0.2	0.85235
4	1 ab zr, flat, from core dish, pale pink, clr, no chem	0.0020	43.6	0.28	1.17	250.0	0.3813	0.0020	6.746	0.040	2075	5	−0.4	0.89250
NS 2830: Maracana basement gneiss-migmatite (overgrowths) (UTM 447628 and 8892989) (2070 ± 32 Ma) ^a														
1	1 Ab tip, pale brown	0.0010	1074	0.10	9.33	369.5	0.3739	0.0014	6.607	0.028	2073	3	1.4	0.90002
2	1 Ab tip, pale brown	0.0010	381.1	0.09	2.88	419.1	0.3723	0.0015	6.560	0.029	2068	3	1.6	0.90898
NS 1351: Ambrosio pluton (UTM 476160 and 8759943) (3068 ± 6 Ma) ^b														
2	1 big rounded zr, clr	0.0020	70.3	0.68	1.18	1219.5	0.6343	0.0027	21.642	0.095	3169	2	0.1	0.96944
3	1 abr zr overgrowth	0.0015	4.2	0.25	0.49	132.4	0.6094	0.0110	19.654	0.366	3079	9	0.5	0.95011
1	1 ab zr, big crack, clr, not well ab, no chem	0.0040	242.1	0.18	6.85	1054.1	0.4902	0.0017	15.796	0.059	3078	2	19.9	0.95943
5	1 ab zr, cracks?, cores?, no chem	0.0010	146.6	0.17	1.65	364.2	0.3009	0.0010	8.451	0.034	2856	3	46.0	0.90154
6	1 zr, crack free?, melt incl on middle	0.0080	49.5	0.45	23.74	80.4	0.3054	0.0010	8.565	0.084	2853	16	45.1	0.23433
4	1 ab zr overgrowht, no chem	0.0030	30.9	0.21	3.26	49.1	0.1398	0.0006	2.534	0.049	2117	28	64.0	0.81159
NS 1599: Araci pluton (UTM 499063 and 8782049) (~ 3070 Ma) ^b														
3	1 ab zr, angular, not well abraded, clr, no chem	0.0005	88.7	0.53	0.82	438.7	0.5307	0.0026	16.863	0.086	3055	3	12.5	0.91998
1	1 ab zr, clr, shine, cloudy spot on surface	0.0030	48.3	0.08	13.87	91.8	0.5396	0.0376	15.672	1.442	2911	103	5.4	0.71359
2	1 abr zr, clr, with a cloudy crack(?), no chem	0.0020	138.6	0.62	2.31	373.8	0.2260	0.0013	6.409	0.035	2872	5	59.7	0.84538
NS 1555: Requeijao pluton (UTM 433371 and 8779131) (~ 2870 Ma) ^b														
2	1 abr zr overgrowth, no chem	0.0005	157.1	0.79	1.59	279.7	0.4169	0.0027	11.461	0.081	2821	5	24.1	0.91541
4	1 abr zr overgrowth, no chem	0.0005	177.2	1.44	1.46	357.0	0.4427	0.0025	12.065	0.068	2807	5	18.9	0.85536
1	5 small zr grains, pale pink, clr	0.0040	86.5	0.54	2.83	572.4	0.3654	0.0018	9.789	0.051	2779	3	32.2	0.95128
3	1 ab zr overgrowth, no chem	0.0005	144.5	0.39	1.75	223.8	0.4232	0.0017	10.843	0.055	2706	4	18.9	0.85485
5	1 no ab zr, flat, spr, cracked, altered, Hf	0.0050	76.6	0.27	6.18	188.1	0.2647	0.0032	5.981	0.073	2496	9	44.0	0.89526
NS 1399: Efaceas pluton (UTM 456913 and 8781230) (2163 ± 5 Ma) ^c														
2	1 ab zr, clr, elong, with small black incl, no chem	0.0004	91.0	0.27	0.70	188.3	0.3837	0.0022	7.097	0.050	2153	7	3.2	0.82405
1	1 clr ab zr, no chem	0.0005	215.4	0.34	0.92	391.9	0.3745	0.0011	6.910	0.025	2149	4	5.3	0.78810
3	1 brown ab zr, little cloudy, no chem	0.0005	371.9	0.31	0.32	1546.6	0.3165	0.0010	5.692	0.020	2104	2	18.0	0.95691
NS 1543: Cipo pluton (UTM 434504 and 8758260) (2164 ± 2 Ma) ^c														
1	1 ab zr, clr, rounded, no chem	0.0015	127.6	0.52	1.79	384.2	0.3983	0.0011	7.421	0.025	2166	3	0.2	0.85658
2	1 ab zr, clr, rounded, melt inclusion, Hf	0.0040	129.2	0.52	3.58	506.4	0.3930	0.0044	7.313	0.081	2163	5	1.4	0.97071
3	1 ab zr, pink, clr, rounded, no chem	0.0020	68.9	0.23	0.71	651.9	0.3823	0.0019	7.039	0.037	2145	3	3.1	0.95391
4	1 ab zr, elong, clr, no chem	0.0020	53.5	0.57	0.69	508.2	0.3812	0.0015	6.795	0.030	2088	3	0.4	0.92134
NS 1358: Itareru Shoshonitic pluton (UTM 468465 and 8741159) (2106 ± 2 Ma) ^d														
3	1 clr, ab zr, with bubble incl, cloudy, no chem	0.0010	100.7	0.32	0.97	367.1	0.3925	0.0016	7.298	0.032	2162	4	1.5	0.84965
2	1 ab zr tip, clr, pale brown, no chem	0.0005	288.4	0.48	2.63	184.8	0.3680	0.0014	6.625	0.034	2106	7	4.7	0.64229
1	1 brown ab zr tip, broked, turbid, no chem	0.0010	350.9	0.43	1.19	947.0	0.3758	0.0010	6.765	0.021	2106	2	2.7	0.92662
4	1 pale pink, clr, ab zr, rounded, no chem	0.0030	32.0	0.42	1.21	264.6	0.3747	0.0013	6.745	0.031	2106	4	3.0	0.84950

NS 1664: Pedra Vermelha Massif (UTM 445681 and 8854669) (2080 ± 8 Ma) ^d														
2	1 small, clr, ab zr, no chem	0.0003	116.6	0.52	0.54	217.8	0.3790	0.0020	6.713	0.045	2077	8	0.3	0.75945
4	1 ab zr frag, pink, clr, little cloudy, incl, no chem	0.0005	121.3	0.39	1.12	172.5	0.3527	0.0030	6.226	0.058	2071	12	6.9	0.70993
3	1 ab zr, pink, shine, clr, no chem	0.0010	161.2	0.62	1.28	317.8	0.3013	0.0008	5.156	0.018	2016	4	17.9	0.79400
1	1 pale pink, irreg shape, ab zr frag, clr, no chem	0.0010	180.1	0.32	2.04	218.5	0.2887	0.0076	4.938	0.135	2015	15	21.4	0.95362
NS 1587: Barroquinhas Massif (UTM 491748 and 8723673) (2073 ± 1 Ma) ^d														
2	2 small zr, irreg shaped, elong, round, clr, pale pink, no chem	0.0030	186.4	0.68	0.58	3000.8	0.3776	0.0014	6.681	0.026	2075	2	0.5	0.95286
3	1 ab zr with cracks, clr, pink, Hf	0.0200	183.7	0.67	2.49	4553.0	0.3737	0.0009	6.607	0.018	2074	1	1.5	0.95252
1	1 big single zr grain, pink, clr, rounded, Hf	0.0100	159.4	0.64	1.28	3911.2	0.3796	0.0009	6.708	0.018	2073	2	−0.1	0.93937
4	1 ab zr, cracks, brown, no chem	0.0040	310.6	0.54	0.99	3856.8	0.3724	0.0027	6.578	0.049	2072	2	1.8	0.98741
5	1 ab zr, clr, pale pink, well rounded, no chem	0.0010	145.1	0.72	1.77	263.9	0.3696	0.0015	6.514	0.032	2068	4	2.3	0.86016
NS 1436: Fazenda Bananas Massif (UTM 444530 and 8759162) (2072 ± 1 Ma) ^d														
4	1 brown zr grain, elong, clr, zoned, no chem	0.0010	409.0	0.56	0.84	1462.8	0.3613	0.0008	6.422	0.017	2083	2	5.3	0.93636
1	2 geminated brown zr, clr, no chem	0.0030	218.0	0.57	1.02	1981.7	0.3746	0.0014	6.619	0.026	2073	2	1.2	0.95796
2	1 pale pink, large zr grain, clr, irreg	0.0070	153.8	0.99	0.96	3488.6	0.3768	0.0010	6.654	0.019	2072	2	0.6	0.93595
3	1 clr zr grain, small, pale pink, rounded	0.0010	53.7	2.18	1.95	83.8	0.3095	0.0016	5.320	0.059	2024	16	16.1	0.58464

^a Basement units: UAUA and Santa Luz complex.

^b Group 1 granitoids.

^c Group 2 granitoids.

^d Group 2 granitoids.

Table 4
Rb–Sr and Sm–Nd data for Serrinha nucleus rocks.

Sample number	Age (Ga)	Rock type	Sm (ppm)	Nd (ppm)	¹⁴³ Nd/ ¹⁴⁴ Nd	¹⁴⁷ Sm/ ¹⁴⁴ Nd	<i>T</i> _{CHUR} (Ga)	<i>T</i> _{DM} (Ga)	<i>E</i> _{Nd(0)}	<i>E</i> _{Nd(T)}	<i>f</i> _{Sm/Nd}	¹⁴⁷ Sm/ ¹⁴⁴ Nd _{Sam}	<i>I</i> _{Nd}	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	<i>I</i> _{Sr}
1536	2.79	Capim Diorite	5.54	23.1	0.511830	0.1449	2.37	2.75	−15.76	2.89	−0.21	0.16	0.509159	71	509	0.4040	0.71574	0.699395
1599	3.07	Araci Monzo-granite	5.65	34.2	0.510718	0.0997	3.00	3.12	−37.45	0.93	−0.41	0.12	0.508696	204	129	4.6350	0.83671	0.630183
1381	3.08	Pedra Alta Trondhjemite	2.02	14.5	0.510362	0.0842	3.03	3.17	−44.40	0.23	−0.52	0.09	0.508650	62	480	0.3740	0.71672	0.700011
1399	2.16	Eficeas Biotite-Trondhjemite	4.98	28.1	0.511441	0.1068	2.02	2.30	−23.35	1.64	−0.41	0.12	0.509919	75	120	1.8130		
1630	2.16	Quijingue Granodiorite	0.94	6.9	0.510423	0.0822	2.93	3.27	−43.21	−11.57	−0.53	0.09	0.509256	76	476	0.4630	0.71952	0.705133
1613	2.10	Euclides Syeno-Granite	13.81	88.9	0.510880	0.0939	2.62	2.87	−34.29	−6.64	−0.50	0.10	0.509583	236	129	5.3710	0.85636	0.694021
1650	2.08	Araras Monzonite	45.40	334.0	0.510656	0.0820	2.42	2.96	−38.66	−8.12	−0.57	0.09	0.509535	190	1110	0.4960	0.72001	0.705171
1548	2.10	Serra do Pintado Syenite	18.54	113.9	0.511068	0.0984	2.37	2.69	−30.63	−4.07	−0.47	0.11	0.509709	199	1040	0.5550	0.71896	0.702185
957	2.10	Morro do Afonso Syenite	19.89	111.7	0.511289	0.1078	2.30	2.56	−26.31	−2.36	−0.45	0.11	0.509800	235	1764	0.3861	0.71567	0.703994
1587	2.07	Barroquinhas Granite	7.26	45.8	0.510723	0.0958	2.59	3.13	−37.33	−10.54	−0.46	0.11	0.509415	259	93	8.2380	0.93432	0.688217
1642	2.07	Maravilhas Granodiorite	5.53	38.1	0.510944	0.0877	3.06	2.67	−33.04	−4.07	−0.52	0.09	0.509748	187	155	3.5260	0.80812	0.702887

Fig. 3. Sample 2830–Migmatite-gneiss Maracana, Uauá complex. (A) Zircon population. (B) BSE images of analyzed crystals. (C) SHRIMP Concordia diagram.

predominate) and peraluminous. They correspond to granodiorites and sub-alkaline granites, mostly of TTG tendency. The REE patterns are LREE enriched, showing small anomalies of Eu (positive and negative) and similarity with Archaean TTG suites.

Rios et al. (2008) presented SHRIMP ages of ca. 3300 Ma for an enclave of the gneissic-migmatitic basement related to the Uauá complex, collected near a fault contact with the Quijingue pluton (Fig. 2). These authors identified rounded and transparent zircons with cores and overgrowths of Mesoarchaeoan age (data scatter between about 3072 Ma and 3314 Ma). The youngest data are associated with low Th/U ratios, which they interpreted as an

Archaean high-grade metamorphic event. This gneiss is interpreted as a crustal remnant that underwent a complex history during the Mesoarchaeoan and whose zircon was relatively unaffected by the Transamazonian event.

The amphibolites have chemical similarities with tholeiites, although some of them show a calc-alkaline tendency. These are sodic ($0.1 > \text{K}_2\text{O}/\text{Na}_2\text{O} > 0.6$), metaluminous rocks, showing contents of TiO_2 , FeO_T , MgO , MnO , P_2O_5 , Cr and V which allow them to be classified (Rios, 2002) as tholeiitic. Their REE contents are similar to low enriched MORB (Wilson, 1989) with low fractionation of LREE and nearly flat HREE patterns (Rios, 2002). They are more

enriched in REE than the mafic rocks from the Itapicuru greenstone belt (see Silva, 1987).

Previous Nd isotopic data showed evidence of Paleoproterozoic mantle extraction ages for the oldest gneisses (T_{DM} of 3336 Ma) (Oliveira et al., 1999). Two samples from the gneiss, one from an amphibolite layer and three from intrusive granitoids were selected for this study.

4.1.1. Uauá complex: Maracanã gneiss—sample NS 2830 (ca 3166 Ma, ca 2079 Ma)

Sample NS 2830 was mapped as gneissic-migmatitic basement of the Uauá complex (Inda et al., 1976). The sample was collected near Monte Santo city, northwestern portion of Serrinha nucleus (Fig. 2), from the “Maracanã” dimension stone quarry where the unit is well exposed. The gneissic bands are oriented 315° – 330° , showing steep SW to sub-vertical dips.

The zircon crystals from this sample show well-developed prisms, many of which consist of large fractured cores surrounded by clear light to pale brown overgrowths (Fig. 3A and B). Data from seven U–Pb SHRIMP analysis are reported in Table 2 and plotted in a conventional U–Pb concordia plot in Fig. 3C. All data are near-concordant and plot in two groups. Three spots on overgrowth material give a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2079 ± 34 Ma, whereas 3 spots on cores cluster within error at 3025 ± 13 Ma. The older age likely represents crystallization of a Mesoarchaean protolith, which was partially melted during the Transamazonian event.

Fragments of overgrowth that were broken off the tips of three zircon crystals from this sample and analyzed by ID-TIMS (Table 3) gave slightly discordant data that are slightly outside of error but, overlap with the SHRIMP data. Together, the Paleoproterozoic data cluster gives an isochron model 2 age of 2077 ± 16 Ma. These data suggest that the time of Transamazonian fabric development was quite late and roughly synchronous with late peraluminous potassic plutonism (see below).

4.1.2. Santa Luz complex—Valente gneiss: sample 1552 (3102 ± 5 Ma)

Sample NS 1552 is a peraluminous biotite-trondhjemite gneiss (Rios, 2002) from the southern part of the Serrinha nucleus (Santa Luz complex, Fig. 2), 8 km east of Valente city. Two zircon populations were identified in this sample. [P1] comprises metamict, honey-brown colored, prismatic zircon crystals, some with cores and overgrowths (Fig. 4A), although the cores are extremely altered. [P2] are mainly euhedral, clear, transparent zircon crystals, colorless to brown-pink, some with black inclusions. Four crystals were analyzed by TIMS (Table 3). Analyses 1–3 [P2] are discordant but give an upper intercept age of 3102 ± 5 Ma (Fig. 4B), which is interpreted as the minimum crystallization age of these rocks, as long as no cores were analyzed. Zircon 4 fragment, from a [P1] overgrowth, gave a concordant 2093 ± 4 Ma age (Table 3), in agreement with the age presented by Melo et al. (1995), and suggests that overgrowths of P1 developed late, probably due to the Transamazonian thermal event that accompanied emplacement of the potassic rocks.

The Rb–Sr and Sm–Nd isotopic ratios obtained for sample 1536, another sample of this 3102 Ma gneiss-migmatite collected near Santa Luz City, gave $\epsilon_{\text{Nd}} = +4.99$, $T_{DM} = 2.85$ Ga, and low initial Sr ratio (Table 4).

4.1.3. Amphibolite from Uauá complex—sample 1662 (metamorphic age 2078 ± 2 Ma)

Sample NS 1662 was collected from an amphibolite layer in a gneiss-migmatitic unit from the northwest area of the Serrinha nucleus (Uauá complex, Fig. 2). These amphibolites have a tholeiitic

Fig. 4. Sample 1552—Biotite-Trondhjemite-Gneiss of Santa Luz complex. (A) Zircon population. (B) ID-TIMS Concordia diagram.

affinity, but it is not certain whether they were originally volcanic or intrusive.

The zircon crystals from sample 1662 are of excellent quality (Fig. 5A); large, colorless to pale pink, anhedral to subhedral, rounded, and without inclusions or fractures. Four zircon crystals were analyzed by ID-TIMS and seven by SHRIMP. The results are concordant, and TIMS data give the most precise concordia age of 2078 ± 2 Ma (Fig. 5B, Table 3). This may represent a magmatic age if the protolith were a gabbro that crystallized magmatic zircon. However, it is much more likely that the zircon is metamorphic in origin, since magmatic zircon is relatively rare in mafic rocks.

4.1.4. Ambrósio pluton—sample 1351 (3162 ± 26 Ma)

The Ambrósio pluton forms the largest pluton in the Itapicuru greenstone belt, clearly intruding the lower volcanic sequence (Fig. 2, Matos and Davison, 1987). It was first described by Matos (1988) and later structural details have been studied by Alves da Silva et al. (1993), Chauvet et al. (1997a) and Lacerda (2004). Its rocks are considered chemically similar to the felsic volcanic (intermediate) sequence of the Itapicuru greenstone belt (Silva, 1987; Matos, 1988). Around the Ambrósio pluton is a metamorphic aureole from amphibolite (~500 m) to greenschist facies (Alves da Silva et al., 1993). The borders of the pluton exhibit variable gneissic foliation trends with a generally sub-vertical dip which is also identified in the surrounding volcanic rocks (Matos and Davison, 1987). The core of the pluton is slightly deformed granite and granodiorite, in contrast to the border rocks, which are composed of strongly foliated and banded granite and trondhjemite. Late granitic dykes, similar to the Morro do Lopes granite (~2070 Ma, Rios et al., 2000, 2004, see below), are found on the borders (Argolo, 1993; Alves da Silva et al., 1993; Rios, 2002; Mello et al., 2006). Amphibolite basement xenoliths, probably representative of the

Fig. 5. Sample 1662–Amphibolite layer at Uauá complex. (A) Zircon general population. (B) ID-TIMS Concordia diagram.

mafic volcanic rocks from the Itapicuru greenstone belt, are found near the margins, with linear contacts and concordant N-S foliation.

Sample NS 1351, a peraluminous granodiorite with trondhjemitic affinity, was collected in the central-south core of the Ambrósio pluton, east of Varzea da Pedra village (Fig. 2). This sample yielded zircon crystals that are generally of poor quality (Fig. 6A). Subhedral grains are zoned with some broad zones of intense alteration. Some totally altered zircons are milky white. BSE images show variable euhedral zonation with some thin overgrowths and occasional rounded cores (Fig. 6B). Analyses were done on six single zircons by ID-TIMS and on seven different crystals by SHRIMP with the data plotted on a conventional concordia diagram (Fig. 6C) and presented in Tables 2 and 3. Most ID-TIMS analysis show severe Pb loss, but two near-concordant data yield different ages of $3079 \pm 9 \text{ Ma}$ and $3169 \pm 2 \text{ Ma}$. The younger age is from a fragment of overgrowth that showed unusually low U concentration. The seven SHRIMP analyzed zircon grains generally show magmatic Th/U (>0.39) ratios. The six most concordant SHRIMP data have $^{207}\text{Pb}/^{206}\text{Pb}$ ages that overlap within error and give an average age of $3162 \pm 26 \text{ Ma}$ ($\text{MSWD} = 1.3$), which agrees with the older TIMS analysis (3169 Ma) and is interpreted as the magmatic age of the Ambrósio pluton. Most SHRIMP analysis were carried out on broadly zoned interiors of crystals to avoid alteration. Attempts to date overgrowths resulted in discordant data. One Palaeopro-

terozoic age (9.1) on a high U overgrowth showed very low Th/U (0.01), suggesting that the sample was metamorphosed during the Transamazonian event.

4.1.5. Araci pluton–samples 1599 and 1602 ($3072 \pm 2 \text{ Ma}$ and 2060 Ma)

The Araci pluton, located at the southeastern border of the Serinha nucleus (Fig. 2), was first described as a pre-tectonic body (Matos and Conceição, 1993; Rios et al., 1998). Its western side is in contact with mafic and sedimentary units of the Itapicuru greenstone belt and on the east, it is partially covered by Mesozoic sediments of the Tucano-Reconcavo basin. Most of the contacts are marked by faults.

Sample NS 1599, a monzo-granite, and NS 1602, a syeno-granite, were collected on the northern border of the Araci pluton (Fig. 2). Zircon from these samples shows considerable complexity, including the presence of cores and multiple stages of growth, as well as considerable alteration (Fig. 7A and B).

Three single zircon crystals from NS1599 were selected for ID-TIMS analysis. Zircon 1 ($2911 \pm 103 \text{ Ma}$) showed the least discordant (5%) result, although there is a high error associated with this analysis and its low Th/U ratio (0.08) suggests that it is of metamorphic origin. The other two TIMS analysis are also Archean but quite discordant, defining an upper concordia intercept age of $3072 \pm 2 \text{ Ma}$ (Fig. 7C).

Fig. 6. Sample 1351–Ambrósio Granodiorite. (A) Zircon population. (B) BSE images of SHRIMP analyzed crystals. (C) ID-TIMS and SHRIMP Concordia diagrams.

Only unzoned cores have sufficiently large unaltered domains to be analyzed by SHRIMP (Fig. 7B). Three analysis (2 from sample 1602 and 1 from sample 1599) overlap on concordia giving an age of 2059 ± 8 Ma (Fig. 7C). Two of these grains show low Th/U ratios (0.07 and 0.15), whereas the third is unusually high (Th/U = 1.32, Table 2) for magmatic zircon (1.3). These data might indicate: (i) that the Archaean zircon analyzed by TIMS is xenocrystic; (ii) that the Araci pluton represents a late Transamazonian phase; or (iii) that the zircon analyzed by SHRIMP was derived from late veins within the sample, or are metamorphic in origin.

The Rb–Sr and Sm–Nd isotope ratios obtained for sample 1599 (at 3070 Ma) result in $\epsilon_{\text{Nd}} = +0.93$, $T_{\text{DM}} = 3.12$ Ga, although the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.6302 is unreliable and probably reflects disturbance of this isotopic system.

4.1.6. Requeijão pluton–sample 1555 (2989 ± 11 Ma)

The Requeijão pluton was identified during a regional mapping project (Melo et al., 1995) and described as belonging to the intru-

sive suite of Palaeoproterozoic rocks. Later, Matos and Conceição (1993) and Rios et al. (1998) re-classified this pluton, interpreting it as one of the pre-tectonic granites of the Serrinha nucleus.

The Requeijão pluton is located in the southwestern area of the Serrinha nucleus, near the boundary with the Salvador-Curaçá mobile belt (Fig. 2). Sample NS 1555 is a biotite-granite and it was collected on the north border zone. Most of the zircon crystals are subhedral to euhedral, show overgrowths, and are highly metamict (Fig. 8A). Typically, BSE images show fine oscillatory zoning with thin unzoned overgrowths. Most grains are strongly affected by cracking and alteration (Fig. 8B). ID-TIMS analysis of a fraction of five small crystals (Zr.1), three overgrowths (Zr. 2–4) and one subhedral non-abraded grain (Zr. 5) gave complex results (Table 3). All of the grains are highly discordant (19–44%, Fig. 8C), giving an upper intercept age of 2870 Ma. The accuracy of this result is unclear because of the discordance but it is consistent with a Mesoproterozoic age for the Requeijão pluton.

Fig. 7. Samples 1599 and 1602–Araci Monzo and Syeno-granites. (A) Zircon populations. (B) BSE images of SHRIMP analyzed crystals. (C) ID-TIMS and SHRIMP Concordia diagrams.

As with TIMS, many SHRIMP U–Pb analysis of zoned zircon domains from sample NS 1555 show lead loss (Fig. 8C), but three analysis overlap on, or near, concordia, giving an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2989 ± 11 Ma (MSWD of 0.89). This is interpreted to represent the age of crystallization of this pluton.

4.2. Pre-tectonic Palaeoproterozoic granitoid rocks

We present new geochronological data for two pre-tectonic TTG plutons; the Eficéas and Cipó plutons.

4.2.1. Eficéas pluton–sample 1399 (2163 ± 5 Ma)

Sample NS 1399 is a biotite–trondhjemite from the central area of Eficéas pluton (Fig. 2). The zircon population is represented by small, subhedral to euhedral, elongated, brownish to colourless crystals, some with black and melt inclusions (Fig. 9A). Most are metamict and fractured. Two colourless grains gave relatively concordant data and, together with a more discordant (18%) brownish

grain with a cloudy interior, define an ID-TIMS lead loss line with an upper intercept age of 2163 ± 5 Ma (Fig. 9C, Table 3). The lower intercept age is of 443 ± 30 Ma.

Many grains show unzoned euhedral interiors with zoned overgrowths under BSE (Fig. 9B). Three out of four SHRIMP analysis overlap within error of concordia (Fig. 9C) and define an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2157 ± 23 Ma (MSWD = 1.1). This is consistent with the 2163 Ma TIMS age, which we interpret as the crystallization age for the Eficéas pluton. The Sm–Nd isotope ratio obtained for sample NS 1399 (at 2163 Ma) gives $\varepsilon_{\text{Nd}} = +1.64$, $T_{\text{DM}} = 2.33$ Ga.

4.2.2. Cipó pluton: sample NS 1543 (2164 ± 2 Ma)

The Cipó pluton is located near the western boundary of the Serinha nucleus, almost 5 km from the Salvador–Curaçá mobile belt (Fig. 2). Matos and Conceição (1993) classified it as a late tectonic granite (Morro do Lopes type).

Sample NS 1543 is a peraluminous granite. Its zircon population is composed of translucent to transparent crystals, honey-coloured

Fig. 8. Sample 1555–Requeijão Biotite-Granite. (A) Zircon population. (B) BSE images of SHRIMP analyzed crystals. (C) ID-TIMS and SHRIMP Concordia diagrams.

to colourless, rounded and elongated, subhedral to euhedral, showing zoning typical of magmatic grains, some with black and yellow melt inclusions. Most crystals are altered and metamict, fractured, and rounded (Fig. 10A and B). BSE images show that the zircon grains generally have unzoned euhedral interiors surrounded by zoned overgrowths (Fig. 10B), as with the Eficás pluton above. Rios et al. (1998) reported a Pb–Pb (Kober methodology) zircon age of $2050 \pm 51 \text{ Ma}$ for this sample. U–Pb TIMS analysis were performed on four grains. Regressing three data (from rounded colourless grains), one of which is concordant, gives an upper intercept age of $2164 \pm 2 \text{ Ma}$ with a lower intercept of $886 \pm 160 \text{ Ma}$. One pink to brown elongated, euhedral crystal (Zr. 4) gave a concordant datum at $2088 \pm 3 \text{ Ma}$ (Fig. 10C). Six out of seven SHRIMP data are within error of

concordia (Fig. 10C), but appear to fall into two clusters. The older cluster gives an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2170 \pm 16 \text{ Ma}$ (MSWD = 1.14), whereas the younger cluster is $2100 \pm 11 \text{ Ma}$ (MSWD = 0.74). Most of these analysis were done on unzoned interiors of grains.

Zircon from the Cipó pluton appears to have a bimodal age distribution, as shown by both SHRIMP and TIMS. Th/U ratios from all analysis fall within the range for magmatic zircon. In view of this and the peraluminous composition of the pluton, there are two possibilities: (i) the crystallization age of the Cipó pluton is 2164 Ma and there was new zircon generation related to the $\sim 2.07 \text{ Ga}$ metamorphic event, or (ii) that this pluton represents a melt of sedimentary rocks derived from pre-tectonic (2.15 Ga) and possibly syntectonic (2.1 Ga) plutons. In that case, its crystallization age would probably

Fig. 9. Sample 1399–Eficas Biotite-Trondhjemite. (A) Zircon population. (B) BSE images of SHRIMP analyzed crystals. (C) ID-TIMS and SHRIMP Concordia diagrams.

be close to the age of the youngest concordant datum, shown by TIMS to be 2088 ± 3 Ma.

4.3. Late-tectonic Palaeoproterozoic granitoid rocks

4.3.1. Itareru diorite: sample NS 1358 (2106 ± 2 Ma)

Zircon from sample NS 1538, a diorite from the central region of the Itareru shoshonitic pluton (Fig. 2), is composed of pink to brown, irregular shaped crystals, subhedral to euhedral, some with black inclusions and overgrowths (Fig. 11A). Two distinct

populations have been identified. [P1] is represented by clear, transparent zircons, which tend to be rounded. [P2] zircon has altered cores with clear and transparent overgrowths. Four crystals were selected for ID-TIMS analysis. Zrs. 1 and 2 are overgrowths manually broken from the P2 grains. Zr. 3, with an altered core, comes from P2. Zr. 4 is one of the clear zircons from P1. Zircon crystals from this sample have high U contents (Table 3). Zircons 1, 2 and 4 gave discordant data that can be regressed with an upper intercept age of 2106 ± 2 Ma, which is interpreted as the crystallization age of this pluton (Fig. 11C). Zr. 3 gave a slightly discordant

Fig. 10. Sample 1543–Cipó Granite. (A) Zircon population. (B) BSE images of SHRIMP analyzed crystals. (C) ID-TIMS and SHRIMP Concordia diagrams.

datum with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2162 \pm 4 \text{ Ma}$ and is interpreted as a xenocryst.

4.3.2. Itareru lamprophyre: sample NS 2595 ($2113 \pm 5 \text{ Ma}$)

Sample 2595 is from a lamprophyric dyke within the Itareru pluton, near the contact with gneisses of the Santa Luz complex (Fig. 2).

Zircon crystals from this sample are large, euhedral, prismatic, brown, translucent and most show internal cloudy areas, zoning and possible cores (Fig. 12A). However, BSE images show little evidence of cores, most grains having euhedral zoning occasionally with thin overgrowths (Fig. 12B). Eight analysis on seven grains produced overlapping concordant data with an average $^{207}\text{Pb}/^{206}\text{Pb}$

Fig. 11. Sample 1358–Itareru Diorite. (A) Zircon populations. (B) ID-TIMS Concordia diagram.

age of 2113 ± 5 Ma, which overlaps with the age of the Itareru diorite (sample 1358).

4.3.3. Pedra Vermelha pluton: sample NS 1664 (2080 ± 8 Ma)

The Pedra Vermelha is a circular pluton located in the north-western area of the Serrinha nucleus, where it intrudes metabasites related to the Uauá complex (Fig. 2, *Inda et al., 1976*). It is considered to be related to the pre-tectonic granites of *Matos and Conceição (1993)*.

Sample 1664 is a biotite-granite. Two distinct zircon populations have been identified: [P1] is represented by altered crystals, metamict and rounded, which could not be analyzed. [P2] consists of small, pale pink to colorless, clear and shiny, subhedral zircon crystals (Fig. 13A). One concordant datum and three variably discordant data from the least cracked grains define a Pb loss line with an upper intercept age of 2080 ± 8 Ma (Fig. 13B, Table 3). This is likely the age of crystallization of the pluton.

4.3.4. Barroquinhas pluton: sample NS 1587 (2073 ± 1 Ma)

The Barroquinhas pluton is a small, slightly E-W elongated pluton, intruding gneisses and basalts of the Santa Luz complex and the Itapicuru greenstone belt, respectively (*Alves da Silva et al., 1993; Chauvet et al., 1997a*). It is located near the southeast limit of Itapicuru rocks, only a few kilometers from the Mina Brasileiro gold mine (Fig. 2).

Sample 1587 is a biotite-granite which yielded two distinct zircon populations: [P1] are metamict, very altered, rounded crystals, which could not be analyzed; [P2] are subhedral to euhedral, pale pink to honey-brown, clear crystals of variable size, some with fractures (Fig. 14A). No core-overgrowth relationships were identified. Five of the best grains were selected for analysis and give data that range from concordant to mildly discordant (Fig. 14B).

A regression line gives an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2073 ± 1 Ma.

4.3.5. Fazenda Bananas pluton: sample NS 1436 (2072 ± 1 Ma)

Sample 1436 is a biotite-monzogranite from a small stock that intrudes the Agulhas-Bananas syenite. It shows two distinct zircon populations: [P1], the most abundant population, is composed of small pink to colorless, clear, transparent, euhedral to subhedral zircon crystals (P class of *Pupin, 1980*); [P2] consists of rare dark brown, subhedral to anhedral, rounded crystals, some with inclusions and zoning.

Four grains were analyzed: two (Zr. 2 and 3) from [P1], and two (Zr. 1 and 4) from [P2]. Grains from different populations produced discordant data but these do not appear to have significant age differences. Two slightly discordant data give overlapping $^{207}\text{Pb}/^{206}\text{Pb}$ ages with an average of 2072 ± 1 Ma (Fig. 15A). Regression of these with the most discordant datum give a similar upper intercept age of 2074 ± 2 Ma (Fig. 15B).

Table 4 gives Rb–Sr and Sm–Nd data for three samples from the Morro do Lopes type granites. The initial Sr and Nd ratios of these rocks are within narrow ranges, 0.688217–0.7029 and 0.509415–0.509748, respectively. $\epsilon_{\text{Nd}}(T)$ values range from -4.07 to -10.54 (Table 4). Nd T_{DM} model ages are 2.67 to 3.10 Ga, assuming a two-stage evolution as proposed by *De Paolo and Schubert (1991)*. These results differ significantly from the ones shown by syenite and shoshonite of the same group (Table 4).

5. Discussion

5.1. Stages of granitoid plutonism

Based on the data presented here (see summary in Table 5), we define three major groups of plutonic rocks exposed in the Serrinha nucleus:

Group 1: This is the oldest group and consists of ca. 3.2–2.9 Ga Mesoarchaean migmatite, gneisses and TTG plutons that occur in the Santa Luz and Uauá complexes, and within the Itapicuru greenstone belt. Ages are scattered in some samples apparently due to the presence of Mesoarchaean remobilization and metamorphism. Zircon crystals with low Th/U metamorphic ratios confirm the minimum age of 3.07 Ga proposed by *Paixão et al. (1995)* for the granulite facies metamorphism.

Group 2: The next major pulse of magmatism was the Palaeoproterozoic emplacement of calc-alkaline and TTG plutons. In this group we include the plutons of Eficás (2163 Ma), Lagoa dos Bois, and Cipó (2164 Ma), as well as the previously dated plutons of Nordestina (2155 Ma), Quijingue (2155 Ma), Trilhado (2155 Ma), Teofilândia (2130 Ma), and Barrocas (2128 Ma) (Fig. 2, see Table 1 for references). These allow us to limit the emplacement of TTG Palaeoproterozoic magmas into the Serrinha nucleus to a period of approximately 30 m.y. (2128–2164 Ma), and to note that the younger bodies are limited to the southernmost area of the Itapicuru belt. The age of the Cipó pluton (zircon at 2164, 2100 and 2088 Ma) is still unclear. *Matos and Conceição (1993)* describe these rocks as belonging to Morro do Lopes (~ 2.07 – 2.08 Ga, group 3) magmatism; *Rios et al. (1998)*, however, showed Pb–Pb Kober ages from the Cipó pluton ranging from 2004 to 2165 Ma (the best analysis is the older). The Nordestina batholith (2.15 Ga) also contains zircon crystals 2088 Ma and younger (*Rios et al., 1998*), but clearly belongs to group 2 granitoids.

Group 3: These represent undeformed, late to post-tectonic, alkaline Palaeoproterozoic intrusions. Group 2 plutons were affected by a major period of deformation before the emplacement of

Fig. 12. Sample 2595–Itareru Lamprophyre. (A) Zircon population. (B) BSE images of SHRIMP analyzed crystals. (C) SHRIMP Concordia diagram.

Table 5
Geochronological summary of U–Pb available data for Serrinha nucleus rocks. Data are from zircon, unless otherwise specified. Zr = multi-grain zircon, Mz = monazite, Ti = titanite, X = xenotime, S = sedimentation. When nothing else is specified, U–Pb analysis are for single zircon crystals.

Pluton/Lithology	Crystallization age (Ma)	Metamorphic age (Ma)	Inherited age (Ma)	Method	Reference
Basement units: Uauá complex (UC) and Santa Luz complex (SLC)					
Quijingue Gneiss-Migmatite (UC)	3195 ± 11	3090	3314 ± 20	SHRIMP	Rios et al. (2008)
Maracanã Gneiss-Migmatite (UC)	ca. 3166	2079 ± 34		SHRIMP	This work
Caldeirao Belt Orthogneiss (UC)	3152 ± 5			SHRIMP	Oliveira et al. (2002)
Trondhjemitic-Gneiss Valente (SLC)	3102 ± 5	2093 ± 4		ID-TIMS	This work
Retirolândia TTG (SLC)	3085			SHRIMP	Cordani et al. (1999)
Granodioritic Ortho-Gneiss (UC)	2991 ± 22 to 3152 ± 5			SHRIMP	Mello et al. (2006), Oliveira et al. (2002)
Gneiss TTG (UC)	2956 ± 39 to 3070 ± 3	2077 ± 11		ID-TIMS	Oliveira et al. (2000)
Enderbite Granulite (UC)	2933 ± 3			ID-TIMS	Oliveira et al. (2002)
Toleitic Dykes (UC)	2778 ± 7	2039 ± 2 (Ti)		ID-TIMS	Oliveira et al. (2000)
Caldeirao Belt Quartzite (UC)	2687 ± 16 (E)	2076 ± 10	3051 ± 13 to 3204 ± 9	SHRIMP	Mello et al. (2006), Oliveira et al. (2002)
Amphibolite Dykes (UC)		2078 ± 2		ID-TIMS	This work
Group 1 granitoids					
Ambrósio Granodiorite	3162 ± 26			ID-TIMS/SHRIMP	This work
Rio Capim Tonalite	3130–3050	2050		SHRIMP	Cordani et al. (1999)
Araci Granite	3072 ± 2	2060		ID-TIMS/SHRIMP	This work
Requeijão Biotite-Granite	2989 ± 11			ID-TIMS/SHRIMP	This work
Ambrósio Gneiss	2930 ± 32 (Zr)			ID-TIMS	Gaal et al. (1987)
Pedra Alta TTG	2650 to 3000			ICP-MS-LA	Batista et al. (1998)
Poco Grande	2645 ± 70	2079 ± 47 (Mz)		ID-TIMS	Melo et al. 1995
Ambrósio Gneissic Enclave			3094 ± 21 to 3159 ± 18	SHRIMP	Mello et al. (2006)
Ambrósio Massive Granodiorite	2077 ± 22		2937 ± 16 to 3162 ± 13	SHRIMP	Mello et al. (2006)
Ambrósio Porphyritic Granodiorite	2063 ± 55		2975 ± 7 to 3126 ± 5	SHRIMP	Mello et al. (2006)
Greenstone belts					
Leucogabbro Rio Capim	2143 ± 21			ID-TIMS	Oliveira et al. (1998)
Diorite Rio Capim	2148 ± 23			ID-TIMS	Oliveira et al. (1998)
Group 2 granitoids					
Cipó Biotite-Trondhjemitic	2164 ± 2	2088 ± 3		ID-TIMS/SHRIMP	This work
Eficéas Biotite-Trondhjemitic	2163 ± 5			ID-TIMS/SHRIMP	This work
Quijingue Trondhjemitic	2155 ± 3		3614–3620	ID-TIMS/SHRIMP	Rios et al. (2008)
Trilhado Undeformed Granodiorite	2155 ± 9			SHRIMP	Mello et al. (2006)
Teofilândia Tonalite to Granodiorite	2130 ± 7	2071 ± 10		SHRIMP	Mello et al. (2006)
Lagoa dos Bois Granodiorite	2107 ± 23 (Zr)			ID-TIMS	Gaal et al. (1987)
Group 3 granitoids					
Morro do Afonso Syenite	2111 ± 10		2641 ± 4	SHRIMP	Rios et al. (2007)
Itareru Lamprophyre	2113 ± 5			SHRIMP	This work
Itareru Diorite	2106 ± 2		2162 ± 4	ID-TIMS	This work
Serra do Pintado Syenite	2098 ± 2			ID-TIMS	Conceição et al. (2002)
Euclides Shoshonite Syenogranite	2097 ± 8		3654 and 2344–2501	ID-TIMS/SHRIMP	Rios et al. (2008)
Pedra Vermelha Biotite-Granite	2080 ± 8			ID-TIMS	This work
Barroquinhas Biotite-Granite	2073 ± 1			ID-TIMS	This work
Faz.Bananas Biotite-Monzogranite	2072 ± 1			ID-TIMS	This work
Late Intrusions and Mineralization					
Dykes cutting Ambrósio	2080 ± 2 (Xe)			SHRIMP	Mello et al. (2006)
Dykes cutting Ambrósio	2079 ± 47 (Zr)			ID-TIMS	Gaal et al. (1987)
Quartz-Feldspar Porphyry Dyke cutting Teofilândia	2128 ± 8	2071 ± 9		SHRIMP	Mello et al. (2006)

Fig. 13. Sample 1664–Pedra Vermelha Granite. (A) Zircon populations. (B) ID-TIMS Concordia diagram.

these alkaline magmas, beginning with syenite and shoshonite plutons at about 2110 Ma. A tectono-thermal metamorphic event is recorded by the emplacement of ellipsoidal syenite and shoshonite plutons, such as the Euclides (2097 ± 8 Ma, U–Pb, Rios et al., 2002, 2008), Cansanção (2105 ± 3 Ma, Pb–Pb), and the Itareru (2106 ± 2 Ma, U–Pb, this work) plutons, the lamprophyric dykes (intruding Itareru shoshonite, 2113 ± 5 Ma, U–Pb, this work), and three syenitic stocks: Morro do Afonso (2111 ± 10 Ma, U–Pb, Rios et al., 2007), Serra do Pintado (2098 ± 2 Ma, U–Pb, Conceição et al., 2002) and Agulhas-Bananas (2086 ± 2 Ma, Pb–Pb, Conceição et al., 2002). 2.07–2.08 Ga magmatic and metamorphic overgrowths are also found on zircon in older rocks.

The greatest surprise, and perhaps one of the most important results of this study, is the significant number of Mesoproterozoic ages. The Sm–Nd and Rb–Sr systems from group 1 plutons also yield T_{DM} ages that are similar to the zircon ages reported here (Table 3, Fig. 2). Group 1 plutons in the Rio Itapicuru greenstone belt and Serrinha nucleus gneissic basement are N–S elongated and have foliated margins, whereas their cores are more isotropic (Matos and Davison, 1987). They are similar to TTG Archean suites of Martin (1994), with strongly fractionated REE patterns, concave terminations and small Eu anomalies (Rios, 2002). Many

Fig. 14. Sample 1587–Barroquinhas Granite. (A) Zircon populations. (B) ID-TIMS Concordia diagram.

of the largest bodies in Serrinha nucleus can be considered as belonging to group 1, including some of the pre- and syntectonic granites of Matos and Conceição (1993). Many of these plutons clearly cut the mafic basal unit of the Itapicuru greenstone belt (Argolo, 1993; Alves da Silva et al., 1993; Chauvet et al., 1997a,b; Lacerda, 2004; Mello et al., 2006), including the Ambrósio, the Pedra Alta and the Poço Grande plutons (Fig. 2). Volcanism and sedimentation within the Rio Itapicuru greenstone belt is Paleoproterozoic in age, based on previous dating (Silva, 1987, Silva et al., 1996) and new SHRIMP data (in preparation). Therefore, the Mesoproterozoic complexes must have been emplaced within the greenstone belt as a result of remobilization during the Transamazonian orogeny. They may represent diapirs or cores of crustal-scale folds.

The São Francisco craton contains evidence of at least three major Archean tectonic-thermal and magmatic events (3380–2900 Ma, 2860–2800 Ma, 2780–2600 Ma; Machado and Carneiro, 1992; Carneiro, 1992; Wilson et al., 1995; Martin et al., 1997), of which the two younger events involved partial reworking of older sialic crust. These authors also found evidence of inherited components up to 3473 Ma and tentatively proposed the existence of a ca. 3.66 Ga old proto-continental crust (Martin et al., 1991, 1997). Xenocrysts of this age have now been found in the groups 2 and 3 plutons (Quijingue and Euclides plutons, Rios et al., 2008).

Fig. 15. Sample 1436–Fazenda Bananas Monzo-Granite. ID-TIMS Concordia diagram. (A) Regression to origin. (B) Lead loss line.

Large N–S elongated plutons like Ambrósio are also described in other regions of the São Francisco craton (e.g. Sete Voltas Massif, Martin et al., 1991, 1997). Based on the present data, we suggest that most large N–S elongated plutons are Archaean in age. In this study, there is little evidence for geological events over the period 2.9–2.2 Ga, with the exception of the pattern of zircon SHRIMP ages from the Euclides pluton, in which ages range from 2087 to 2501 Ma (Rios et al., 2008).

The earliest Palaeoproterozoic granitic units of group 2 have normal calc-alkaline to subordinate TTG trends and metaluminous to peraluminous character (Rios, 2002). Chemically, they are very similar to group 1 granitoids, although they are less deformed, less elongated, and show more juvenile isotopic compositions (Table 4). They are located in the central portion of the Serrinha nucleus, most along the edge of the Itapicuru greenstone belt where they intrude the Archaean gneiss-migmatite and the volcano-sedimentary rocks. Like the group 1 granitoid bodies, most of them show a gneissic border that grades to an isotropic core (Rios, 2002), but they appear to be regionally less deformed than the Archaean plutons.

Xenoliths of Itapicuru rocks as well as gneiss-migmatite and mafic micro-granular enclaves are frequent. Meso- to Eoarchaean

zircons, interpreted as basement xenocrysts, are found in group 2 plutons (Rios, 2002; Rios et al., 2002, 2008). 2.07–2.08 Ga overgrowths are also identified. Most of the plutons are peraluminous, except Nordestina, which shows metaluminous character. HREE values are lower than those of post-Archaean suites of Martin et al. (1997), suggesting they were generated in the garnet stability zone (Rios, 2002; Cruz Filho et al., 2005).

Younger alkaline magmatism (group 3) makes up a distinct but volumetrically minor assemblage of rock types that is most prominently developed in the southwestern area of the nucleus. Plutons occur as small, semi-circular (<30 km²) bodies and dykes, comprising three geochemically distinctive sub-groups: (i) shoshonite (Euclides, Araras, Cansção e Itareru), (ii) potassic-ultrapotassic (Morro do Afonso, Agulhas-Bananas, and Serra do Pintado), and (iii) K-peraluminous granites (Morro do Lopes type).

Serrinha nucleus shoshonite and syenite bodies have a slightly ellipsoidal, N–S elongated form, and some of them also show a slightly foliated border, in which basement xenoliths have been identified. These foliations are discordant to the regional pattern, have magmatic character, and there are no other deformational textures (Nascimento, 1996; Oliveira, 2001; Rios et al., 2007; Nascimento et al., 2004), indicating that they intruded near the end of the Transamazonian orogeny. Syenite bodies are aligned closely with the 39° meridian, suggesting that their emplacement was controlled by a deep regional fault structure.

Both syenite and shoshonite are characterized by high LILE and HFSE contents (Conceição et al., 1995, 2002; Rios, 2002; Plá Cid et al., 2006; Rios et al., 2007). According to Foley et al. (1987), Foley and Peccerillo (1992) and Ringwood (1990), rocks with the characteristics of Serrinha nucleus syenites are probably related to a deep mantle source, and influenced by subduction-enriched mantle and contamination with continental crust (Thompson and Fowler, 1986).

The available data allow us to say that syenitic and shoshonitic magmas are coeval and related to lamprophyric magmas and to constrain the time of their emplacement at 2097–2113 Ma, as well as to confirm the presence of crustal participation in their genesis as shown by zircon inheritance and Neoarchaean T_{DM} ages (Table 4).

5.2. Inferred tectonic and regional implications

The present data, along with other isotopic and geochronological studies, indicate that the Serrinha nucleus shows a long history of reworking in the Mesoarchaean. Major crust forming events are dominantly in the range 2989–3162 Ma, since rocks of these ages appear to be regionally extensive. Mesoarchaean crust may have been formed on an older 3.6 Ga basement as shown from xenocrysts.

The new ages of $3200 \pm 12 \text{ Ma}$ for a Uauá complex gneiss-migmatite near Quijingue and $3162 \pm 26 \text{ Ma}$ from the Ambrósio tonalite extend the known rock record in the Serrinha nucleus to 3.20 Ga, closer to the 3.34 Ga mantle extraction ages indicated from Nd isotopes (Oliveira et al., 1999, 2000, 2002), whereas a 2.16-Ga TTG body (Quijingue) contains inheritance up to 3.61 Ga in age (Rios et al., 2002). Thus, Archaean phases in Serrinha nucleus appear to have developed by progressive reworking of pre-existing crust. In terms of its age distribution, this older crust somewhat resembles parts of the Kaapvaal and Pilbara cratons, where 3.1–3.3 Ga rocks are abundant (Kamo and Davis, 1994; Van Kranendonk et al., 2007). There is a notable lack of evidence for Neoarchaean activity, in contrast to many other Archaean cratons.

The Transamazonian orogeny is one of the most important crustal formation events in South America. Santos et al. (2003) present the precise time span of the orogenic cycle, and identify four main orogenies, although other authors have proposed that at least

12 orogenic pulses may have occurred (Hartmann et al., 2004). In the Serrinha nucleus, we identify two main Transamazonian pulses at 2163–2128 Ma and 2110–2070 Ma.

Tectonic interpretations in ancient highly deformed terranes like Serrinha nucleus are necessarily limited. Nevertheless, available geochemistry, isotope and age data are suggestive of that the Paleoproterozoic rocks of Serrinha nucleus developed as an arc on the (present-day) southern edge of a Mesoarchaeoan continental margin. Itapicuru and Capim greenstone belts (Fig. 2) likely represent the remains of this arc. These rocks were previously interpreted on the basis of geochemistry to have formed in back-arc basins (Kishida and Riccio, 1980; Silva, 1992, 1996; Winge, 1984; Figueiredo, 1989). Coeval group 2 granitoids, most with ages near 2160 Ma, also show geochemical arc affinities. They contain Mesoarchaeoan xenocrysts and cores and show Archean Nd mantle extraction ages. They were deformed later during the Transamazonian orogeny.

The 2.07–2.11 Ga group 3 granitoid rocks mainly comprise late to post-tectonic plutons that must have been associated with a considerable input of heat as shown by similar age zircon rims in older rocks and by many of the Rb–Sr, K–Ar, Ar–Ar and Pb–Pb isotopic data measured on older granitoid and felsic volcanic rocks (see Table 1). This pattern of arc-associated magmatism followed by regional deformation and intense late- to post-tectonic plutonism is characteristic of Archean collision tectonics but in some areas apparently lasted into the Palaeoproterozoic. A distinct suite of Mg-rich rocks enriched in both compatible and incompatible elements (the sanukitoid suite) is suggested to form from melting of mantle previously enriched by subduction processes (Shirey and Hansen, 1984; Stern and Hansen, 1991). Similar rocks have been recognized in the Serrinha nucleus (Itareru pluton, ~2.1 Ga, Rios et al., 2000). Enrichment of the source mantle most likely occurred during earlier phases of Palaeoproterozoic or Archean subduction. The thermal pulse necessary to melt this mantle in a post-subduction environment may have been from a sudden influx of asthenospheric mantle following collision and slab break off (Davies and Von Blanckenburg, 1995). A similar model has been proposed for late plutonism in the Neoarchaeoan Superior province (Beakhouse and Davis, 2005). Thus, different aged Palaeoproterozoic rocks that make up the Transamazonian ‘cycle’ likely did not form during multiple orogenies but during different phases of the same ocean closure event.

Mello et al. (2006) suggest that the peak of the tectono-metamorphic-magmatic activity related to the formation of the Itapicuru basin must have occurred during a collisional period between 2130 Ma and 2080 Ma. The thermal event related to the emplacement of Morro do Lopes type granites (2.07–2.08 Ga) agrees with $^{40}\text{Ar}/^{39}\text{Ar}$ biotite and muscovite ages measured for gold mineralization, which are bracketed between ca. 2083 Ma and 2031 Ma (Vasconcelos and Becker, 1992; Mello et al., 2006), suggesting that this late plutonic activity could be responsible for the hydrothermal activity that transported and concentrated gold. Fluids may have been of magmatic origin and/or derived from dehydration of buried supracrustal units. Other authors have suggested a similar model and that the gold concentration process post-dates Transamazonian ductile deformation (horizontal thrusting and vertical movement; Alves da Silva et al., 1998).

Group 2 and group 3 plutons are coeval with similar units identified in West Africa (Hirdes et al., 1992, 1996; Doumbia et al., 1998) and Guiana (Norcross et al., 2000) although, in contrast to Serrinha nucleus, the West Africa rocks seem to be almost entirely juvenile (Davis et al., 1994). Thus, the Transamazonian-Eburnean Orogeny was probably very extensive and involved both oceanic and continental arc construction. The African equivalent of Serrinha nucleus may be found elsewhere, perhaps in the Congo craton.

6. Conclusions

The major events that affected the region are as follows:

Ca. 3.6 Ga to 3.2 Ga: Formation of Eo to Mesoarchaeoan crust.

3.2 to 2.9 Ga: Intrusion of group 1 granitoids, which are associated with, or postdated, greenstone belt formation. These granitoids have typical features of Archean TTGs, implying varying degrees of partial melting of underplated crust with an Archean metamorphic event at ~ 3070 Ma.

2.16 to 2.13 Ga: Intrusion of group 2 granitoids in a continental arc environment floored by Mesoarchaeoan crust.

2.11 to 2.07 Ga: Intrusion of group 3 granitoids, following ocean closure and slab break off. The geochronology, geochemical and spatial associations and lithostratigraphy indicate two stages of alkaline magmatism: a first stage (2114–2097 Ma), with intrusion of shoshonite, syenite and ultrapotassic lamprophyric rocks; and a second stage (ca. 2080–2070 Ma), with intrusion of small semi-circular peraluminous isotropic K-granites and dykes. These were the probable heat source driving Palaeoproterozoic metamorphism at ~ 2070–2080 Ma.

If these interpretations are correct, evidence for at least two major phases of regional deformation and metamorphism (Archean and Transamazonian) should be present in at least some of the group 1 plutons, whereas only the Transamazonian events should have affected group 2 plutons.

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