Evolution of polycyclic basement complexes in the Araçuaí Orogen, based on U–Pb SHRIMP data: Implications for Brazil–Africa links in Paleoproterozoic time[☆]

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Abstract

Paleoproterozoic basement of the Araçuaí Orogen is composed of amphibolite and granulite facies orthogneiss units known as Mantiqueira and Juiz de Fora complexes. Six U–Pb SHRIMP crystallization ages for the Mantiqueira Complex range from 2137 ± 19 to 2041 ± 7 Ma. Studied samples are characterized by the abundance of inherited Archean zircon grains, T_{DM} model ages ranging from 2.9 to 3.2 Ga, and strongly negative $\varepsilon_{Nd(t)}$ (–9 to –13). Gneiss protholits were mainly generated by partial melting of older continental material, and the Mantiqueira Complex is related to active margin and syn-collisional magmatism. High-grade gneiss samples of the Juiz de Fora Complex yields crystallization ages of 2119 ± 16 and 2084 ± 13 , and inherited zircon grains are absent. This plutonic unit much probably evolved within an oceanic magmatic arc setting, or on a very stretched continental crust.

The Mantiqueira and Juiz de Fora complexes, together with the Kimezian basement of the West Congo Belt, were parts of a Paleoproterozoic orogenic system disrupted and deeply reworked during the evolution of the Araçuaí–West Congo Orogen. Neoproterozoic metamorphic overprint is dated at ca. 590–574 Ma.

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1. Introduction

The Araçuaí Orogen (southeastern Brazil) and the West Congo Belt (southwestern Africa) are counterparts of a Brasiliano–Pan African orogenic system developed between the São Francisco and Congo cratons, during the assembly of Gondwanaland in late Neoproterozoic

time (Fig. 1). From the oldest evidence of the pre-collisional stage to the latest post-collisional processes, orogeny lasted approximately from 630 to 490 Ma in the Araçuaí Orogen. The metamorphic peak related to the syn-collisional stage took place at ca. 585–560 Ma (Pedrosa-Soares et al., 2001; Tack et al., 2001; Silva et al., 2005a; Alkmim et al., 2006; Frimmel et al., 2006).

Basement units in the Araçuaí Orogen are essentially composed of orthogneiss complexes of Archean and Paleoproterozoic age. These complexes are exposed in the external (western) and internal (eastern) tectonic domains of the Araçuaí Orogen (Fig. 1). The

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Fig. 1. The Araçuaí–West Congo Orogen and the adjacent São Francisco–Congo craton in the context of West Gondwana (after Alkmim et al., 2006). Geological map of the orogen showing the distribution of basement units (modified from DeWit et al., 1988; Pedrosa-Soares et al., 2001; Tack et al., 2001; Delgado et al., 2003; Silva et al., 2005a).

external domain is the low metamorphic grade, fold-and-thrust belt bordering the São Francisco Craton. The internal domain is the high-grade core of the Araçuaí Orogen, where the pre-collisional magmatic arc and widespread syn-collisional granites are found, and regional metamorphism reached the granulite facies. Indeed, such distinct locations of basement complexes in the Araçuaí Orogen imply in different intensities of tectonic reworking and isotopic resetting of the Archean and Paleoproterozoic rocks during the Brasiliano orogeny.

The basement of the Araçuaí Orogen evolved during the assembly of the São Francisco–Congo landmass that probably was a part of a larger Paleoproterozoic continent (e.g., Atlantica Paleocontinent, Rogers and Santosh, 2004). The ancient São Francisco and Congo blocks were stitched together by a Paleoproterozoic orogenic system, called Itabuna–Salvador–Curaça, in Brazil (Barbosa and Sabaté, 2004), or Eburnean, in Africa (Ledru et al., 1994). Absence of Neoproterozoic orogeny allowed the reconstruction of this Paleoproterozoic orogenic system along the cratonic connection on both sides of the Atlantic Ocean, the Bahia-Gabon bridge (Fig. 1): a cratonic link that lasted from ca. 2 Ga up to the Meso-

zoic (Porada, 1989; Ledru et al., 1994; Trompette, 1994; Brito Neves et al., 1999; Barbosa and Sabaté, 2004; D'Agrella Filho et al., 2004; Alkmim et al., 2006). The same task, i.e., to reconstruct the Paleoproterozoic orogenic system is much more difficult when dealing with the disrupted and deeply reworked basement remnants within the Araçuaí Orogen (Alkmim and Marshak, 1998; Noce et al., 2000; Teixeira et al., 2000; Silva et al., 2005a). Contributions for achieving this task must consider the correlations between basement units of the West Congo Belt and Araçuaí Orogen, as we discuss afterwards.

This paper focus on the polycyclic evolution of basement complexes of the Araçuaí Orogen, based on U–Pb SHRIMP and Sm–Nd data. Eight samples of amphibolite and granulite facies orthogneisses were analysed through the U–Pb SHRIMP method, disclosing a complex and protracted magmatic and metamorphic evolution prior to the Neoproterozoic tectonic reworking. These samples are from the Mantiqueira and Juiz de Fora complexes. We also discuss possible correlations with the basement of the West Congo Belt, and suggest a model for the evolution of the Paleoproterozoic orogenic system.

Fig. 2. Geological map of part of the Araçuaí Orogen (see location in Fig. 1), showing the distribution of the Mantiqueira and Juiz de Fora complexes, and sample location (modified from Peres et al., 2004). Archean gneissic complexes (1) and supracrustal rocks (2); Mantiqueira Complex (3); Juiz de Fora Complex (4); Brasiliano units: granitoids (5) and supracrustal rocks (6); Borrachudos Suite (7).

2. Basement of Araçuaí Orogen

Two of the basement units of the Araçuaí Orogen, the Guanhanes and Mantiqueira gneissic complexes (Fig. 2), consist of large autochthonous and parautochthonous gneissic units that can be traced into the cratonic domain. They are therefore considered to be the reworked margin of the São Francisco Craton, now located in the Araçuaí Orogen. The Guanhanes Complex is part of the Archean cratonic nuclei that was bordered by a marginal Paleoproterozoic orogen (Teixeira et al., 2000). The Araçuaí Orogen transects the former Archean–Paleoproterozoic boundary and the Mantiqueira Complex is envisaged as a deeply reworked fragment of a continental magmatic

arc. Another Paleoproterozoic basement unit is the Juiz de Fora Complex (Fig. 2), made up of tectonic slices of granulitic orthogneiss and amphibolite. The Mantiqueira and Juiz de Fora complexes were juxtaposed by a dextral-reverse, high-angle shear zone of Brasiliano age (the Abre Campo Fault).

The Mantiqueira Complex consists predominantly of banded biotite-amphibole orthogneiss. The thickness of the alternating light and dark bands varies from centimetric to metric, and concordant amphibolite boudins, lenses and layers are very common. The gneissic banding can be explained either by migmatization and/or by intense deformation of distinct magmatic protholits, where tectonism erased any original discordant contacts between individual bodies and stretched them into concordant layers. Regional gneissic banding/foliation trends N–S to NNE–SSW and is parallel to the Brasiliano structures, resulting from intense folding and transposition of an earlier banded structure.

Mantiqueira gneisses are tonalitic to granitic in composition and make up calc-alkaline suites, whereas basic layers and enclaves belong to transitional basaltic series (Duarte et al., 2004). Geochemical modeling, Sr and Nd signatures suggest that the gneiss protholits were dominantly generated by partial melting of crustal material, and that the Mantiqueira Complex evolved at a continental magmatic arc setting (Duarte et al., 2004, 2005). Remnants of supracrustal rocks within the Mantiqueira Complex are very subordinate and mainly represented by calc-silicatic and quartzite xenoliths (Figueiredo and Teixeira, 1996).

The Juiz de Fora Complex occurs as large tectonic lenses intercalated with Neoproterozoic paragneisses. It is composed of granulite facies orthogneisses, with predominance of enderbite and minor charnockitic compositions. These rocks make up calc-alkaline suites of juvenile affinity (Figueiredo and Teixeira, 1996; Duarte et al., 1997; Fischel et al., 1998). Lens-shaped bodies of various sizes composed of basic granulites are also present in the Juiz de Fora Complex, and are characterized by Costa (1998) as low-K tholeiites similar to island-arc and ocean floor basalts.

2.1. Previous geochronological data

U–Pb SHRIMP ages for the Mantiqueira Complex are in the 2180–2058 Ma time range (Silva et al., 2002), and an age of 2203 ± 17 Ma obtained through the Laser Ablation-MC-ICPMS method is reported by Heilbron et al. (2001). Available U–Pb ages for enderbite and charnockite gneiss of the Juiz de Fora Complex are 2134 Ma (Machado et al., 1996), 2127 ± 33 Ma

(Heilbron et al., 2001), and 2195 ± 15 Ma (Silva et al., 2002).

The polycyclic evolution of Paleoproterozoic basement units of the Araçuaí Orogen was highlighted by these previous geochronological studies. SHRIMP U–Pb geochronology showed that those highly transposed, amphibolite and granulite facies orthogneisses had been accreted to, and modified in, several magmatic and metamorphic events (Silva et al., 2002; Silva et al., 2005a). The oldest components intruded in a magmatic arc setting at ca. 2200–2100 Ma. The syn-collisional phase took place between 2100 and 2050 Ma, which is the approximate age of the first metamorphic event (M_1), dated on several metamorphic overgrowths on zircon grains from the older orthogneisses (indicating high temperatures were reached during M_1), and on magmatic zircons from syn-collisional plutons (Silva et al., 2002, 2005a). A second, and better constrained, metamorphic overprinting (M_2), corresponding to the Neoproterozoic collage of the Araçuaí Orogen onto the eastern São Francisco cratonic margin, yielded U–Pb SHRIMP metamorphic ages at 580–570 Ma also obtained on zircon metamorphic overgrowths.

3. Sample descriptions

The isotopic analyses were performed on six samples of amphibolite facies gneiss from the Mantiqueira Complex, and two samples of granulite facies gneiss from the Juiz de Fora Complex.

Mantiqueira gneisses display granoblastic textures in this section, and main mineral constituents are quartz, microcline, plagioclase, hornblende and biotite. Zircon, titanite, apatite and opaque minerals are the common accessory minerals, plus secondary minerals like chlorite, sericite, epidote and carbonate. On the R1–R2 diagram (after De la Roche et al., 1980) gneiss samples fall mainly on the granodiorite field (LC-67, LC-70,

LC-77, LC-78). Sample RP-1 is tonalitic and sample LC-79 is granitic in composition (Table 1). A description of sampled outcrops of Mantiqueira Complex is given below:

- *Sample RP-1*. Medium-grained migmatized gneiss displaying a well-developed centimetric banding, in some places tightly folded. Banded structure is characterized by alternating plagioclase-rich layers and dark layers rich in mafic minerals (biotite and hornblende). Mafic rocks (amphibolites) make up concordant bands and some large disrupted bodies (Fig. 3a and b). Leucosome veins are both concordant and discordant to the rock banding. Collected sample of the banded gneiss did not include leucosome veins, and is tonalitic in composition.
- *Sample LC-70*. Banded biotite granodiorite gneiss, folded and strongly sheared; sample was taken from a homogeneous light band about 10 cm thick.
- *Sample LC-77*. Relatively homogeneous fine-grained biotite granodiorite gneiss with minor hornblende, exhibiting a thin banding.
- *Sample LC-79*. Complex-folded migmatized gneiss exhibiting alternating banded and more massive layers, plus concordant amphibolite enclaves. Sample was collected from the massive layers. It is medium- to coarse-grained, leucocratic, with biotite and hornblende as mafic minerals, and granitic in composition.
- *Sample LC-78*. Fine-grained biotite granodiorite gneiss, relatively homogeneous and displaying a well-developed banding characterized by alternating light and dark layers that are few millimeters in thickness. Amphibolite enclaves, disrupted and concordant to the rock banding, are also present.
- *Sample LC-67*. This is a massive, hornblende–biotite granodiorite gneiss, only locally exhibiting a poorly developed banding (Fig. 3c).

Table 1
Major element data for studied samples

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3(t)}	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	LOI	Total
Mantiqueira Complex											
RP-1	63.6	14.7	7.7	0.09	2.81	3.41	2.97	2.86	1.37	0.47	99.98
LC-70	68.8	14.7	5.24	0.04	2.99	2.29	2.37	2.22	0.36	0.32	99.33
LC-77	68.9	18.8	2.39	0.02	2.25	1.32	2.62	2.79	0.28	0.11	99.48
LC-79	69.1	15.1	1.87	0.02	2.57	2.54	3.55	4.48	0.21	0.13	99.57
LC-78	67.7	17.4	3.99	0.05	1.54	2.45	2.6	2.83	0.55	0.32	99.43
LC-67	69.8	14.1	4.5	0.06	2.38	1.86	2.44	3.54	0.49	0.32	99.49
Juiz de Fora Complex											
LC-66a	53.8	17.9	9.61	0.14	3.68	7.05	2.78	2.46	1.09	0.79	99.3
Ub-1	67.4	14.9	4.78	0.04	2.25	3.89	2.58	2.41	0.59	0.31	99.15

Fig. 3. (A) Banded tonalite gneiss with disrupted mafic bodies and leucosome veins (Mantiqueira Complex, sample RP-1); (B) in the same outcrop as previous picture, the gneiss displays a former banded structure partially transposed by the flat-lying regional Brasiliano foliation; (C) homogeneous granodiorite gneiss strongly foliated (Mantiqueira Complex, sample LC-67); (D) Enderbite gneiss with light leucosome bands of charnockitic composition (Juiz de Fora Complex, sample Ub-1).

Granulite facies orthogneisses of the Juiz de Fora Complex are often migmatized. One investigated outcrop consists of a complex folded, stromatic migmatite with pink granite veins that display concordant to cross-cutting relations with the migmatitic banding. Sample LC-66a is a mafic granulite, composed of plagioclase and pyroxenes, taken from a dark-green paleosome band. Pyroxenes can be replaced by hornblende, by its turn replaced by minor biotite. Quartz and opaque minerals are the main accessory minerals. Chemical composition suggests a gabbro-diorite protolith for this rock (Table 1).

Sample Ub-1 is a migmatized enderbite gneiss rich in leucosome veins of light green charnockite (Fig. 3d), and also with mafic enclaves (basic granulite). The enderbite is composed of plagioclase, quartz, orthopyroxene and clinopyroxene, with biotite and hornblende as retro-grade minerals. Leucosome veins are generally less than

one to a few centimeters wide, and parallel to the gneiss foliation. It was not possible to separate them from the collected sample.

4. Isotopic results

4.1. Analytical procedures

Zircon, titanite and monazite concentrates were extracted from rock samples using conventional gravimetric and magnetic (Frantz isodynamic separator) techniques. Final separation was achieved by hand picking using a binocular microscope. Zircon SHRIMP analyses were carried out at the Research School of Earth Sciences, Australian National University. Zircon grains were mounted in a 1 in. diameter epoxy disk with standard RSES zircon crystals and sectioned approxi-

Table 2

Summary of SHRIMP U–Pb zircon data for Mantiqueira gneiss samples

Grain spot	% ²⁰⁶ Pb	U (ppm)	Th (ppm)	²³² Th/ ²³⁸ U	²⁰⁶ Pb ^a (ppm)	²⁰⁶ Pb/ ²³⁸ U age ^b	²⁰⁷ Pb/ ²⁰⁶ Pb age ^b	% discordant	²⁰⁷ Pb ^a / ²⁰⁶ Pb ^{a,b}	±%	²⁰⁷ Pb ^a / ²³⁵ U ^b	±%	²⁰⁶ Pb ^a / ²³⁸ U ^b	±%	Error correction
Sample RP-01															
1.1	0.02	158	52	0.34		2,656 ± 25	3096.8 ± 4.5	14	0.23653	0.28	16.62	1.2	0.5097	1.1	0.971
1.2	0.04	320	121	0.39	126.0	2,425 ± 24	3148.8 ± 4.2	23	0.24439	0.26	15.39	1.2	0.4568	1.2	0.976
2.1	0.02	257	171	0.69	116.0	2,723 ± 25	2876.3 ± 3.6	5	0.20625	0.22	14.95	1.1	0.5257	1.1	0.981
2.2	0.03	366	50	0.14	114.0	1,990 ± 19	2932.7 ± 6.7	32	0.21356	0.42	10.65	1.2	0.3616	1.1	0.937
3.1	0.03	62	52	0.87	34.2	3,182 ± 36	3224.2 ± 5.9	1	0.25631	0.37	22.56	1.5	0.6382	1.4	0.967
4.1	0.02	99	63	0.65	30.5	1,974 ± 20	2110.1 ± 8.6	6	0.1309	0.49	6.467	1.3	0.3583	1.2	0.926
5.1	0.01	271	85	0.33	116.0	2,608 ± 29	2828.0 ± 3.6	8	0.20022	0.22	13.77	1.4	0.4987	1.3	0.987
6.1	0.02	279	96	0.36	86.2	1,982 ± 22	2635.7 ± 7.6	25	0.17815	0.46	8.84	1.4	0.36	1.3	0.941
6.2	0.01	240	97	0.42	123.0	3,014 ± 27	3232.3 ± 4.4	7	0.25763	0.28	21.17	1.2	0.5961	1.1	0.971
7.1	0.10	113	91	0.84	36.8	2,079 ± 22	2131.8 ± 8.8	2	0.13253	0.5	6.955	1.3	0.3806	1.2	0.923
8.1	0.02	208	100	0.50	102.0	2,922 ± 27	3229.2 ± 3.4	10	0.25712	0.22	20.33	1.2	0.5734	1.1	0.982
8.2	0.02	397	82	0.21	120.0	1,950 ± 20	2671.2 ± 5.4	27	0.182	0.33	8.86	1.2	0.3532	1.2	0.963
9.1	0.04	124	109	0.91	62.1	2,970 ± 33	3168.3 ± 4.5	6	0.24741	0.28	19.96	1.4	0.5851	1.4	0.980
9.2	0.08	342	226	0.68	88.5	1,696 ± 18	2886.5 ± 4.3	41	0.20755	0.27	8.61	1.2	0.3009	1.2	0.976
10.1	0.00	322	210	0.67	154.0	2,854 ± 26	3263.4 ± 2.9	13	0.26277	0.18	20.18	1.1	0.5569	1.1	0.987
10.2	0.07	127	53	0.44	45.6	2,253 ± 23	2403.4 ± 6.7	6	0.15514	0.4	8.95	1.3	0.4184	1.2	0.952
11.1	0.01	134	106	0.82	61.5	2,756 ± 26	2982.8 ± 8.3	8	0.2203	0.52	16.2	1.3	0.5334	1.2	0.914
11.2	0.06	91	66	0.74	26.6	1,880 ± 20	2126 ± 10	12	0.13213	0.59	6.169	1.4	0.3386	1.2	0.902
12.1	0.04	98	36	0.38	36.4	2,319 ± 23	2738.2 ± 8.2	15	0.18955	0.5	11.32	1.3	0.433	1.2	0.923
12.2	0.00	403	114	0.29	112.0	1,804 ± 18	2095.7 ± 4.5	14	0.12984	0.26	5.782	1.1	0.323	1.1	0.974
13.1	0.00	169	74	0.45	79.0	2,803 ± 26	2975.4 ± 4.2	6	0.21928	0.26	16.46	1.2	0.5446	1.2	0.976
14.1	0.00	331	90	0.28	98.4	1,915 ± 19	3083 ± 11	38	0.2345	0.72	11.19	1.3	0.346	1.1	0.845
14.2	0.02	94	53	0.59	28.1	1,929 ± 20	2117.1 ± 9.4	9	0.13143	0.53	6.321	1.3	0.3488	1.2	0.915
15.1	0.01	272	121	0.46	120.0	2,665 ± 25	3218.1 ± 4.2	17	0.25532	0.27	18.02	1.2	0.512	1.1	0.974
16.1	0.04	441	58	0.14	119.0	1,767 ± 18	2675 ± 11	34	0.1825	0.63	7.93	1.3	0.3154	1.2	0.880
16.2	0.01	141	80	0.58	41.4	1,897 ± 19	2521.4 ± 6.8	25	0.16636	0.4	7.846	1.2	0.3421	1.2	0.946
Sample LC-70															
1.1	0.01	449	304	0.70	197.0	2,658 ± 16	2688.6 ± 3.8	1	0.18393	0.23	12.94	0.8	0.5102	0.8	0.958
1.2	0.01	885	171	0.20	276.0	1,999 ± 12	2077.6 ± 3.8	4	0.1285	0.22	6.441	0.8	0.3635	0.7	0.958
2.1	0.04	121	32	0.27	49.3	2,512 ± 19	2616.3 ± 8.5	4	0.17608	0.51	11.57	1	0.4764	0.9	0.870
3.1	0.01	1296	431	0.34	409.0	2,016 ± 12	2042.6 ± 3.4	1	0.12598	0.19	6.377	0.7	0.3671	0.7	0.965
3.2	0.03	282	129	0.47	123.0	2,640 ± 17	2674.7 ± 4.7	1	0.18238	0.28	12.73	0.8	0.5061	0.8	0.941
4.1	0.00	683	264	0.40	213.0	1,995 ± 13	2045.0 ± 4.3	2	0.12615	0.24	6.309	0.8	0.3627	0.7	0.950
5.1	0.08	207	10	0.05	84.8	2,508 ± 23	2600 ± 11	4	0.1743	0.68	11.43	1.3	0.4755	1.1	0.849
6.1	0.03	952	454	0.49	337.0	2,224 ± 13	2512.8 ± 5.9	11	0.16552	0.35	9.404	0.8	0.4121	0.7	0.898
7.1	0.13	866	168	0.20	269.0	1,986 ± 12	2107.6 ± 4.6	6	0.13072	0.26	6.504	0.8	0.3609	0.7	0.940
8.1	0.08	310	174	0.58	114.0	2,297 ± 18	2543.0 ± 5.1	10	0.16852	0.3	9.947	10	0.4281	1	0.952
9.1	0.32	119	95	0.82	48.2	2,483 ± 18	2681.2 ± 8.6	7	0.18311	0.52	11.87	1	0.47	0.9	0.859
10.1	0.05	350	229	0.67	151.0	2,625 ± 16	2691.4 ± 4.1	2	0.18424	0.25	12.77	0.8	0.5027	0.8	0.951
10.2	0.04	304	114	0.39	124.0	2,499 ± 16	2582.4 ± 7.7	3	0.17254	0.46	11.26	0.9	0.4735	0.8	0.858
11.1	0.01	1674	25	0.02	536.0	2,041 ± 12	2043.6 ± 2.9	0	0.12605	0.17	6.474	0.7	0.3725	0.7	0.974
12.1	0.00	986	416	0.44	297.0	1,938 ± 12	2037.7 ± 3.6	5	0.12563	0.2	6.073	0.8	0.3506	0.7	0.962
13.1	0.09	120	66	0.57	51.9	2,618 ± 20	2681.1 ± 6.9	2	0.18298	0.42	12.64	1	0.501	0.9	0.911
14.1	0.04	324	231	0.74	126.0	2,409 ± 15	2528.2 ± 4.7	5	0.16704	0.28	10.438	0.8	0.4532	0.8	0.940
15.1	0.01	723	324	0.46	219.0	1,948 ± 12	2023.7 ± 4.5	4	0.12464	0.25	6.064	0.8	0.3529	0.7	0.945
Sample LC-77															
1.1	0.00	1916	34	0.02	599.0	2,002 ± 16	2018.3 ± 3.1		0.12426	0.17	6.239	0.9	0.3641	0.9	0.983
1.2	0.02	56	38	0.71	25.7	2,777 ± 29	2727 ± 18	−2	0.1882	1.1	13.98	1.7	0.5385	1.3	0.770
2.1	0.04	813	14	0.02	265.0	2,072 ± 17	2067.8 ± 4.4		0.12779	0.25	6.680	1	0.3791	1	0.967
2.2	0.26	64	30	0.48	24.2	2,358 ± 25	2598 ± 23	9	0.1742	1.4	10.61	1.9	0.4416	1.3	0.675
3.1	0.00	155	82	0.55	70.6	2,748 ± 24	2696 ± 18	−2	0.1847	1.1	13.54	1.5	0.5316	1.1	0.694
3.2	0.00	2426	53	0.02	799.0	2,092 ± 17	2039.0 ± 4.9		0.12572	0.28	6.647	1	0.3834	0.9	0.958
4.1	0.00	44	26	0.61	19.5	2,659 ± 30	2693 ± 14	1	0.1844	0.85	12.98	1.6	0.5105	1.4	0.849
4.2	0.45	1624	30	0.02	463.0	1,841 ± 15	2050.5 ± 9.1		0.12655	0.52	5.767	1.1	0.3305	0.9	0.875
5.1	0.24	1763	216	0.13	542.0	1,969 ± 16	2311.7 ± 6.7		0.14704	0.39	7.241	1	0.3572	0.9	0.922
5.2	0.03	840	498	0.61	462.0	3,190 ± 24	3145.2 ± 2.7		0.24384	0.17	21.52	1	0.6402	1	0.984
6.1	−0.01	154	100	0.67	76.8	2,948 ± 25	2935.1 ± 5.9		0.21386	0.37	17.1	1.1	0.5798	1.1	0.946
7.1	0.06	45	28	0.64	20.6	2,746 ± 39	2728 ± 19	−1	0.1884	1.1	13.8	2.1	0.531	1.8	0.838
8.1	0.06	436	131	0.31	156.0	2,243 ± 18	2551.7 ± 6.8		0.1694	0.4	9.72	1	0.4161	1	0.922
9.1	0.12	967	196	0.21	328.0	2,142 ± 17	2328.0 ± 4.8		0.14844	0.28	8.065	1	0.394	0.9	0.959
10.1	0.02	187	92	0.51	85.6	2,749 ± 23	2721.2 ± 5.8		0.18759	0.35	13.76	1.1	0.5319	1	0.947
11.1	0.02	384	54	0.15	196.0	3,005 ± 24	2960.3 ± 7.1		0.21723	0.44	17.79	1.1	0.5939	1	0.915
12.1	0.01	357	182	0.53	170.0	2,838 ± 25	2912.5 ± 3.7		0.21091	0.23	16.08	1.1	0.553	1.1	0.978
12.2	0.13	1065	167	0.16	317.0	1,915 ± 18	2383.2 ± 7.9		0.15332	0.46	7.314	1.2	0.346	1.1	0.918
13.1	0.00	436	177	0.42	190.0	2,644 ± 21	2684.2 ± 5.7		0.18344	0.35	12.82	1	0.507	1	0.941
14.1	0.04	81	48	0.62	35.3	2,657 ± 25	2730.9 ± 8.3		0.18871	0.5	13.27	1.2	0.5102	1.1	0.915
Sample LC-79															
1.1	0.03	205	115	0.58	98.8	2,866 ± 21	2885.8 ± 7.7	1	0.20745	0.47	16.01	1	0.5597	0.9	0.886
2.1	0.01	1273	129	0.10	596.0	2,803 ± 16	2827.5 ± 2.4	1	0.20015	0.15	15.03	0.7	0.5446	0.7	0.979
3.1	0.01	855	23	0.03	356.0	2,547 ± 15	2734.1 ± 3.0	7	0.18908	0.18	12.633	0.8	0.4846	0.7	0.969

Table 2 (Continued)

Grain spot	% ²⁰⁶ Pbc	U (ppm)	Th (ppm)	²³² Th/ ²³⁸ U	²⁰⁶ Pb ^a (ppm)	²⁰⁶ Pb/ ²³⁸ U age ^b	²⁰⁷ Pb/ ²⁰⁶ Pb age ^b	% discordant	²⁰⁷ Pb ^a / ²⁰⁶ Pb ^{a,b}	±%	²⁰⁷ Pb ^a / ²³⁵ U ^b	±%	²⁰⁶ Pb ^a / ²³⁸ U ^b	±%	Error correction
4.1	0.07	1016	346	0.35	284.0	1,812 ± 11	2022.2 ± 4.1	10	0.12453	0.23	5,573	0.8	0.3246	0.7	0.952
4.2	0.25	3935	904	0.24	546.0	963.4 ± 6.3	1603.4 ± 8.3	40	0.0989	0.44	2,198	0.8	0.1612	0.7	0.847
5.1	0.11	3216	765	0.25	619.0	1,302 ± 10	1823.1 ± 3.8	29	0.11145	0.21	3,440	0.9	0.2238	0.9	0.972
6.1	0.67	2881	108	0.04	432.0	1031.0 ± 7.7	1633 ± 2	37	0.1005	1.2	2,403	1.5	0.1734	0.8	0.555
7.1	0.01	1367	555	0.42	414.0	1,947 ± 12	2029.3 ± 4.8	4	0.12503	0.27	6,080	0.8	0.3527	0.7	0.934
8.1	0.02	2064	478	0.24	481.0	1545.9 ± 9.7	1923.0 ± 3.7	20	0.11779	0.2	4,401	0.7	0.271	0.7	0.961
9.1	0.07	1166	266	0.24	348.0	1,923 ± 12	2034.5 ± 8.5	5	0.1254	0.48	6,010	0.9	0.3476	0.7	0.838
10.1	0.05	492	33	0.07	198.0	2,479 ± 15	2759.7 ± 5.1	10	0.19204	0.31	12,42	0.8	0.469	0.8	0.923
11.1	0.11	926	328	0.37	282.0	1,955 ± 12	2043.2 ± 4.4	4	0.12602	0.25	6,155	0.8	0.3542	0.7	0.947
11.2	0.01	1585	768	0.50	470.0	1,911 ± 13	2010.4 ± 5.4	5	0.12371	0.31	5,885	0.8	0.345	0.8	0.928
12.1	0.07	185	105	0.59	58.1	2,004 ± 22	2044 ± 0	2	0.1261	1.1	6.34	1.7	0.3646	1.3	0.739
13.1	0.00	1318	34	0.03	555.0	2,572 ± 15	2728.3 ± 4.1	6	0.18841	0.25	12,738	0.8	0.4904	0.7	0.945
14.1	0.03	1691	569	0.35	411.0	1,607 ± 10	1933.5 ± 3.6	17	0.11849	0.2	4,625	0.8	0.2831	0.7	0.963
15.1	0.01	651	486	0.77	282.0	2,636 ± 16	2708.8 ± 5.1	3	0.18619	0.31	12,97	0.8	0.5052	0.7	0.923
16.1	0.00	1348	489	0.37	417.0	1,983 ± 19	2030.6 ± 9.3	2	0.12513	0.52	6,215	1.2	0.3602	1.1	0.903
Sample LC-78															
1.1	0.00	186	103	0.57	49.8	1,748 ± 20	1972.7 ± 9.8	11	0.12111	0.61	5,201	1.4	0.3115	1.3	0.920
2.1	0.01	1608	538	0.35	537.0	2,116 ± 22	2597 ± 10	19	0.174	0.42	9.32	1.4	0.3885	1.2	0.896
3.1	0.00	316	156	0.51	92.2	1,883 ± 20	2022.8 ± 7.4	7	0.12458	0.66	5,828	1.3	0.3393	1.3	0.948
4.1	0.00	214	217	1.05	65.5	1,968 ± 22	2029 ± 12	3	0.12504	0.8	6,157	1.4	0.3571	1.3	0.887
5.1	0.04	288	129	0.46	88.5	1,968 ± 23	2061 ± 14	5	0.1273	0.95	6,264	1.6	0.357	1.3	0.859
6.1	0.10	230	180	0.81	57.6	1,645 ± 22	1923 ± 17	14	0.1178	0.4	4,722	1.8	0.2908	1.5	0.844
7.1	0.07	328	158	0.50	97.3	1,914 ± 21	2040.1 ± 7.0	6	0.1258	0.31	5,995	1.3	0.3456	1.2	0.953
8.1	0.00	431	509	1.22	141.0	2,082 ± 22	2048.8 ± 5.5	−2	0.12642	0.35	6,644	1.3	0.3811	1.2	0.970
8.2	0.03	373	452	1.25	113.0	1,943 ± 21	2034.7 ± 6.1	5	0.12542	0.74	6,083	1.3	0.3518	1.2	0.963
9.1	0.00	249	187	0.78	96.8	2,407 ± 26	2693 ± 12	11	0.1844	0.39	11.51	1.5	0.4526	1.3	0.872
10.1	0.00	604	479	0.82	280.0	2,779 ± 28	2728.8 ± 6.5	−2	0.18846	1.9	14	1.3	0.5388	1.2	0.952
10.2	0.00	191	141	0.76	57.8	1,944 ± 22	2041 ± 34	5	0.1259	0.32	6.11	2.3	0.3519	1.3	0.562
7.2	−0.02	226	182	0.83	96.8	2,612 ± 27	2673.1 ± 5.4	2	0.18221	0.44	12.55	1.3	0.4996	1.3	0.969
11.1	−0.01	586	252	0.45	243.0	2,543 ± 26	2652.2 ± 7.2	4	0.17992	0.52	12	1.3	0.4836	1.2	0.941
12.1	0.03	150	147	1.01	42.7	1,850 ± 23	2026.8 ± 9.3	9	0.12486	0.53	5,721	1.5	0.3323	1.4	0.937
13.1	0.07	161	136	0.87	51.5	2,041 ± 23	2027.3 ± 9.5	−1	0.12489	0.46	6,414	1.4	0.3725	1.3	0.925
13.2	0.00	226	155	0.71	66.5	1,901 ± 21	2020.1 ± 8.1	6	0.12439	2.7	5,883	1.4	0.343	1.3	0.941
13.3	0.81	25	9	0.37	3.7	1,012 ± 17	1538 ± 50	34	0.0955	0.61	2,238	3.2	0.1699	1.8	0.565
Sample LC-67															
1.1	0.02	192	38	0.21	84.1	2,650 ± 36	2697.0 ± 5.2	2	0.18486	0.31	12.96	1.7	0.5085	1.7	0.982
2.1	0.02	311	138	0.46	173.0	3,225 ± 33	3219.8 ± 3.2	0	0.2556	0.2	22.88	1.3	0.6492	1.3	0.988
3.1	0.04	126	86	0.71	40.3	2,043 ± 23	2053.3 ± 9.8	1	0.12675	0.56	6,516	1.4	0.3729	1.3	0.922
3.2	0.03	165	88	0.55	88.1	3,123 ± 32	3188.1 ± 5.3	2	0.25052	0.34	21.53	1.3	0.6232	1.3	0.968
4.1	0.00	320	117	0.38	91.9	1,859 ± 21	2031.3 ± 6.2	8	0.12518	0.35	5,768	1.4	0.3342	1.3	0.966
5.1	0.00	493	196	0.41	222.0	2,715 ± 27	3203.2 ± 5.8	15	0.25293	0.37	18.27	1.3	0.5238	1.2	0.958
6.1	0.00	105	70	0.69	32.4	1,985 ± 23	2040.8 ± 10.0	3	0.12585	0.56	6,257	1.5	0.3606	1.3	0.922
6.2	0.00	531	36	0.07	150.0	1,835 ± 20	2015.6 ± 4.9	9	0.12407	0.28	5,634	1.3	0.3293	1.2	0.976
7.1	0.10	102	77	0.79	31.5	1,984 ± 23	2050 ± 11	3	0.12652	0.6	6,288	1.5	0.3604	1.3	0.912
8.1	1.25	164	10	0.07	53.9	2,066 ± 24	2393 ± 54	14	0.1542	3.2	8.03	3.5	0.3778	1.4	0.399
8.2	0.00	268	139	0.53	82.4	1,970 ± 21	2029.9 ± 6.0	3	0.12508	0.34	6,163	1.3	0.3574	1.3	0.965
9.1	−0.01	297	115	0.40	118.0	2,457 ± 26	2833 ± 13	13	0.2008	0.78	12.84	1.5	0.4638	1.3	0.857
10.1	0.02	109	52	0.50	46.0	2,568 ± 28	2898 ± 11	1	0.2091	0.65	14.11	1.5	0.4894	1.3	0.898
11.1	0.01	128	79	0.64	67.0	3,073 ± 34	3127.1 ± 6.3	2	0.24107	0.39	20.3	1.5	0.6108	1.4	0.963
11.2	0.04	96	55	0.59	31.1	2,054 ± 24	2053 ± 10	0	0.12675	0.57	6,558	1.5	0.3752	1.3	0.919
12.1	0.01	147	106	0.75	54.3	2,309 ± 25	2528 ± 18	9	0.167	1.1	9.92	1.7	0.4308	1.3	0.767
12.2	0.03	178	69	0.40	83.5	2,812 ± 29	3141 ± 22	10	0.2432	1.4	18.34	1.9	0.5469	1.3	0.682
13.1	0.00	74	118	1.64	22.1	1,916 ± 26	2047 ± 12	6	0.12633	0.69	6.03	1.7	0.346	1.6	0.916
14.1	0.00	542	200	0.38	237.0	2,650 ± 27	3045 ± 12	13	0.229	0.77	16.06	1.5	0.5085	1.2	0.847
14.2	0.00	221	87	0.41	63.8	1,870 ± 21	2046.4 ± 7.4	9	0.12625	0.42	5,858	1.4	0.3365	1.3	0.951
15.1	−0.01	155	55	0.37	77.8	2,968 ± 32	3205.2 ± 4.6	7	0.25325	0.29	20.42	1.4	0.5848	1.3	0.977
15.2	0.07	107	40	0.38	33.6	2,005 ± 23	2049 ± 12	2	0.12646	0.66	6,361	1.5	0.3648	1.3	0.897
16.1	0.02	385	136	0.37	187.0	2,887 ± 30	3050.7 ± 7.2	5	0.2298	0.45	17.9	1.4	0.565	1.3	0.946
17.1	0.06	68	101	1.53	21.6	2,031 ± 24	2051 ± 13	1	0.12656	0.72	6.46	1.6	0.3703	1.4	0.890

Errors are 1-sigma. Error in standard calibration was 0.38% (not included in above errors but required when comparing data from different mounts).

^a Pbc and Pb indicate the common and radiogenic portions, respectively.

^b Common Pb corrected using measured ²⁰⁴Pb.

mately in half. The mount surface was then polished to expose the grain interiors and photographed in order to obtain cathodo-luminescence (CL) images. Ion microprobe analyses were carried out using SHRIMP RG. Analytical methods and data treatment followed those described by Williams (1998) and Williams and Meyer

(1998). Common lead corrections were performed using the Cumming and Richards (1975) model. Uncertainties reported in Tables 1 and 2 for analyses are given at the 1 σ level, and final ages are quoted at 2 σ confidence level. The data have been processed using SQUID and Isoplot/Ex software (Ludwig, 2001a,b).

ID-TIMS U–Pb analyses were carried out at the Geochronology Laboratory of the University of Brasília. Monazite grains were dissolved in concentrated H_2SO_4 (5 μL), and titanite grains in concentrated HF and HNO_3 (HF:HNO₃ = 4:1). A mixed ^{205}Pb – ^{235}U spike was used. Chemical extraction followed standard anion exchange technique, using Teflon micro columns, following procedures modified from Krogh (1973). Pb and U were loaded together on single Re filaments with H_3PO_4 and

Si gel for monazite analyses, and separately for titanite analyses. Isotopic analyses were carried out on a Finnigan MAT-262 multi-collector mass spectrometer equipped with secondary electron multiplier-ion counting. Procedure blanks for Pb, at the time of analyses, were better than 15 pg. For data reduction and age calculation, PBDAT (Ludwig, 1993) and ISOPLOT-Ex (Ludwig, 2001a) were used. Errors for isotopic ratios are 2σ .

Fig. 4. Concordia diagrams and CL images of zircon grains, Mantiqueira gneiss. Data-point error ellipses are 68.3% confidence level. (4.a) Sample RP-1, five points discordia line, MSWD = 1.5; (4.b) sample LC-70; (4.c) sample LC-77; (4.d) sample LC-79, 10 points discordia line, MSWD = 2.8; (4.e) sample LC-78, 17 points discordia line (14 zircon and 3 titanite points), MSWD = 2.1; (4.f) sample LC-67.

Fig. 4. (Continued).

4.2. U–Pb data for the Mantiqueira Complex

4.2.1. Sample RP-01

Twenty-six spot analyses were obtained on 16 zircon grains (Table 2), disclosing a large age spectrum with $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2096 to 3263 Ma (Fig. 4a). This is due to the preponderance of inherited zircon grains with varied morphological aspects, which yield discordant analysis essentially of Archean age. Many inherited grains display a magmatic overgrowth and an older core also magmatic-textured.

Crystallization age is given by four zircon grains displaying magmatic (oscillatory-zoned) overgrowths and inherited cores, and one homogeneous grain (without

core/rim separation). Analyses of this grain (spot analysis 7.1) and the overgrowths (spot analyses 4.1, 11.2, 12.2, 14.2) plot on a discordia line with an upper-intercept age of $2137 \pm 19 \text{ Ma}$. The lower intercept is poorly constrained, but most zircon grains display a thin and bright luminescent outer rim in CL images that may be related to the Neoproterozoic metamorphic imprint.

The zircon ages obtained for this tonalite gneiss revealed a crystallization age of $2137 \pm 19 \text{ Ma}$ and the abundance of inherited zircon grains of Archean age. Analyses of inherited grains are in general highly discordant and yield a polymodal $^{207}\text{Pb}/^{206}\text{Pb}$ age distribution, what can be explained by a combination of different crystallization ages, and multiple episodes of lead loss plus

Fig. 4. (Continued).

recent lead loss. The same pattern is found for all samples of Mantiqueira gneiss discussed below.

4.2.2. Sample LC-70

Eighteen spot analyses were carried out on 15 zircon crystals (Table 2). Seven grains are subhedral and poorly faceted, displaying a core with oscillatory or complex-zoned magmatic texture, and a large low luminescent overgrowth with a faint zoning. Thin rims with bright luminescence are observed around all crystals. The low luminescent overgrowths (spot analyses 1.2, 3.1, 4.1, 7.1, 11.1, 12.1, 15.1) have high U and high

(magmatic) Th/U ratios with one single exception (11.1), which is the most U-enriched (1674 ppm) but has a low Th/U ratio of 0.02. The magmatic nature of overgrowths is also deduced by the fact that some inherited cores are irregular-shaped and display engulfment of overgrowth material, apparently due to a process of magmatic corrosion. The best estimate for this episode of zircon growth is given by the mean $^{207}\text{Pb}/^{206}\text{Pb}$ age for the more concordant analyses (3.1, 4.1, 11.1) of $2044 \pm 4\text{Ma}$ (Fig. 4b). Slightly older spot analyses 1.2 and 7.1 probably represent mixed core/rim domains and were thus discarded.

The magmatic age of this gneiss sample is assumed at 2044 ± 4 Ma. Inherited cores and xenocrysts yield discordant Archean ages, except for a group of near-concordant analyses (1.1, 3.2, 10.1, 13.1) with a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2685 ± 12 Ma.

4.2.3. Sample LC-77

Twenty spot analyses were obtained on 14 zircon grains (Table 2) of morphologically distinct populations. Cathodoluminescence (CL) images show a dominant zircon type with length/width ratios of 3:1, bright luminescent cores and dark rims. Cores have high Th/U ratios (0.4–0.7) and display magmatic oscillatory zoning. Seven spot analyses (spots 1.2, 3.1, 4.1, 7.1, 10.1, 13.1, 14.1) are almost concordant with a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2720 ± 13 Ma, assumed as the magmatic event that crystallized the inherited cores. Of the four spot analyses of the dark rims (spots 1.1, 2.1, 3.2, 4.2), three are concordant to near-concordant but spread along the concordia line with $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 2018 ± 3 and 2068 ± 4 Ma (Fig. 4c). These overgrowths owe their low luminescence in CL images to the very high U-content, up to 2426 ppm, and the low Th/U ratios (0.02) may be explained by this anomalous enrichment in U rather than by a metamorphic origin. In fact, the overgrowths must be melt-precipitated due to features like oscillatory zoning and the protruding of rim into the core. Therefore, a magmatic age between 2018 ± 3 and 2068 ± 4 Ma is assumed for gneiss sample LC-77.

Besides the ca. 2720 Ma inherited zircon cores, older inherited ones are also present in this rock; one is concordant at 2935 ± 6 Ma (spot 6.1) and the other at 3145 ± 3 Ma (spot 5.2). A remaining group of highly discordant analyses refer to other Archean xenocrysts that underwent a combination of Paleoproterozoic and younger episodes of lead loss.

4.2.4. Sample LC-79

Eighteen spot analyses of 16 zircon crystals (Table 2) resulted in two age groups. One age group comprises inherited Archean zircon grains; two of them are almost concordant at 2828 and 2886 Ma. The largest group is represented by prismatic, euhedral zoned crystals (spot analyses 4.1, 4.2, 5.1, 7.1, 8.1, 9.1, 11.1, 11.2, 14.1, 16.1) with low luminescence (high U contents of 926 to 3935 ppm). Oscillatory zoning and Th/U ratios ranging from 0.24 to 0.50 are indicative of a magmatic origin. A dark overgrowth of similar characteristics (spot 6.1), and a high luminescent subhedral zircon crystal with a complex-zoned magmatic texture (spot 12.1), also fall into this age group. Regression of these data yields a discordia line with an upper intercept

age of 2051 ± 10 Ma and a less-precise lower intercept of 569 ± 31 Ma (Fig. 4d). The first is assumed as the magmatic age of the gneiss. The Neoproterozoic metamorphic event at ca. 569 Ma led only to a lead-loss process, because the grains do not display any metamorphic rim.

4.2.5. Sample LC-78

Zircon grains can be divided into three populations: (1) prismatic medium-dark luminescent crystals with a well-developed oscillatory zoned magmatic texture; (2) zircon grains with a core similar to the previous type, but displaying a bright magmatic zoned overgrowth (Th/U ratios of 0.46–1.05); (3) anhedral grains displaying a complex-zoned texture and high Th/U ratios (0.71–1.25). Five spot analyses of zircon grains of the first population and inherited cores of the second one (spot analyses 2.1, 7.2, 9.1, 10.1, 11.1) yield Archean ages.

Magmatic overgrowths (spot analyses 1.1, 3.1, 4.1, 5.1, 6.1, 7.1, 10.2, 12.1), and zircon grains of the third group (spot analyses 8.1, 8.2, 13.1, 13.2, 13.3) define a linear array pointing to a Paleoproterozoic age (Table 2, Fig. 4e). Three U–Pb ID-TIMS analyses of titanite fractions are almost concordant with a mean age of 569 ± 4 Ma (Table 3). Regression of the titanite and zircon data gives an upper intercept age of 2051 ± 12 Ma, and a lower intercept age of 570 ± 36 Ma (Fig. 4e). Zircon spot analysis 13.3 is not included in the age calculation because of very low U content and large errors on isotopic ratios.

The upper intercept age of 2051 ± 12 Ma can be interpreted as the magmatic age of the gneiss. Neoproterozoic metamorphic overprint, that is probably reflected by a thin bright luminescent outer rim displayed by most zircon crystals, is better constrained by the titanite age of 569 ± 4 Ma.

4.2.6. Sample LC-67

The dominant zircon type is subhedral to irregular-shaped, displaying a zoned core and a large bright luminescent overgrowth. A thin outer rim of even higher luminescence can also be present. A second group comprises elongate to rounded grains displaying only the thin external rim. The zircon cores and this second group of zircon grains yield Archean ages. Most of the spot analyses are highly discordant and are scattered on the concordia diagram (Table 2, Fig. 4f). One inherited core is concordant at 3220 ± 3 Ma (spot analysis 2.1).

The rock crystallization age is given by nine spot analyses (3.1, 4.1, 6.1, 7.1, 8.2, 11.2, 13.1, 14.2, 17.1) on the bright luminescent magmatic overgrowths,

Table 3
Summary of ID-TIMS titanite and monazite data

Sample fraction	Weight (mg)	U ^a ppm	Pb ^a ppm	²⁰⁶ Pb/ ²⁰⁴ Pb ^b	²⁰⁷ Pb/ ²³⁵ U ^c	Error (%)	²⁰⁶ Pb/ ²³⁸ U ^c	Error (%)	Error correlation	²⁰⁷ Pb/ ²⁰⁶ Pb	Error (%)	²⁰⁶ Pb/ ²³⁸ U ^c	Age ^d	²⁰⁷ Pb/ ²³⁵ U ^c	Age ^d	²⁰⁷ Pb/ ²⁰⁶ Pb	Error (Ma)
LC-78 (titanite)																	
2	0.167	94	13	263	0.7341	1.69	0.0924072	1.12	0.67374	0.057618	1.25	569.76	515.27	558.97	515.27	515.27	27
1A	0.162	110	15	275	0.7608	0.804	0.092451	0.624	0.80198	0.0596862	0.481	570.02	592.22	574.49	592.22	592.22	10
2A	0.137	75	10	183	0.7641	1.19	0.0916716	0.992	0.83713	0.0604535	0.653	565.42	619.85	576.38	619.85	619.85	14
LC-66b (monazite)																	
1	0.013	1222	1664	3202	0.7752	0.535	0.0947724	0.513	0.959848	0.0599325	0.15	583.7	579.03	582.75	579.03	579.03	3.3
2	0.021	893	1100	5097	0.7589	0.24	0.0931037	0.158	0.67456	0.0591214	0.177	573.87	571.57	573.4	571.57	571.57	3.9

^a Total U and Pb concentrations corrected for analytical blank.

^b Observed ²⁰⁶Pb/²⁰⁴Pb not corrected for blank or non-radiogenic Pb.

^c Radiogenic Pb corrected for blank and initial Pb; U corrected for blank.

^d Ages given in Ma using decay constants recommended by Steiger and Jäger (1977).

which display a faint oscillatory zoning and high Th/U ratios (0.38–1.64). Analyses are collinear, concordant to 8% discordant and with a mean ²⁰⁷Pb/²⁰⁶Pb age of 2041 ± 7 Ma. Lead-loss must be related to the Neoproterozoic metamorphic episode.

4.3. U–Pb data for the Juiz de Fora Complex

4.3.1. Sample LC-66a

Zircon grains are prismatic to equal-sided, with rounded terminations. They are low luminescent showing a sector-zoned or oscillatory-zoned magmatic texture, and a thin bright luminescent rim. Although morphologically homogeneous, the zircon population has contrasting Th/U ratios; one group has high (magmatic) ratios whilst the other has very low ratios due to a strong Th depletion. Metamorphic zircons of a granulite facies orthogneiss displaying a quite similar morphology and amount of Th depletion have been described elsewhere (Piuzana et al., 2003).

Eight spot analyses are discordant but colinear, defining a discordia line with an upper intercept age of 2113 ± 20 Ma. Two analyses of grains with low Th/U ratios (spot analyses 4.1, 7.1) plot above the discordia line. A regression of the six points representing zircon grains with typical magmatic high Th/U ratios (spot analyses 1.1, 2.1, 3.1, 5.1, 6.1, 10.1) yields an upper intercept age of 2119 ± 16 Ma, assumed as the best estimate for the gabbro-diorite magmatic age (Table 4, Fig. 5). The high-grade Paleoproterozoic metamorphic event is probably slightly younger than the intrusion age, and is responsible for the disturbance of the isotopic system of part of the zircon grains.

Two monazite grains from the late pink granite veins (sample LC-66b) were analyzed by ID-TIMS, and are concordant at ca. 584 and 574 Ma (Table 3), thus providing a good constrain for the Neoproterozoic metamorphic overprint.

4.3.2. Sample Ub-1

Zircon population is composed of prismatic and equal-sided grains, presenting oscillatory zoned cores and a bright luminescent overgrowth. Th/U ratios mostly above 0.3 for both cores and overgrowths are typically magmatic, but the latter show a strong U- and Th-depletion. Core/overgrowth boundary is quite irregular, with many features suggesting the engulfment of overgrowth material into the core. This is clearly seen in one of the zircon grains, together with the presence of a bright halo around a dark mineral inclusion within the core (Fig. 5b). Similar features have been already described in zircon crystals from migmatites, and the

Table 4
Summary of SHRIMP U–Pb zircon data for Juiz de Fora gneiss samples

Grain spot	% ^{206}Pb c	U (ppm)	Th (ppm)	$^{232}\text{Th}/^{238}\text{U}$	$^{206}\text{Pb}^a$	$^{206}\text{Pb}/^{238}\text{U}$ age ^b	$^{207}\text{Pb}/^{206}\text{Pb}$ age ^b	% discordant	$^{207}\text{Pb}^a/^{206}\text{Pb}^{a,b}$	±%	$^{207}\text{Pb}^a/^{235}\text{U}^b$	±%	$^{206}\text{Pb}^a/^{238}\text{U}^b$	±%	Error correction
Sample LC-66a															
1.1	0.05	585	246	0.43	172.0	$1,900 \pm 13$	2077.2 ± 6.1	9	0.1284764	0.35	6.0718254	0.8	0.3427637	0.8	0.912
2.1	0.06	703	845	1.24	180.0	$1,680 \pm 12$	2033.5 ± 4.8	17	0.1253356	0.27	5.1456066	0.8	0.2977563	0.8	0.944
3.1	0.04	678	373	0.57	164.0	$1,597 \pm 11$	2005.4 ± 6.5	20	0.1233643	0.37	4.7801732	0.8	0.2810302	0.7	0.896
4.1	0.03	719	45	0.06	202.0	$1,818 \pm 12$	$1,982 \pm 9.1$	8	0.1217751	0.51	5.4706988	0.9	0.3258241	0.8	0.828
5.1	0.03	407	598	1.52	118.0	$1,874 \pm 12$	$2,083 \pm 5.5$	10	0.1288995	0.32	5.9942908	0.8	0.3372758	0.8	0.923
6.1	0.07	525	141	0.28	160.0	$1,953 \pm 13$	2083.0 ± 8.7	6	0.1288995	0.49	6.2891893	0.9	0.3538686	0.7	0.834
7.1	0.00	724	43	0.06	185.0	$1,681 \pm 11$	$1,946 \pm 9$	14	0.11933	0.52	4.9020078	0.9	0.297936	0.7	0.818
8.1	0.02	857	66	0.08	245.0	$1,854 \pm 12$	2067.9 ± 4.0	10	0.1277951	0.23	5.8708981	0.8	0.3331877	0.7	0.954
9.1	0.00	1100	20	0.02	303.0	$1,794 \pm 11$	$2,044 \pm 3.8$	12	0.1260935	0.21	5.5771202	0.7	0.3207866	0.7	0.961
10.1	1.36	487	631	1.34	136.0	$1,789 \pm 75$	$2,045 \pm 33$	13	0.1261447	1.87	5.5636943	5.2	0.3198845	4.8	0.932
Sample Ub-1															
1.1	0.00	371	289	0.80	103.0	$1,805 \pm 24$	$2,011 \pm 12$	10	0.12378	0.69	5.514	1.7	0.3231	1.5	0.910
2.1	0.52	23	14	0.61	2.6	792 ± 28	$1,256 \pm 78$	37	0.0824	4.00	1.486	5.5	0.1307	3.8	0.688
2.2	0.00	912	350	0.40	232.0	$1,673 \pm 22$	1969.0 ± 8.3	15	0.12087	0.47	4.938	1.6	0.2963	1.5	0.955
3.1	0.06	212	229	1.12	56.0	$1,730 \pm 22$	$2,033 \pm 10$	15	0.12529	0.59	5.319	1.6	0.3079	1.5	0.930
3.2	0.03	363	102	0.29	113.0	$1,994 \pm 25$	2089.7 ± 6.3	5	0.12939	0.36	6.469	1.5	0.3626	1.4	0.970
4.1	0.04	411	603	1.52	97.9	$1,575 \pm 20$	$1,936 \pm 11$	19	0.11868	0.62	4.530	1.6	0.2768	1.5	0.920
4.2	0.01	964	460	0.49	247.0	$1,679 \pm 21$	2017.4 ± 7.5	17	0.1242	0.42	5.096	1.5	0.2976	1.4	0.958
5.1	0.01	513	275	0.55	157.0	$1,962 \pm 24$	2057.4 ± 5.1	5	0.12704	0.29	6.231	1.5	0.3557	1.4	0.980
5.2	0.00	832	523	0.65	229.0	$1,794 \pm 23$	2028.0 ± 5.6	12	0.12494	0.32	5.528	1.5	0.3209	1.5	0.978
6.1	0.00	2524	1684	0.69	461.0	$1,243 \pm 16$	1790.9 ± 9.6	31	0.10949	0.53	3.211	1.5	0.2127	1.4	0.939
6.2	2.75	33	10	0.32	3.6	734 ± 19	$1,120 \pm 80$	34	0.0769	9.20	1.28	9.6	0.1207	2.7	0.285
7.1	0.05	159	67	0.44	28.2	$1,205 \pm 17$	$1,754 \pm 14$	31	0.10728	0.74	3.041	1.7	0.2056	1.5	0.898
7.2	0.15	951	388	0.42	208.0	$1,460 \pm 19$	$1,907 \pm 11$	23	0.11673	0.61	4.093	1.5	0.2543	1.4	0.920
8.1	0.14	131	117	0.92	41.2	$2,004 \pm 28$	$2,064 \pm 14$	3	0.1275	0.80	6.41	1.8	0.3647	1.6	0.898
8.2	0.20	652	58	0.09	87.5	934 ± 17	$1,636 \pm 19$	43	0.1007	1.00	2.163	2.2	0.1559	2.0	0.895
9.1	0.04	255	80	0.32	73.4	$1,863 \pm 24$	2045.9 ± 7.6	9	0.12621	0.43	5.832	1.5	0.3351	1.5	0.960
10.1	0.13	264	177	0.69	79.8	$1,939 \pm 25$	2046.1 ± 8.4	5	0.12623	0.48	6.107	1.6	0.3509	1.5	0.952
11.1	0.01	1030	897	0.90	341.0	$2,104 \pm 25$	2078.9 ± 4.0	–1	0.1286	0.22	6.845	1.4	0.386	1.4	0.988
12.1	0.15	70	43	0.63	20.4	$1,869 \pm 28$	$2,053 \pm 30$	9	0.1267	1.70	5.88	2.4	0.3363	1.7	0.708
13.1	0.00	1708	1338	0.81	517.0	$1,947 \pm 24$	2046.0 ± 3.3	5	0.12622	0.19	6.136	1.4	0.3526	1.4	0.991

Errors are 1-sigma. Error in standard calibration was 0.31% (not included in above errors but required when comparing data from different mounts).

^a Pbc and Pb indicate the common and radiogenic portions, respectively.

^b Common Pb corrected using measured ^{204}Pb .

Fig. 5. Concordia diagrams and CL images of zircon grains, Juiz de Fora gneiss. Data-point error ellipses are 68.3% confidence level. (5.a) Sample LC-66a, eight points discordia line, MSWD = 1.7; (5.b) sample Ub-1 nineteen points discordia line, MSWD = 3.1.

overgrowth forming mechanism attributable to anatectic melting-precipitation of new zircon material (e.g., Silva et al., 2005b).

Twenty spot analyses of core and overgrowth were obtained on 13 zircon grains (Table 4), and the data define a discordia line with an upper intercept age of $2084 \pm 13 \text{ Ma}$ and a lower intercept age of $594 \pm 37 \text{ Ma}$ (Fig. 5b). When data for cores and overgrowths are regressed separately the same upper intercept age within errors is obtained. Spot analyses are concordant to highly discordant and the overgrowths in general experienced a

more severe lead loss during the Neoproterozoic metamorphic overprint.

The coincidence of core and overgrowth ages at $2084 \pm 13 \text{ Ma}$ may be explained by migmatization shortly following the pluton intrusion probably during a syn-collisional stage.

5. Discussion

A summary of U–Pb data together with Nd signatures are presented in Table 5. Samples of Mantiqueira gran-

Table 5
Summary of isotopic data

Sample	Gneiss composition	Sample location	Magmatic age	Metamorphic age(s)	T_{DM} (Ga)	$\varepsilon_{Nd(t)}$
Mantiqueira Complex						
RP-1	Tonalite	Quarry in the vicinity of Alto Rio Doce	2137 ± 19		3.0	−13.0
LC-70	Granodirite	Road cut between Mariana and Ponte Nova	2044 ± 4		2.9	−9.0
LC-77	Granodiorite	Road cut close to São Domingos do Prata.	2018 ± 3 to 2068 ± 4		3.1	−11.4
LC-79	Granite	Quarry in the town of Coronel Fabriciano	2051 ± 10	569 ± 31	2.9	−9.6
LC-78	Granodiorite	Outcrop at the margin of Doce river, within the Natural Rio Doce Park	2051 ± 12	570 ± 36 (569 ± 4)	3.2	−12.0
LC-67	Granodiorite	Road cut near Rio Casca	2041 ± 7		3.2	−12.0
Juiz de Fora Complex						
LC-66	Norite	Abre Campo quarry	2119 ± 16	584–574	2.3	−0.4
Ub-1	Enderbite	Astolfo Dutra quarry	2084 ± 13	594 ± 37	2.6	−3.5

odiorite and granite gneiss crystallized at ca. 2050 Ma, and are characterized by the abundance of inherited Archean zircon grains, T_{DM} model ages ranging from 2.9 to 3.2 Ga, and strongly negative $\varepsilon_{Nd(t)}$ (−9 to −12). These data indicate that the Archean crust was the main source of magmas that gave origin to the gneiss protholites. The preservation of large volumes of inherited zircon crystals in crustal anatexic melts has been explained by low melting temperatures (Watson and Harrison, 1983), as is the case for diatexite migmatites (Tikhomirova, 2002). Sample RP-1 crystallized at ca. 2137 Ma, is tonalitic in composition and also carries a large amount of inherited Archean zircon grains. It yields a strongly negative $\varepsilon_{Nd(t)}$ of −13, and should derive from a crust-contaminated magma at an active-margin setting.

These results are in agreement with previous U–Pb SHRIMP data for three Mantiqueira gneiss samples, which yielded crystallization ages at 2102–2058 Ma, with inherited zircon nuclei dated at 2180–2160 Ma (Silva et al., 2002). It was proposed that inherited zircon nuclei derived from partial melting of arc-related granitoids during syn-collisional magmatism at 2102–2058 Ma. A banded gneiss dated by Heilbron et al. (2001) records a metamorphic event at 2040 ± 47 Ma, and its crystallization age at 2203 ± 17 Ma suggests a complex and protracted evolution for the magmatic arc(s) plutons included into the Mantiqueira Complex.

The most striking feature of the results for Mantiqueira gneisses is the spread out of the analytical data observed in all of the concordia diagrams, which simulates the distribution pattern of zircon grains from metasedimentary rocks. In fact, this pattern is essentially a consequence of the polycyclic history of the

Mantiqueira Complex. Most analyses of inherited zircon grains are moderately to highly discordant due to multiple episodes of lead loss during the Paleo and Neoproterozoic, resulting in a large spread of $^{207}\text{Pb}/^{206}\text{Pb}$ ages. Besides, for some of the samples inherited zircon grains and cores may fall into more than one age group, a feature that can be found in other continental arc-related plutonic rocks (for example, some tonalite gneiss and granodiorite of the Minto block, northeastern Superior Province; Percival et al., 2001).

Juiz de Fora gneiss samples have no inherited zircons. The gabbro-dioritic rock (sample LC-66a) yields a juvenile Nd signature, with a T_{DM} model age of 2.3 Ga and a $\varepsilon_{Nd(t)}$ value close to zero, whilst the enderbitic gneiss (sample Ub-1) has a Late Archean T_{DM} model age (2.6 Ga) and a negative $\varepsilon_{Nd(t)}$ value of −3.5. For the latter, a mixed source of juvenile Paleoproterozoic material with contribution of Archean crust material is suggested. Intrusion ages for Juiz de Fora gneiss, from this and previous studies fall into the 2134–2084 Ma time range, with the exception of one older age of 2195 ± 15 Ma (Silva et al., 2002).

Isotopic evidence, specially for Juiz de Fora gneiss samples, suggest the studied units underwent a migmatization process during the Paleoproterozoic. This is in agreement with field observation that the gneissic banding results from the transposition of an earlier banded structure during the Brasiliano Orogeny (Fig. 3b).

5.1. Correlation with the West Congo Belt

The basement of the West Congo Belt is represented by the Paleoproterozoic Kimezian Supergroup, to the

west and north, and Archean complexes, to the southeast (Fig. 1). The Kimezian Supergroup is essentially a series of metasedimentary rocks and consists of paragneiss, amphibolite, migmatite, and minor quartzite and marble, metamorphosed around 2 Ga (Delhal and Ledent, 1976; Vicat and Pouclet, 2000; Tack et al., 2001). Deformed granitoids dated at ca. 2.0 Ga have been interpreted as plutons of a Paleoproterozoic continental magmatic arc (Maurin et al., 1990, 1991; Vicat and Pouclet, 2000). The Paleoproterozoic basement was reworked during the Pan African orogeny under greenschist facies conditions to the east (i.e., towards the foreland of the West Congo Belt), and under amphibolite facies conditions to the west (i.e., to the westernmost part of the West Congo Belt).

U–Pb data for Kimezian rocks comes from ID-TIMS analyses on unabraded zircon fractions, and analytical points are usually very discordant resulting in not well-constrained upper-intercept ages for crystallization events. Two migmatitic gneisses (Mpozo-Tombagadio and Boma migmatites) yielded an age of 2150–2125 Ma, interpreted as the migmatization age (Delhal and Ledent, 1976). Dated plutonic bodies are

- Guéna gneiss, a banded biotite gneiss tonalitic in composition, dated at 2014 ± 56 Ma (Maurin et al., 1991); it has an Archean T_{DM} model age (2.6 Ga) and negative $\varepsilon_{Nd(t)}$ values ranging from -4.8 to -6.2 (Djama et al., 1992).
- Les Saras granodiorite, dated at 2000 ± 80 Ma (Maurin et al., 1990).
- Fougamou granitoid, comprising porphyritic rocks ranging in composition from granite to diorite, and dated at $1915 \pm 10/-9$ Ma (Caen-Vachette et al., 1988).
- The Gombou massif, composed of granodiorite gneiss, and with a less-deformed facies dated at $2083 \pm 27/-25$ Ma (Caen-Vachette et al., 1988).
- Vista Alegre granodiorite, dated at 1940 Ma (Cahen et al., 1979).
- Mpozo syenite, dated at 1960 Ma (Delhal and Ledent, 1978).

Les Saras and Guéna gneissic plutons are interpreted as calc-alkaline intrusions related to a magmatic arc built up at a continental margin in response to subduction of oceanic lithosphere under an Archean craton to the east (Maurin et al., 1990, 1991). Vicat and Pouclet (2000) also suggests a continental, active-margin setting for the calc-alkaline to alkaline, Paleoproterozoic (2083–1915 Ma) magmatism recorded in the basement of the West Congo Belt, which was produced by partial melting of Archean-aged protholits.

A correlation arises from the available data: granitoid plutons of the Mantiqueira Complex and the West Congo Belt basement are probably related to two orogens that evolved along the margins of the Archean nuclei of São Francisco and Congo cratons. Orogenic evolution was diachronic; magmatism in the Mantiqueira Complex ended at ca. 2041 Ma, but extended until ca. 1915 Ma in the Kimezian Supergroup of the West Congo Belt basement. The Juiz de Fora Complex seems to have no correlative in the basement of the West Congo Belt.

6. Final remarks and evolutionary model

All directions refers to the present-day position of South America and Africa.

A Paleoproterozoic belt (the West Central African Belt, Feybesse et al., 1998) extends along the western side of the Congo Craton, and is interpreted as a result of the collision between the São Francisco–Nigerian shield and a former Congo megacraton (Lerouge et al., 2006). This Paleoproterozoic belt represents the external sector of a larger orogen whose internal zones are preserved in the Itabuna–Salvador–Curaçá belt that runs along the eastern side of the São Francisco Craton facing the Atlantic Ocean (Ledru et al., 1994; Barbosa and Sabaté, 2004; Lerouge et al., 2006). Evolution of the Brasiliano–Pan African Araçuaí–West Congo Orogen disrupted and deeply reworked a segment of this Paleoproterozoic orogen to the south of the Itabuna–Salvador–Curaçá belt and its African counterpart. Its fragments are now the basement of the Araçuaí–West Congo Orogen, consisting of the following rock assemblages associated to distinct tectonic settings:

- (1) The Mantiqueira Complex mainly comprises the plutonic rocks generated in an orogen that evolved along the Archean margin of the São Francisco Paleocontinent, approximately between 2180 and 2041 Ma.
- (2) The Juiz de Fora Complex probably evolved within an oceanic magmatic arc setting, or on a very stretched continental crust, between 2195 and 2084 Ma.
- (3) The Kimezian Supergroup, a series of metasedimentary rocks of unknown depositional age, metamorphosed during the Eburnean Orogeny.
- (4) Calc-alkaline to alkaline granitoids evolved in a similar setting as the Mantiqueira Complex, but along the Archean margin of the Congo Paleocontinent, from 2083 to 1915 Ma.

Fig. 6. Cartoon illustrating the possible scenarios for the evolution of Paleoproterozoic magmatic arcs in the São Francisco and Congo paleocontinents.

The presented data and interpretations of tectonic environments encourage the authors to offer a hypothesis in order to inspire future works on the evolution of the focused Paleoproterozoic basement terranes, as follows (Fig. 6):

- If the Juiz de Fora Complex is a remnant of an island arc, the model requires an intra-oceanic subduction zone and also implies that, much probably, a very large ocean separated the São Francisco and Congo paleocontinents during this stage (ca. 2180–2100 Ma). The Mantiqueira magmatic arc would be in part coeval to the Juiz de Fora arc, but developed on the eastern active margin of the São Francisco Paleocontinent.
- Evidence from zircon data suggest a collision between the Juiz de Fora arc and the São Francisco Paleocontinent in the interval of ca. 2100–2085 Ma.
- Orogenic, calc-alkaline magmatism would have begun in the Kimezian basement at ca. 2083 Ma. This requires subduction to the east, under the active mar-

gin of the Congo Paleocontinent. The stage from 2085 Ma to 2040 Ma would record the last calc-alkaline magmatism in the Mantiqueira arc in a syn- to late collisional tectonic setting. The younger (ca. 1915 Ma) alkaline plutons of the Kimezian basement could represent the post-collisional magmatism that followed the amalgamation of the São Francisco–Congo Paleocontinent.

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