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SHRIMP U–Pb, $^{207}Pb/^{206}Pb$ zircon dating, and Nd isotopic signature of the Umburanas greenstone belt, northern São Francisco craton, Brazil

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Abstract

The Gavião block in the northern portion of the São Francisco craton, northeast Brazil, is one of the oldest Archean fragments of the South American platform. It underwent polycyclic evolution from very old juvenile components dated between 3400 and 3000 Ma. The studied parts of the Umburanas greenstone belt (UGB) formed over 'stable' continental crust. SHRIMP U/Pb isotopic analyses of detrital zircons from conglomeratic quartzites of the UGB's lower unit yield dates between 3335 and 3040 Ma. These dates indicate provenance from crustal materials of different ages and a maximum age of deposition as young as 3040 ± 24 Ma (single zircon analysis) but certainly after 3147 ± 16 Ma (three analyses).

$^{207}Pb/^{206}Pb$ zircon evaporation analyses from a meta-andesite of the intermediate unit of the UGB yield 2744 ± 15 Ma, which is interpreted as the time of magmatic crystallization. The Sm/Nd whole-rock systematics of three metakomatiites from the base of the lower unit indicate that they are isotopically disturbed. Additional Sm/Nd analyses of one metabasalt (lower unit) and two meta-andesites (intermediate unit) were compared with those of the country rocks. Their similarity suggests that crustal contamination processes play an important role in the formation of volcanic rocks. As a whole, the isotopic picture is in agreement with an ensialic tectonic setting of the studied parts of the UGB.

Keywords: Archaean-Paleoproterozoic; Nd isotopic signature; São Francisco craton

Sumário

O Bloco Gavião, situado na porção setentrional do Cráton do São Francisco, expõe um dos mais preservados segmentos de crosta arqueana da Plataforma Sul-Americana. As épocas principais de acresção juvenil do Bloco Gavião foram datadas entre 3,4–3,1 Ga e 3,1–3,0 Ga, e resultaram na consolidação de um fragmento continental há cerca de 3,0 Ga atrás, sobre o qual se instalou o greenstone belt de Umburanas (GBU). Análises isotópicas U/Pb (SHRIMP) de zircões detríticos de quartzitos conglomeráticos da unidade inferior do GBU revelaram idades entre 3335 e 3040 Ma, apontando a existência de contribuições de diferentes fontes crustais à bacia. Caso o resultado mais jovem seja representativo (3040 ± 24 Ma; apenas uma análise de zircão), esta seria a idade máxima de sedimentação da unidade inferior do GBU. Contudo, um limite temporal seguro para a sedimentação é dado pela idade de 3147 ± 16 Ma (três análises).

Análises $^{207}Pb/^{206}Pb$ em zircões pelo método de evaporação em meta-andesito da unidade intermediária do greenstone belt revelaram idade de 2744 ± 15 Ma, interpretada como a época de cristalização magmática. Por outro lado, os parâmetros isotópicos Sm/Nd em três metakomatiítos da unidade inferior do GBU são diagnósticos de distúrbio isotópico. Em adição, as assinaturas isotópicas de Nd em metabasalto da unidade inferior e dois meta-andesitos da unidade intermediária, comparados com as assinaturas das rochas trondjemítico-tonalítico-granodioríticas encaixantes, sugerem a existência de processos de contaminação crustal. O conjunto de dados isotópicos apóia um modelo tectônico ensiálico para o GBU.

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1. Introduction

The Archaean-Paleoproterozoic (3400–1900 Ma) tectonic evolution of the São Francisco craton (SFC) is characterized by a series of juvenile plutonic pulses, crustal reworking, and tectonic accretion (Fig. 1A; Cordani et al., 1985; Sabaté et al., 1990; Martin et al., 1997; Nutman and Cordani, 1993; Nutman et al., 1994; Teixeira et al., 1996; Alkmin and Marshak, 1998; Bastos Leal et al., 2000).

The granitic-gneissic-migmatitic Archean terrains of the SFC are best exposed in its northern central portion (Bahia state) and include relatively well-preserved lithological assemblages of volcanosedimentary rocks (e.g. the Ibitira-Brumado, Umburanas, and Contendas-Mirante greenstone belts; see Fig. 1), which makes this area important for investigations of the early evolution of the craton. Systematic geologic mapping supported by geochronologic, isotopic, and geochemical data has led to the characterization of the Gavião, Jequié, and Serrinha Archean blocks in the northern central SFC (Teixeira et al., 2000). Such blocks generally have tectonic boundaries developed during Paleoproterozoic orogenies (Teixeira and Figueiredo, 1991; Barbosa and Sabaté, 2002). The most significant of these is the Contendas-Jacobina lineament (Fig. 1A), which was formed by the collision of the Archean blocks during the so-called Transamazonian orogeny (2.1–1.9 Ga). This played a major role in the evolution of the Jacobina foreland basin and the Contendas-Mirante greenstone belt (Fig. 1B) and controlled the emplacement of peraluminous granites (Sabaté et al., 1990; Cunha and Fróes, 1994; Ledru et al., 1997; Barbosa and Sabaté, 2002). In addition, during Transamazonian crustal shortening, some Archaean gneiss and granitoid material from the Gavião block was uplifted and thrust over the adjoining Contendas-Mirante basin in a few mantled gneissic domes, including the Sete Voltas, Boa Vista/Mata Verde, and Lagoa do Morro (Nutman et al., 1994; Fig. 1B).

The Gavião block consists of Archaean supracrustal assemblages, including the Umburanas and Contendas-Mirante greenstone belts, tonalite-trondhjemite-granodiorite (TTG) associations (e.g. nearby Brumado, Aracatu, Piripá), migmatites, and granitoids (e.g. Mariana, Aracatu, Bernarda, Serra do Eixo, Lagoa do Macambira) (Fig. 1B). The Transamazonian event was also responsible for anatectic partial melting processes of the country rocks and granitoid intrusions such as the Umburanas granite (e.g. Santos Pinto et al., 1998; Bastos Leal et al., 2000; Cordani et al., 2000).

The Paramirim province (Fig. 1A) includes most of the Gavião block. This province contains the uranium–associated plutonism of Lagoa Real (1720–1700 Ma) and felsic volcanism (1750 Ma) in the northern Espinhaço metasedimentary system (Turpin et al., 1998; Cordani et al., 1992; Babinski et al., 1999). Thrust faults, regional shear zones, and polyphase deformation denote the complex framework of this province. Moreover, regional metamorphism of the Paramirim rocks took place during the Mesoproterozoic (1300 Ma), as indicated by Rb–Sr and K–Ar ages (Cordani et al., 1985, 1992; Turpin et al., 1998), and the southern end of the Gavião bock was affected by the much younger tectonic and metamorphic events related to the Araçuaí belt (650–500 Ga) (Fig. 1A).

This article reports the first integrated geochronological investigation of the Archaean Umburanas greenstone belt (UGB), one of the main supracrustal units of the Gavião block, as part of a reconnaissance dating program in the northern SFC. SHRIMP U–Pb zircon and Pb–Pb zircon evaporation, as well as Sm/Nd whole-rock analyses, were carried out on selected rocks from the UGB's lower and intermediate lithostratigraphic units, respectively. The obtained data are used to draw comparisons with SHRIMP U–Pb and $^{207}Pb/^{206}Pb$ zircon evaporation ages of the adjoining TTG terrains (Santos-Pinto, 1996; Bastos Leal et al., 1998), thereby improving the assessment of the crustal evolution of the Gavião block. Moreover, some insights are given for the understanding of the provenance history and tectonic setting of the UGB.

2. Geochronological background

Previous SHRIMP U–Pb zircon, Pb–Pb zircon evaporation, and Sm–Nd ages available for the Gavião block are summarized in Table 1. The oldest identified rocks are located in the mantled gneissic domes of the Contendas-Mirante belt (Sete Voltas, Boa Vista/Mata Verde; Fig. 1B) and yield ages up to 3403 ± 5 Ma (Nutman and Cordani, 1993; Martin et al., 1997; Bastos Leal et al., 1998). For the gneissic and granitoid rocks of the Gavião block, the Sm/Nd (T_{DM}) model ages between 3.7 and 3.2 Ga, coupled with $\varepsilon_{Nd(t)}$ values between + 5.0 and − 6.8, suggest that they are formed by both juvenile crustal components and material from older continental crust that has not been identified (Marinho, 1991; Santos-Pinto et al., 1996; Cordani et al., 1997; Bastos Leal, 1998).

During Mesoarchaean times, the Gavião block was intruded by granodioritic to granitic bodies, such as the Lagoa do Morro and Malhada de Pedras plutons at 2.8 Ga (Rb/Sr and Pb–Pb age determinations; Bastos Leal et al., 1998). Slightly younger Rb/Sr ages available for some of the country rocks are interpreted as associated with Neoarchean tectonometamorphic episodes of the Jequié orogenic cycle (Mascarenhas and Garcia, 1986), because comparable Rb/Sr ages (ca. 2.7 Ga) are reported for calc-alkaline enderbite-charnockites of the Jequié block (Cordani et al., 1985). However, the existence of an Archaean granulite metamorphism in the Jequié block, given the occurrence of granulitic migmatites, is still a matter of debate (Teixeira et al., 2000). This high grade event and some of the charnockitic intrusions have been genetically related to a westward subduction of oceanic crust under the Gavião

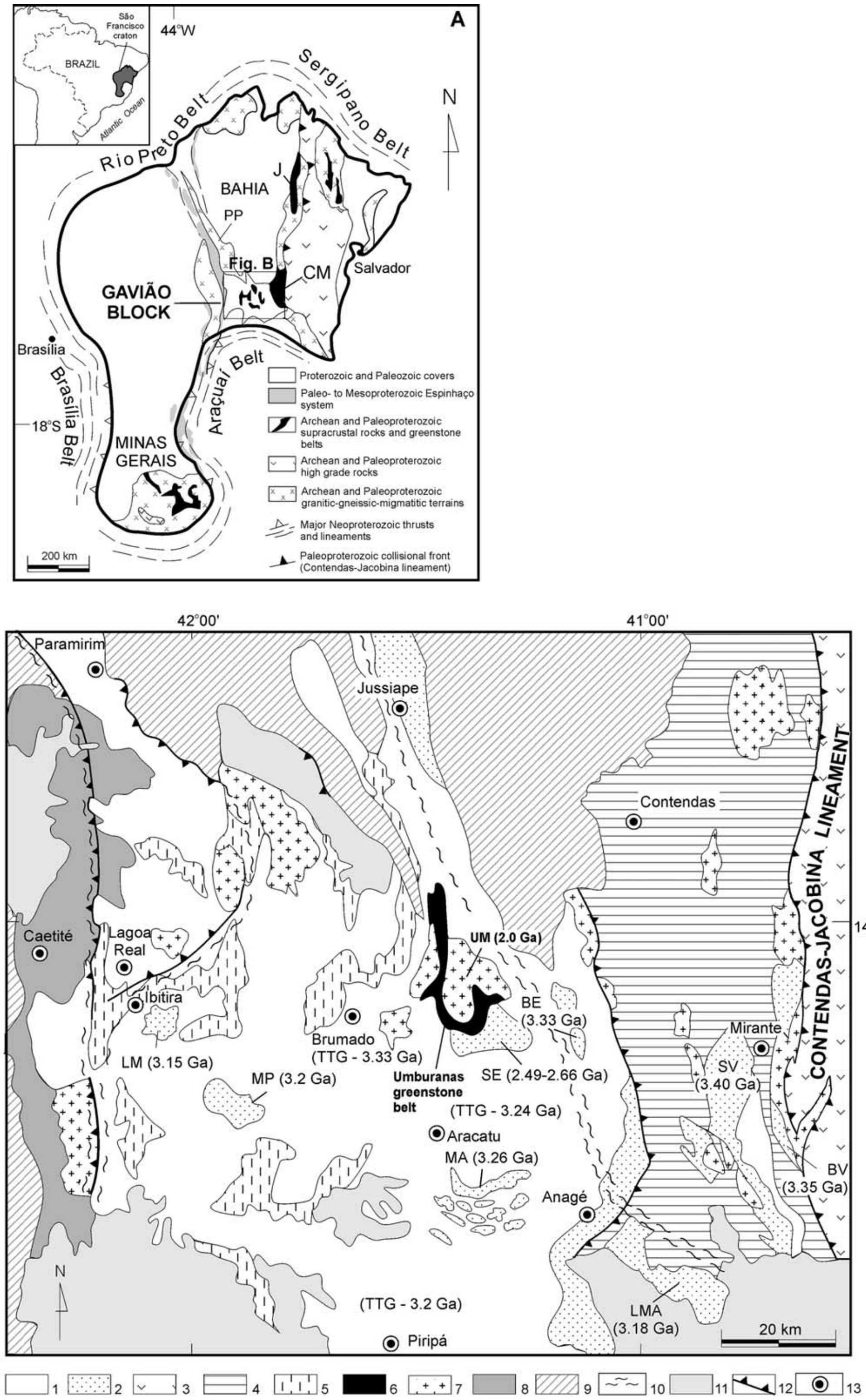

Fig. 1. Geologic framework of the northern central SFC. A: simplified sketch map of the main geologic units (after Barbosa and Sabaté, 2002). Key: PP = Paramirim Province; J = Jabobina basin; CM = Contendas–Mirante greenstone belt. B: Details of the Gavião block (after Cunha and Fróes, 1994). Key: 1 = Archean gneissic-migmatitic terrains of the TTG association; 2 = Archean granitoids; 3 = Archean high grade terrain of the Jequié block; 4 = Archean-Paleoproterozoic Contendas-Mirante greenstone belt; 5 = Archean supracrustal sequence, including the Ibitira-Brumado greenstone belt; 6 = UGB; 7 = Transamazonian granitoids; 8 = Paleo- to Mesoproterozoic Lagoa Real granitoid complex; 9 = Paleo- to Mesoproterozoic units (Espinhaço supergroup); 10 = shear zones; 11 = Cenozoic cover; 12 = regional thrust zones; and 13 = towns: LM = Lagoa da Macambira, MP = Malhada de Pedras, MA = Mariana, SE = Serra do Eixo, BE = Bernarda, SV = Sete Voltas, BV = Boa Vista, and LMA = Lagoa do Morro/Anagé. UM = Umburanas granite (2.05 Ga). Ages are given in Ga.

Table 1
Summary of the available geochronological data of the Gavião block

Geological units	Rb/Sr ages	SHRIMP U/Pb (zr), $^{207}Pb/^{206}Pb$(zr) and Pb–Pb wr	Sm/Nd (T_{DM} model ages)	References
Tonalite, trondhjemite and granodiorite (Archean)	2.7–3.4 Ga	3403 ± 5 Ma to 3158 ± 5 Ma	3.7–3.2 Ga	Nutman and Cordani, 1993; Santos-Pinto, 1996; Martin et al., 1997; Bastos Leal et al., 1998
Contendas–Mirante greenstone belt	2.2–2.1 Ga	2.67–2.61; 2.38–2.32; 2.17 Ga	3.5; 3.3–3.0; 2.4 Ga	Cordani et al., 1985; Marinho, 1991; Nutman et al., 1994; Sato, 1998
Umburanas greenstone belt	2.2 Ga	3335–3150 Ma; 3040 Ma; 2750 Ga	3.5–1.4 Ga	Bastos Leal et al., 1998; this work
Granitoids (Paleoproterozoic)	2.0–1.8 Ga	2049 ± 5 Ma to 1944 ± 7 Ma	3.6–2.7 Ga	Marinho, 1991; Santos-Pinto, 1996; Bastos Leal et al., 2000

zr = zircon; wr = whole rock.

block as a result of the Transamazonian collision (Ledru et al., 1994). Ages of ca. 2.7 Ga were obtained from rocks of the Guanambi-Correntina block (Mascarenhas and Garcia, 1986), west of the Gavião block, which confirm the important role of the Neoarchaean events in the northern central SFC.

Published U–Pb and Sm/Nd ages for the volcanosedimentary sequences at the base of the Ibitira–Brumado and Contendas–Mirante greenstone belts and UGB suggest early mafic–ultramafic volcanism took place between 3.3 and 3.0 Ga ago (Marinho, 1991; Bastos Leal, 1998; Sato, 1998). In contrast, calc-alkaline metavolcanics of the intermediate units of the UGB and Contendas–Mirante greenstone belt yield much younger ^{207}Pb–^{206}Pb and Pb–Pb ages of ca. 2.75 and 2.55 Ga (see Table 1), respectively (Marinho, 1991; Bastos Leal et al., 1998). These isotopic and geochemical results, particularly the T_{DM} crustal residence ages between 3.5 and 2.4 Ga for the metasediments (Sato, 1998), support a continental setting for the Contendas-Mirante belt (Marinho, 1991). However, some of the $\varepsilon_{Nd(2.5\ Ga)}$ values suggest a short crustal residence time for the source material, in agreement with the T_{DM} age of the underlying metavolcanic, mafic member (Marinho, 1991).

In addition to an Archaean basal volcanic unit, the Contendas-Mirante basin includes a Paleoproterozoic unit, from which a metaconglomerate (upper member) yields detrital zircons with SHRIMP U–Pb zircon ages of 2670–2610 Ma, 2400–2300 Ma, and 2200–2150 Ma (Nutman et al., 1994). The oldest ages may be related to a source similar to the Jequié rocks, whereas the 2.3/2.4 Ga zircons may be related to granitoid source rocks recognized in adjacent areas (Cordani et al., 1985). The youngest, most prominent age group is centered at 2170 Ma (Nutman et al., 1994) and constrains a maximum depositional age for the upper unit. This group of zircons may be related to sources such as the collisional granites of the Transamazonian belt that yield Rb/Sr ages and U–Pb zircon ages between 1950 and 2000 Ma. Such granitoid rocks exhibit initial $^{87}Sr/^{86}Sr$ ratios between 0.711–.760, negative $\varepsilon_{Nd(t)}$ values (-6.9 to -15.6), and Sm/Nd (T_{DM}) ages in the range 2.6–3.6 Ga, thus suggesting a crustal derivation (Sabaté et al., 1990; Santos-Pinto, 1996; Bastos Leal et al., 1998, 2000) (Table 1).

3. The UGB

The UGB crops out as a narrow, elongated unit in the Archaean gneissic-migmatitic rocks of the Gavião block. It is intruded by the Serra do Eixo alkaline granite (2495–2656 Ma) and the Umburanas granite (2049 ± 5 Ma; Santos-Pinto, 1996). The belt consists of mafic-ultramafic volcanics (komatiites, basalts), as well as intermediate volcanics associated with chemical and clastic sediments (Cunha and Fróes, 1994). The presence of mature, quartz-rich terrigenous and carbonate sediments in the UGB indicates that at least a part of it might represent platform sequences. The rocks were repeatedly deformed, and their metamorphic grade ranges from greenschist to amphibolite facies, thereby obscuring their primary geologic relations with the country rocks, other than the intrusive contacts of the younger granitoids. In addition to the metamorphic and tectonic imprint, hydrothermal activity has taken place, particularly in the case of the komatiites. As a result, their primary textures have been destroyed by hydratation, carbonation, and weathering, and primary minerals have been replaced by secondary serpentine, chlorite, and amphibole.

Following Cunha and Fróes (1994), the UGB can be divided into three units (Fig. 2), from bottom to top, as follows:

Lower unit composed of basal metakomatiites and tholeiitic metabasalts, intruded by basic-ultrabasic rocks and overlain by quartzites, metaconglomerates, and metacherts. The latter may occur as lenticular beds in the basal volcanics, with thicknesses from a few meters to hundreds of meters. At the top of the basal unit, calc-silicate rocks with subordinate beds of felsic to mafic metavolcanic rocks occur, intercalated with metalimestones and BIFs;

Intermediate unit composed of metadacites, metarhyolites, and meta-andesites, as well as minor mafic metavolcanic rocks, metatuffs, metalimestones, and BIFs. Metabasalts occur at the top of this unit. These rocks may exhibit tectonic or transitional contacts with the rock assemblage of the lower unit; and

Upper unit composed essentially of metacarbonates.

The polyphase tectonic and metamorphic history of the UGB and adjacent gneisses also includes two compressive

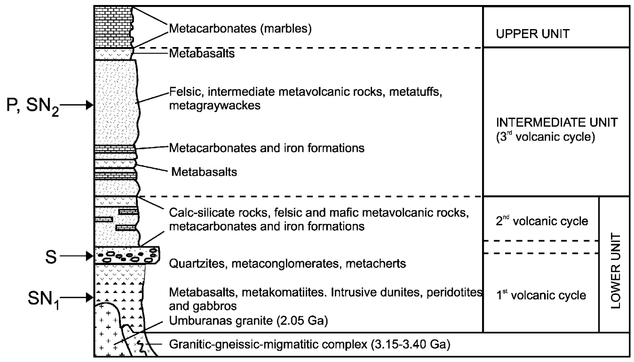

Fig. 2. Schematic stratigraphic column for the UGB (after Cunha and Fróes, 1994). Letters refer to approximate sample sites in this study: S = SHRIMP U–Pb zircon analysis (sample BRJC330); P = Pb/Pb zircon evaporation analysis (sample BRJC337); SN = Sm/Nd analysis (samples 711D, 702L, 707B and 479J [SN_1] and 337 and 357B [SN_2]). See Tables 2–4 for analytical details.

deformational events and three shear phases. These phases are associated with the development of NW-SE shear zones, semiparallel faults, mylonites, and regional tectonic fabric. Close to the shear zones, the country rocks show retrogression from amphibolite to greenschist facies, with associated hydrothermal alteration (Cunha and Fróes, 1994), whereas the intrusive plutons exhibit strong lineation and/or foliation in areas adjacent to the shear zones (Bastos Leal, 1998). Such tectonic and metamorphic episodes similarly affected the Espinhaço system and coeval metasedimentary assemblages that crop out in the northern and western parts of the region (Fig. 1B). They are therefore associated with Meso and Neoproterozoic overprinting episodes (Cordani et al., 1992; Cunha and Fróes, 1994; Bastos Leal et al., 1998).

4. Analytical methods and data assessment

Standard heavy liquid and isodynamic techniques were used to produce zircon concentrates, which were further handpicked under a binocular microscope to produce an assortment of grains. Dark and fractured crystals were selected for analysis. Assessment and choice of sites for the SHRIMP analyses were based on transmitted and reflected light microscopy (analyses were undertaken in the mid 1990s, just before CL imaging was a standard technique for SHRIMP analyses at the Australian National University [ANU]).

U–Th–Pb isotopic ratios and concentrations were determined using the SHRIMP-I instrument in Canberra at ANU and the standard zircon SL13 (572 Ma; $^{206}Pb/^{238}U = 0.0928$). Zircon analytical procedure and data assessment followed reports by Compston et al. (1984), Claoué-Long et al. (1995), Stern (1998), and Williams (1998). SHRIMP analyses are presented in Table 2, the second column of which contains a brief description of each grain and analytical site. Quoted errors on isotopic ratios take into account nonlinear fluctuations in ion count rates beyond that expected from counting statistics. For many of the $^{207}Pb/^{206}Pb$ measurements reported, this causes a doubling or more of the errors. For zircon populations that suffered ancient loss of radiogenic Pb, error amplification will slightly reduce the population's calculated weighted mean age but increase the size of the attached uncertainty. Errors based purely on counting statistics can give a false impression of precision and, hence, ease of resolution of geological events. In addition, Pb/U ratios have an extra error component (typically 1.5–2.5%) from the calibration of the measurements using the standard zircon SL13. The U decay constants and modern $^{235}U/^{238}U$ ratio are after Steiger and Jäger (1977).

Only 15 SHRIMP zircon analyses were undertaken; therefore, additional data are needed to provide a more robust picture of the provenance history of the quartzite

Table 2
SHRIMP U/Pb zircon analyses corrected using a 3100 Ma model Pb age (Cumming and Richards, 1975). Common ^{206}Pb% is the percentage of ^{206}Pb that is nonradiogenic according to ^{204}Pb correction method

Grain	Grain/type	U (ppm)	Th (ppm)	Th/U	^{206}Pb% common	^{206}Pb/^{238}Pb corrected	^{207}Pb/^{206}Pb corrected	Date ^{207}Pb/^{206}Pb corrected	% Disc
1	m,p,c,cl	141	96	0.68	0.08	0.657 ± 0.019	0.2622 ± 0.0015	3260 ± 9	0
2	l,p,c,yb	199	109	0.55	02	0.603 ± 0.014	0.2283 ± 0.0017	3040 ± 12	0
3	m,p,c,cl	407	476	1.17	0.03	0.590 ± 0.012	0.2551 ± 0.0012	3217 ± 7	−7
4	l,p,fr,c,yb	102	54	0.53	0.35	0.662 ± 0.037	0.2750 ± 0.0020	3335 ± 12	−2
5	m,p,fr,c,cl	391	160	0.41	0.05	0.610 ± 0.012	0.2537 ± 0.0008	3208 ± 5	4
6	m,p,c,yb	189	165	0.87	0.28	0.522 ± 0.016	0.2512 ± 0.0016	3192 ± 10	−15
7	l,p,fr,c,cl	171	97	0.57	0.11	0.613 ± 0.015	0.2434 ± 0.0019	3142 ± 13	−2
8	m,p,c,cl	102	68	0.67	0.24	0.641 ± 0.020	0.2611 ± 0.0035	3254 ± 21	−2
9	l,p,fr,c,yb	101	61	0.60	0.18	0.625 ± 0.016	0.2450 ± 0.0019	3153 ± 12	−1
10	m,p,c,yb	104	74	0.71	0.41	0.604 ± 0.024	0.2622 ± 0.0036	3260 ± 22	−7
11	l,fr,c,yb	154	37	0.24	0.25	0.597 ± 0.019	0.2527 ± 0.0033	3202 ± 21	−6
12	l,p,fr,c,yb	154	71	0.46	0.44	0.608 ± 0.018	0.2437 ± 0.0029	3144 ± 19	−3
13	m,p,c,cl/yb	96	62	0.64	1.21	0.663 ± 0.030	0.2528 ± 0.0068	3203 ± 43	2
14	m,p,t,cl	47	49	1.04	2.08	0.678 ± 0.033	0.2563 ± 0.0059	3224 ± 37	−4
15	m,p,t,cl	303	217	0.72	0.14	0.649 ± 0.020	0.2591 ± 0.0022	3241 ± 14	−1

Grain type: m = medium (100–250 μ); l = large (>250 μ); p = prismatic; fr = fragment; c = center; t = tip; cl = clear; yb = pale yellow/brown. Errors are stated at the two sigma level.

sample. However, most of the analyses yield close to concordant ages, as shown in Fig. 3 and the data table, and serve to identify the major detrital components in the sample (there is a 5% probability of missing an age component that forms 25% of the population; for example, see Fig. 3 of Nutman, 2001).

The ^{207}Pb/^{206}Pb zircon evaporation analyses were performed at the Isotope Geology Laboratory of the Federal University of Pará (UFPA), Brazil, using a VG 54E mass spectrometer. The ^{207}Pb/^{206}Pb ages were obtained on single crystals using a single Re filament. According to the procedure described by Gaudette et al. (1998), the ^{207}Pb/^{206}Pb ratio was plotted against the block number on a binary diagram (see Fig. 4). Thus, a representation of the emission from domains within the zircon grain is obtained, which shows changes with temperature (block #) until the Pb emission from the coherent domains is attained. Here the ^{207}Pb/^{206}Pb ratio, or the age calculated from it, will achieve a plateau because it will not change significantly. This plateau describes the average age of the single zircon grain.

A data treatment was created to eliminate from age calculation the blocks that yielded ^{204}Pb/^{206}Pb ratios >0.001 to avoid significant errors caused by inaccurate common lead correction, as well as those analyses that spread above the expected two standard deviations from the plateau average value. Moreover, the age determinations that contrast with the plateau average age were eliminated.

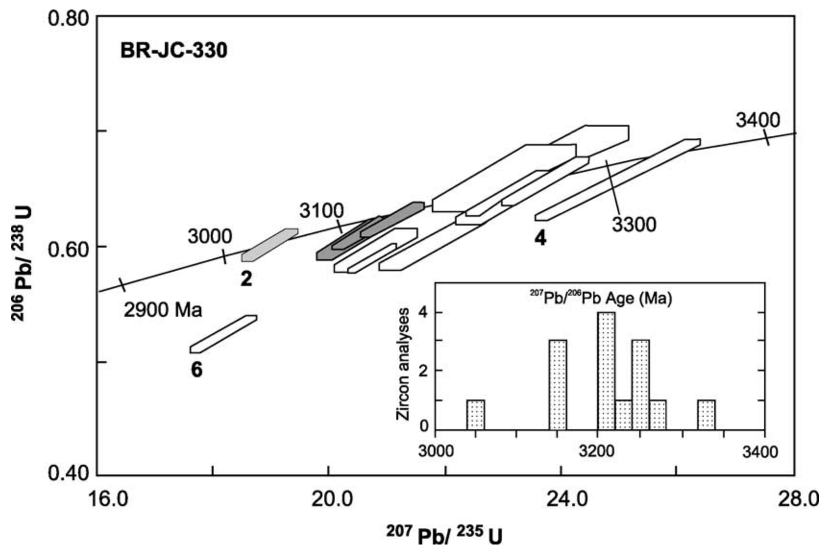

Fig. 3. Concordia diagram of detrital zircons from sample BR-JC-330. Inset shows ^{207}Pb/^{206}Pb age frequencies of the data set.

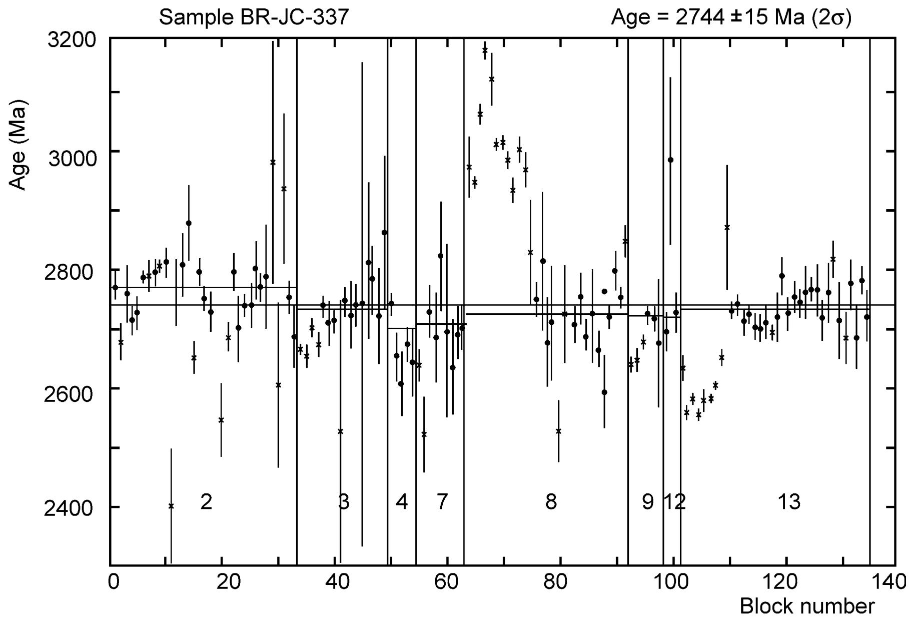

Fig. 4. Diagram of age versus number of blocks showing six $^{207}Pb/^{206}Pb$ ratios for zircons of the meta-andesite BR-JC-337. "x" = neglected blocks; the zircon grain number is indicated. Age errors are given at 95% confidence level.

The calculated age for one zircon grain is the weighted mean and standard error of the accepted (data) blocks. Isotope ratio uncertainties and age errors are listed at the two sigma level (see Table 3), and the decay constants are after Steiger and Jäger (1977).

Sm–Nd whole-rock analyses (Table 4) were carried out at the Geochronology Research Center of São Paulo University (CPGeo-USP), Brazil, using the two-column technique (Sato et al., 1995). Ion exchange resin was used for primary separation of the rare earth elements (REE), followed by a second HDEHP-coated teflon powder column for separation of Sm and Nd. The isotope ratios were measured on a VG-354 multicollector mass spectrometer, and the quoted errors are given at the two sigma level. During the period of analyses, the measured $^{143}Nd/^{144}Nd$ ratio obtained for the La Jolla standard was 0.511875 ± 0.000046 (2σ), and the laboratory blanks for the chemical procedure yielded maximum values of 0.4 ng for Nd and 0.7 ng for Sm. The calculations were performed according to the constants proposed by Michard et al. (1985), and Sm/Nd model ages were calculated using the depleted mantle model of DePaolo (1981).

5. Results and discussion

5.1. SHRIMP U–Pb zircon analyses

Fifteen zircons from conglomeratic quartzite BR-JC-330 (UGB basal unit) were analyzed. The crystals are essentially of two types: generally small (100–250 μm long), clear (or more rarely, pale yellow) prismatic grains with euhedral pyramidal terminations and larger, generally pale yellow/-brown grains of prismatic habit. Six of the latter type occur as fragments. Optical microscopy could not detect any internal structure (overgrowths + cores), and both types have an indistinguishable range of U and Th/U (Table 2). Despite the small number of SHRIMP analyses undertaken, it is possible to estimate the ages of the source rocks because

Table 3
Pb–Pb zircon evaporation data of meta-andesite BR-JC-337 from the intermediate unit of the UGB

Sample/# of zircons	# Of ratios	$^{204}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	Age (Ma)
BR-JC-337/2	132	0.000637 ± 0.000038	0.193629 ± 0.001618	2775 ± 14
BR-JC-337/3	66	0.000260 ± 0.000081	0.189385 ± 0.002411	2738 ± 21
BR-JC337/4	30	0.000070 ± 0.000037	0.185448 ± 0.005214	2705 ± 46
BR-JC-337/7	42	0.000345 ± 0.000174	0.186080 ± 0.004865	2709 ± 43
BR-JC-337/8	84	0.000500 ± 0.000074	0.189516 ± 0.003432	2741 ± 30
BR-JC-337/9	18	0.000229 ± 0.000049	0.188018 ± 0.002877	2725 ± 25
BR-JC-337/12	18	0.000262 ± 0.000144	0.187499 ± 0.007187	2723 ± 68
BR-JC-337/13	144	0.000199 ± 0.000033	0.188971 ± 0.001454	2735 ± 13

Age is given at the two sigma level.

Table 4
Sm/Nd whole-rock analytical data for various metavolcanic rocks from the UGB

UGB	Rock	Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$f_{Sm/Nd}$	T_{DM} (Ga)	$\varepsilon_{Nd\ (t=2.75\ Ga)}$	$\varepsilon_{Nd(o)}$
Lower unit	Metakomatiite	BR-JC-711D	0.207 ± 0.001	0.764 ± 0.002	0.1638 ± 0.0002	0.512604 ± 0.000290	−0.17	–	+1.9	−0.7
	Metakomatiite	BR-JC-702L	0.931 ± 0.001	3.359 ± 0.001	0.1676 ± 0.0001	0.512486 ± 0.000050	−0.15	–	+7.2	−3.0
	Metakomatiite	BR-JC-707B	0.353 ± 0.001	1.097 ± 0.001	0.1946 ± 0.0004	0.512875 ± 0.000230	−0.01	–	+5.4	+4.6
	Metabasalt	BR-JC-479J	2.932 ± 0.001	11.889 ± 0.004	0.1481 ± 0.0001	0.511754 ± 0.000026	−0.24	–	−0.6	−17.2
Intermediate unit	Meta-andesite	BR-JC-337A	27.309 ± 0.010	147.117 ± 0.222	0.1122 ± 0.0002	0.511198 ± 0.000020	−0.43	2.80	+1.5	−28.1
	Meta-andesite	BR-357B	23.043 ± 0.007	99.742 ± 0.141	0.1397 ± 0.0002	0.511403 ± 0.000021	−0.29	3.46	−4.1	−24.1

they yielded close to concordant ages (Fig. 3). The only exception was grain 6, which is not considered further here.

The clear prismatic grains (first type) with euhedral pyramidal terminations yield $^{207}Pb/^{206}Pb$ dates of 3260–3200 Ma, regardless of whether the center or edges of the grains are analyzed. Therefore, these grains form a distinct population, probably affected by some ancient variable amounts of radiogenic Pb loss. Assuming this model, rejection of the grains with the youngest ages (until an MSWD of ~1.0 is achieved) yields a weighted mean $^{207}Pb/^{206}Pb$ date of 3252 ± 12 Ma (2σ, $n = 6$).

The less euhedral, fragmented, larger, pale yellow/brown grains (second type) yield younger dates, except for the center of grain 4, with a $^{207}Pb/^{206}Pb$ age of 3335 ± 24 Ma (2σ). Analysis of grain 2 yields a $^{207}Pb/^{206}Pb$ date of 3040 ± 24 Ma (2σ), as the remaining three analyses of this grain type yield a weighted mean $^{207}Pb/^{206}Pb$ date of 3147 ± 16 Ma (2σ, $n = 3$).

Thus, despite the limited number of analyses undertaken, four ages of zircon are observed: rare ≥3300 Ma, ca. 3250 Ma, ca. 3150 Ma, and 3040 Ma (Fig. 3). It is uncertain, on the basis of the small number of analyses undertaken, whether grain 2, which yields the youngest $^{207}Pb/^{206}Pb$ age (3040 Ma), is a site in an older zircon that underwent ancient loss of radiogenic Pb or represents the presence of a yet younger generation of zircon.

5.2. $^{207}Pb/^{206}Pb$ zircon evaporation analyses

Eighteen zircon grains from meta-andesite BR-JC-337 (UGB intermediate unit) were chosen for analysis. They are prismatic, brown, semitransparent, euhedral crystals, very distinct in type from the zircon crystals of the underlying quartzite, and dated by SHRIMP. After data assessment and elimination of the measurements with high common lead content, the analytical data of eight crystals (Table 3) were used for the age calculation. The mean $^{207}Pb/^{206}Pb$ age was 2744 ± 15 Ma (2σ), interpreted as the time of extrusion of the UGB meta-andesites (Fig. 4). Rb/Sr whole-rock analyses yield an age of ca. 2.2 Ga with a large error, which suggests a metamorphic overprint due to the Transamazonian event, as already discussed (Cordani et al., 1985; Bastos Leal et al., 1998).

The zircon evaporation date constrains a maximum age limit for the Serra do Eixo intrusive granite, for which $^{207}Pb/^{206}Pb$ zircon evaporation determinations between 2495 and 2656 Ma are available (Santos-Pinto, 1996).

5.3. Sm/Nd whole-rock analyses

Three metakomatiites and one metabasalt belonging to the first volcanic cycle of the UGB lower unit, which stratigraphically underlies the metaconglomerates dated by SHRIMP, were selected for Sm/Nd study. They yield high $^{147}Sm/^{144}Nd$ ratios (0.15–0.20) and $f_{Sm/Nd}$ ranging from −0.12 to −0.24 (Table 4). In the particular case of the metakomatiites, a significant variation of the $f_{Sm/Nd}$ values (−0.16 to −0.12) was observed, probably resulting from late disturbance of the Sm/Nd systematics, as is supported by the presence of post-crystallization features. Therefore, the metabasalt sample is considered as a better representative of the primary isotopic signature of the UGB lower volcanic unit.

Two meta-andesites (BR-JC-337 A and BR-JC-357B) from the UGB intermediate unit have $f_{Sm/Nd}$ values of ca. −0.43 and −0.29 and T_{DM} model ages of 2.82 and 3.51 Ga, respectively (see Table 4). The disparity in the model ages reinforces the idea that the Sm/Nd whole-rock systematics from the UGB rocks have been disturbed in some way, as might be expected considering the polyphase geologic framework of the Gavião block.

Fig. 5 shows the $\varepsilon_{Nd(2.75\ Ga)}$ versus $^{147}Sm/^{144}Nd$ ratios for the measured UGB samples. In the same figure, the fields of the Gavião block TTG rocks and the mafic–ultramafic rocks from the basal sequence of the Contendas–Mirante belt are also plotted. The TTG samples exhibit negative $\varepsilon_{Nd(2.75\ Ga)}$ values and a $^{147}Sm/^{144}Nd$ mean ratio of ca. 0.09, extrapolated to be the typical Nd isotopic signature of the Archean continental crust in the region. The Contendas-Mirante samples exhibit a significantly higher $^{147}Sm/^{144}Nd$ mean ratio of ca. 0.14, with $\varepsilon_{Nd(2.75\ Ga)}$ values between +4 and −2. This signature suggests an interaction with the early crust, in accordance with the whole-rock geochemistry

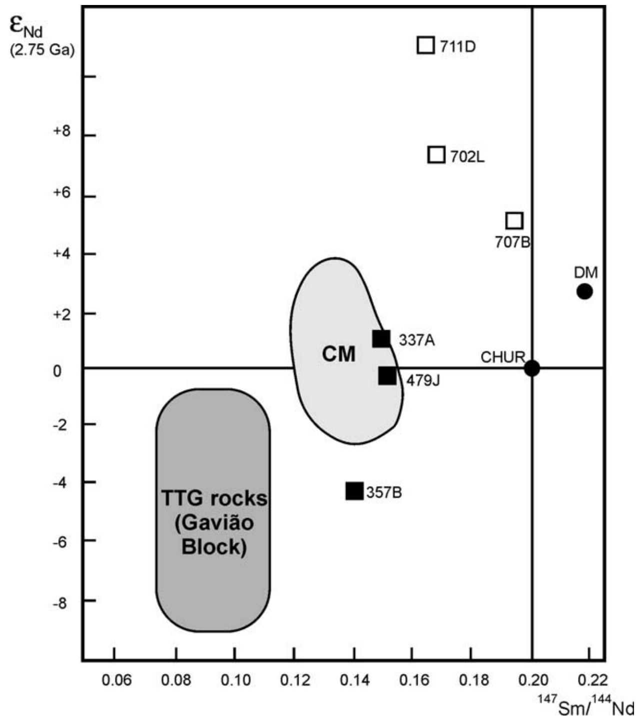

Fig. 5. $^{147}Sm/^{144}Nd$ ratios versus $\varepsilon_{Nd(t=2.75\ Ga)}$ values for mafic-ultramafic and intermediate volcanic rocks of the UGB (full squares). Open squares are samples with isotopic disturbance. The isotopic signatures of the mafic-ultramafic basal sequence of the Contendas–Mirante (CM) greenstone belt and the Gavião block TTG rocks (shaded fields) are also plotted. DM = depleted mantle, CHUR = chrondritic uniform reservoir.

of the metamafics, as indicated by the large variation in their Zr/Y, Rb/K, and Zr/Nb ratios (Marinho, 1991).

Taking into account a minimum age of ca. 2.75 Ga for the metakomatiitic samples, they exhibit extreme positive $\varepsilon_{Nd(2.75\ Ga)}$ values (from +5.4 to +10.9; Table 4, Fig. 5), which are anomalous when compared with the Archean depleted mantle. The remaining three UGB samples (metabasalt 479J, meta-andesites 337A and 357B) exhibit $\varepsilon_{Nd(t=2.75)}$ values of −0.6, +1.5, and −4.1, respectively (Table 4). In our interpretation, the distribution of these data in Fig. 5 demonstrates magma interaction of these rocks with Archaean continental material—a mechanism similarly reported for the Archaean components of the Contendas–Mirante greenstone belt (Marinho, 1991).

Crustal contamination (or fractionation between Sm and Nd) also is supported by the geochemistry of the UGB samples, such as the chaotic REE patterns and strong Nd depletion of metakomatiites 711D and 702L, as well as by the anomalous variations of Al_2O_3/TiO_2 (4.2–37.0) and Zr/Nb (7.4–42.0) and the low values of the Nb/Th ratios (<4.0), Ni (13–42 ppm), and Cr (27–120 ppm), as reported by Cunha and Fróes (1994). Moreover, the mafic-ultramafic rocks of the lower unit of the UGB are interlayed with chemical and clastic sediments, and the meta-andesites of the intermediate unit show contrasting $\varepsilon_{Nd(t=2.75\ Ga)}$ values of +1.3 and −4.4. These details support the idea of crustal interaction of the magmatic precursors. The isotopic evidence suggests that the studied parts of the UGB were formed over sialic crust, interpreted to be composed of Archean materials comparable to those exposed in the Gavião block.

6. Concluding remarks

Zircons from a conglomeratic quartzite from the lower unit of the UGB are rounded to euhedral and yield SHRIMP U–Pb ages of 3335–3040 Ma, which indicates derivation from a continental source region that contains rocks of different ages. The available data constrain the maximum time of deposition for the UGB to as young as 3040 ± 24 Ma (single zircon analysis) and certainly after 3147 ± 16 Ma (three analyses).

The older group of zircons indicates the proximity and perhaps involvement of Mesoarchaean crust when the lower sequences of the UGB were formed (Table 1, Fig. 6). The range of ages for the older detrital zircon population agrees with U–Pb ages reported for the adjoining Aracatu (3240 ± 9 Ma) and Mariana (3259 ± 5 Ma) granitoids, whereas the 3335 ± 24 Ma grain could have been derived from a source such as the Bernarda tonalite (3330 ± 7 Ma) (Santos-Pinto, 1996). The three zircon grains of the 3147 ± 16 Ma population in the UGB could have been derived from a source like the Lagoa da Macambira granitoid, which was formed at 3146 ± 12 Ma (Santos--Pinto, 1996; Bastos Leal et al., 1998).

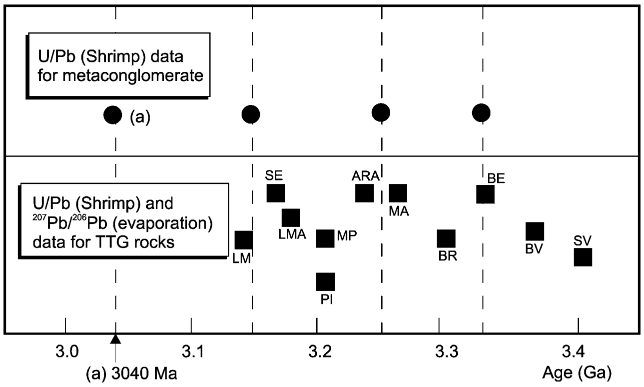

Fig. 6. Comparative diagram of the zircon ages from the orthoconglomeratic quartzite of the UGB (circles) and the TTG terrain and mantled gneissic domes of the Gavião block (squares). TTG data were compiled from Nutman and Cordani (1993), Martin et al. (1997), Santos-Pinto (1996), Cordani et al. (1997), and Bastos Leal et al. (1998). (a) maximum age for the UGB. Key: LM = Lagoa da Macambira; SE = Serra do Eixo; ARA = Aracatu; MA = Mariana; BE = Bernarda; BV = Boa Vista; SV = Sete Voltas; PI = Piripá; MP = Malhada de Pedras; BR = Brumado; and LMA = Lagoa do Morro. See Fig. 1B for geographic distribution of the radiometric ages.

In summary, the range of the U–Pb single zircon ages is compatible with successive magmatic events as revealed in the crustal evolution of the Gavião block, thereby implying that the unit was the source of detritus for the UGB rocks. This supports the existence of a continental basement for the studied parts of the UGB and, by analogy, for similar greenstone belts in the Gavião block. However, geologic evidence for an unconformity at the base of the UGB is still lacking because of the overprinting deformation and metamorphism of the volcanosedimentary package.

The UGB intermediate unit felsic volcanics were formed 2744 ± 15 Ma ago, and some might be genetically related to contemporary Neoarchaean granitoids intrusive in the Gavião block, such as the Lagoa do Morro pluton (Mascarenhas and Garcia, 1986).

The isotopic and chemical evidence indicates that crustal contamination, combined with juvenile accretion processes, has played an important role in the magmatic evolution of the UGB. The broad picture is consistent with either an intraplate or proximal continental setting for the basin. Finally, considering the existence in the northern SFC of different greenstone belts (e.g. Contendas–Mirante) and continental fragments (e.g. Jequié block), which were juxtaposed during a Paleoproterozoic collision (e.g. Barbosa and Sabaté, 2002), a more complete interpretation of the nature of the tectonic framework is dependent on detailed radiometric and isotopic studies.

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