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Final stages of the Brasiliano Orogenesis in SE Brazil: U-Pb and $^{40}Ar/^{39}Ar$ evidence for overprinting of the Brasília Belt by the Ribeira Belt Tectonics

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Abstract: Around the southern margins of the São Francisco Craton, there is a zone of tectonic interference between the Brasília belt to the west and the younger Ribeira belt to the east. U-Pb monazite and $^{40}Ar/^{39}Ar$ cooling age determinations carried out in the area reveal the cooling histories of these belts and the timing of tectonic overprint, unraveling the final stages of Brasiliano Orogeny in SE Brazil. The U-Pb monazite data from migmatized paragneisses and late-stage pegmatites in the Socorro-Guaxupé Nappe System of the southern Brasília belt show that migmatization peaked between ca. 613 ±1 and 607±3 Ma. $^{40}Ar/^{39}Ar$ biotite and muscovite ages of paragneisses and schists in this area indicate that the northern high-grade core of the Nappe System (Guaxupé Domain) was uplifted and cooled through the 350°C isotherm between 599±1 and 587±1 Ma. In contrast, samples from the southern high-grade core of the Nappe System, the Socorro Domain, south of the Jacutinga shear zone, yields a broader and younger spectrum of $^{40}Ar/^{39}Ar$ biotite ages between 571±1 and 562±1 Ma, attributed to a later uplift and cooling of the crust. The cooling ages can be assigned to local resetting of the $^{40}Ar/^{39}Ar$ system during transpressive tectonic overprint due to reactivation as a result of collision of the Ribeira belt. A younger group of $^{40}Ar/^{39}Ar$ mica ages (537±1 to 521 ±1Ma) in schists of the Socorro Domain, are associated with transpressional structures of the Ribeira belt. Rock samples from the Jacutinga and Três Corações shear zones, yield $^{40}Ar/^{39}Ar$ biotite-muscovite ages around 520 Ma. These are typical cooling ages of the Ribeira belt, and are interpreted to mark the western limit of the Ribeira belt transpressional regime within the Brasília belt. The youngest biotite-muscovite cooling ages in schists of the Socorro Domain, between 510±2 and 491±1 Ma, mark the final cooling and exhumation of that part of the Brasília belt.

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Introduction

The Pan-African/Brasiliano Orogeny in South America comprises a series of late Neoproterozoic to Cambrian mobile belts that formed during the assembly of West Gondwana (e.g., Trompette, 1994). The belts are broadly coeval in their development, and tectonic aspects. Nevertheless, they are not completely simultaneous; hence structural and tectonic interferences related to either thrusting or transpression exist where they intersect each other. One well-exposed case of tectonic interaction is in southeastern Brazil where the Ribeira belt transects the Brasília belt, in the southern margin of the São Francisco Craton. The interaction between these two mobile belts during the Brasiliano Orogeny generated a complex array of structures (e.g., Ribeiro et al., 1995; Ebert and Hasui, 1998; Hackspacher and Godoy, 1999; Campos Neto and Caby, 1999; Heilbron and Machado, 2003; Valeriano et al., 2004). It is generally accepted that the final collision of the Ribeira belt was later than that of the southern Brasília belt (Hasui et al., 1990; Trouw et al., 2000; Campos Neto and Figueiredo, 1995). However, to what degree the transpressional regime of the Ribeira belt overprinted the Brasília belt rocks remains weakly constrained.

Accurate and precise radiometric ages are necessary to reconstruct the Brasiliano Orogeny and to better understand the regional geologic framework and major structural features of each belt. In order to correlate geologic, structural and geochronologic features of the interference zone, we present new U-Pb monazite and $^{40}Ar/^{39}Ar$ mica data from selected granitoids, pegmatites, paragneisses and schists that crop out in the intersection between the Brasília belt and central part of the Ribeira belt. These data provide the first detailed age constraints on the late stage of metamorphism, uplift and cooling of the southern Brasília belt, and reveal the thermal and structural overprint of the Ribeira belt collision that led to assembly of West Gondwana.

Geologic Framework

The Neoproterozoic framework of the eastern part of the South American Platform comprises mostly older cratons surrounded by Brasiliano-Pan-African mobile belts (Fig. 1). Convergence between the São Francisco – Congo, Amazonian and Rio de La Plata Cratons during the assembly of West Gondwana generated two major Neoproterozoic belts: the Brasília and Ribeira belts (see Cordani et al., 2000; and Heilbron et al., this volume, for a full description of the geology of the belts). The Brasília belt resulted from the closure of the Goianides Ocean (e.g., Pimentel et al., 2000) along the western-southwestern margin of the São Francisco Craton, and merges with the Borborema Province to the north (Fonseca et al., this volume), whereas the Ribeira belt is associated with the closure of the Adamastor Ocean to the east-southeast of the craton (e.g., Campos Neto, 2000). During oceanic closure, subduction gave rise to magmatic arc suites that preceded arc-continent and continent-continent collisions. A sequence of rocks were involved in the amalgamation of West Gondwana including: Paleo- and Mesoproterozoic basement rocks and intracratonic successions; Neoproterozoic passive margin successions; magmatic arcs of intraoceanic and active continental margin settings with pre- and syn-collisional granitoids; late-orogenic sedimentary succession and post tectonic granites and pegmatites (e.g., Heilbron et al., 2004).

The Brasília belt in the region is mainly comprised of a Neoproterozoic passive margin metasedimentary succession (Araxá and Andrelândia Groups), (Table 1). The Araxá Group comprises quartzite, schist and mafic rocks (Valeriano et al., 2004), whereas the Andrelândia Group contains paragneiss with amphibolite, quartzite, schist, gondite and calc-silicate rocks (Ribeiro et al., 1995; Paciullo et al., 2000). Pimentel et al. (2004a, b) summarized the evolution of the Brasília belt and its relation to the Goiás Magmatic Arc (Table 1), as follows: a) formation of intraoceanic island arcs, Goiás Magmatic Arc, characterized by calc-alkaline volcanic rocks and tonalitic to dioritic plutons, between 890-800 Ma; b) intrusion of mafic- ultramafic complexes in high metamorphism grade, probably linked to a continental rift environment at ca. 800 Ma; c) high-grade metamorphism related to collision between the northern Goiás Magmatic Arc and the western border of the São Francisco proto-craton, between 770-760 Ma (Ferreira Filho et al., 1994); d) period of igneous quiescence between 760-680 Ma; e) intrusion of tonalitic, granodioritic, granitic and mafic-ultramafic bodies between 670 and 600 Ma, considered by Junges et al. (2002) as the second period of generation of tonalites and crustal accretion of the arc; f) peak of metamorphism in the Goías Magmatic Arc associated with the final closure of the Goianides Ocean between ca. 630 and 600 Ma (Fischel et al., 1998; Pimentel et al., 2000; Piuzana et al., 2002); and g) cooling and regional uplift between 580-560 Ma (K-Ar, Pimentel et al., 2004b).

In the southern Brasília belt, closer to the Ribeira belt, the final oceanic closure (point f above) was associated with the development of significant eastward thrust of nappes, towards the São Francisco Craton or tangential to it (Fig. 1, Table 1; Valeriano et. al, 2004). This Nappe System (subdivided into the Guaxupé and Socorro Domains) represents a thick Neoproterozoic sheet composed of a pile of high grade metamorphic crustal rocks (Campos Neto and Caby, 1999; Campos Neto, 2000). Ages between 611 to 604 Ma in the Socorro and Guaxupé Domains were interpreted by Trouw and Pankhurst (1993) as a thermal peak associated with the earlier thrusting and stacking of the Nappe System. The Socorro-Guaxupé Domains were affected by a late- to post-orogenic magmatism between 630 – 620 Ma (Töpfner, 1996) and 610 – 590 Ma (Janasi et al., 1993; Ebert et al., 1996; Töpfner, 1996; Wernick, 1998), respectively Numerous NE-trending, dextral, transcurrent-transpressive shear zones of the Ribeira belt (Ebert and Hasui, 1998) overprint the Brasília belt thrust sheets, particularly in the southern reworked margin of the São Francisco Craton (Fig. 2, Table 1). This has also led to relative vertical displacement of the main Precambrian units of the Ribeira along the Atlantic coast (Hackspacher and Godoy, 1999; Heilbron et al., 2004).

Figure 2 and Table 1 show the studied area, with division of the regional geology into tectonic units: a) the São Francisco Craton, composed of Archean to Paleoproterozoic orthogneisses and migmatitic complexes; b) the Reworked Cratonic Border, composed mainly of Archean to Paleoproterozoic tonalitic and granodioritic orthogneisses, strongly reworked during the Neoproterozoic; c) the Brasília belt and associated Metasedimentary Succession Domain (Araxá and Andrelândia Groups), the Guaxupé and the Socorro Domains; and d) the Central Ribeira belt (Heilbron et al., 2004).

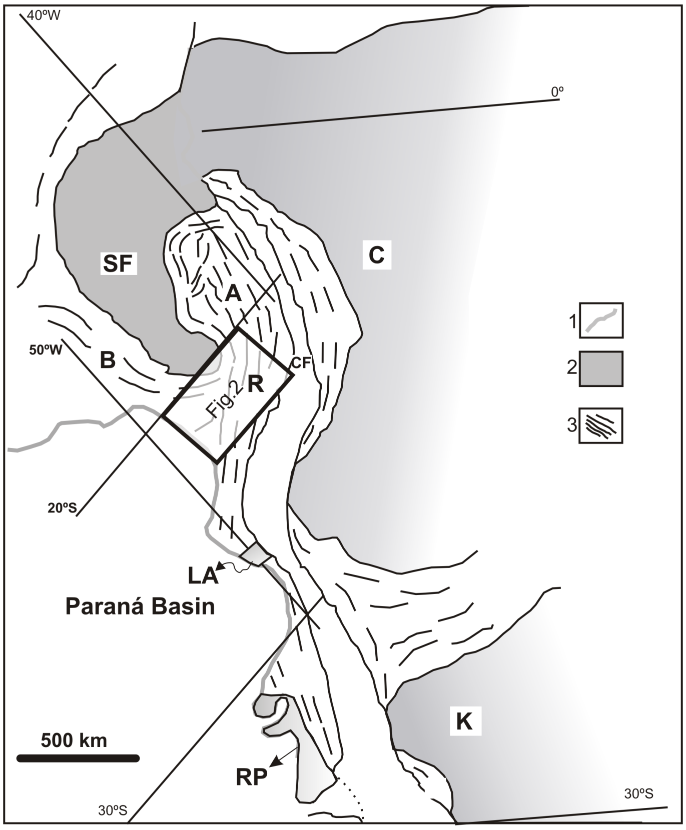
Like the Brasília belt, the Central Ribeira belt (Figure 1), across the states of Rio de Janeiro and São Paulo, is a result of convergence between the São Francisco Craton and some Neoproterozoic fragments, and the Congo Craton. Collision processes resulted in the docking of distinct tectonostratigraphic terranes, such as (see Heilbron et al., this volume):

a. the Occidental terrane comprised of Paleoproterozoic basement rocks;
b. Mesoproterozoic volcano-sedimentary successions;
c. Neoproterozoic units associated to: intra-oceanic arcs (Adamastor Ocean) and active continental margin settings (790 Ma to 585 Ma), as the Paraíba do Sul, Embu, Costeiro and the Oriental Terrane (Rio Negro Magmatic Arc), passive margin and back-arc lithological successions and syn-collisional granitoids related to different collisional episodes; and
d. post-orogenic sedimentary successions and related bimodal magmatism of the Cabo Frio Allocthonous Terrane (520 Ma; Tupinambá et al., 2000, Heilbron et al., 2004, and this volume).

Geochronological studies in the Central Ribeira belt have shown that the closure of the Adamastor Ocean was a protracted process. The evolution of the Rio Negro Magmatic Arc started as early as 790 Ma ago (Heilbron and Machado, 2003). The earliest collisional stages followed, between 640 to 620 Ma, with west-verging thrusting towards the São Francisco Craton. Sediments of the São Roque Group were deposited 610 Ma in a back-arc basin (Hackspacher et al., 2000). Major collision of the Ribeira belt with the Sao Francisco Craton was accompanied by an important tectono-thermal event dated between 590 and 565 Ma (Machado et al., 1996), interpreted to be associated with thrusting and development of dextral shear zones. In addition, the tectonic history of the Ribeira belt includes an important escape tectonic event, with transpressional character, juxtaposing different crustal levels (amphibolite and greenschist facies), along NE-trending shear zones. This event took place between 600 and 580 Ma ago, as constrained by U-Pb age of post-kinematic syenitic rocks (Töpfner, 1996; Hackspacher and Godoy, 1999). Vertical movement during this event led to the exhumation of the Brasília and Ribeira belt rocks, with erosion and continental sedimentation in small NE-trending basins developed between 570-540 Ma (Teixeira et al., 1999; Zanardo and Oliveira, 1990).

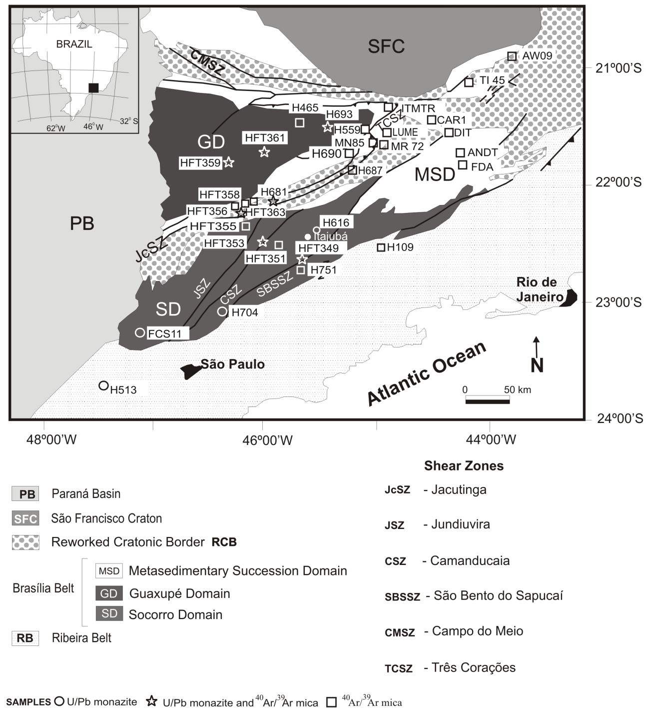
Subsequent thrusting and development of shear zones occurred in the Central Ribeira belt between 535 and 520 Ma, during the postulated docking of the Cabo Frio terrane (Schmitt et al., 1999) to the Oriental terrane in the eastern part of the belt. The late-stage magmatism related to this docking took place between 503 and 492 Ma (Wiedemann 1993, Machado et al., 1996, Schmitt et al., 1999).

Figure 1. Precambrian framework of Western Gondwana



Precambrian framework of Western Gondwana with the location of the studied area; the southern Brasília belt. (modified from Trompette, 1994): 1- Phanerozoic basins; 2- Neoproterozoic Cratons: SF- São Francisco, LA- Luis Alves, RP- Rio de La Plata, C- Congo, K- Kalahari; 3- Neoproterozoic mobile belts: B- Brasília, A- Araçuaí, R- Ribeira. Locality: CF: Cabo Frio.

Figure 2. Geologic map of SE Brazil



Geologic map of SE Brazil (modified after CPRM, 2002) with U-Pb and ^{40}Ar/^{39}Ar sample locations and numbers.

Table 1. Tectonic units of the southern Brasília belt (Valeriano et al., 2004) and Ribeira belt, as well as the regional shear zones.

Geologic Period	Brasília Belt	Re-worked Craton Border	Central Ribeira Belt	Tectonic Process
Neoproterozoic		Jacutinga / Ouro Fino / Três Corações shear zones		Transpression 520 Ma
			Cabo Frio Terrane	Collision 520 Ma
		Jacutinga / Ouro Fino / Três Corações shear zones		Transpression 580-520 Ma
			Costeiro Terrane	Collision ca. 580 Ma
	Passive Margin Sedimentation: Araxa and Andrelania Groups Granulitic nappes: Guaxupe and Socorro domains		São Rogue Group Embu Terrane Occidental Terrane Oriental Terrane (Rio Negro Arc) Paraiba do Sul	Collision ca. 620 Ma
	Goiás Magmatic Arc			770 Ma
Meso/Paleoproterozoic		Meso/Paleoproterozoic	Meso/Paleoproterozoic	
Paleoproterozoic/ Archean		Paleoproterozoic/ Archean	Paleoproterozoic/ Archean	

Geochronology

U-Pb analyses

Initial preparation of monazite crystals for isotopic analysis was done at Department of Petrology and Metallogeny State University of São Paulo (UNESP), Brazil. Single monazite crystals, spiked with a ^{205}Pb-^{235}U tracer solution, were dissolved in 7 ml Teflon Savillex beakers using a solution of concentrated ultra pure H2SO4 (5 uL), 6M HCl (40 uL) and 7M HNO3 (40 uL). Dissolution of the monazite was achieved by placing the beakers on a conventional hot plate (at 125-140oC) for 24 hours to ensure complete dissolution. Samples were then partially dried, as the H2SO4 is difficult to evaporate, and conditioned with 3.1M HCl prior to microcolumn chromatography, adapted from Krogh (1973). Isotopic ratios were measured at Geoscience Institute, National University of Brasília (UnB), Brazil, using a Finnigan MAT multi-collector mass spectrometer equipped with an ion counting system.

Eleven samples of prismatic monazite were analyzed for both Pb and U isotopic compositions on single Re filaments using silica gel and phosphoric acid. The analyses were corrected for average mass discrimination of 0.12 ± 0.05% per mass unit for multi-collector analyses (based on replicate analyses of common Pb standard SRM 981). Uranium fractionation was monitored by replicate analyses of SRM U-500. Uncertainties in U-Pb ratios due to uncertainties in fractionation and mass spectrometry were around ± 0.5%, as all signals measured were relatively strong. Radiogenic Pb isotopes were calculated by correcting for modern blank Pb and for original no radiogenic original Pb corresponding to Stacey and Kramers (1975) model Pb for the approximate age of the sample. Uncertainties in radiogenic Pb ratios in the studied samples are typically ± 0.1%. Decay constants and isotopic ratios used in the age calculations are those listed by Steiger and Jäger (1977). Total procedure blanks over the course of analyses ranged from 10 to 46 pg for lead and 0.5 to 2 pg for uranium. The U-Pb monazite data (see Table 3) were regressed using the ISOPLOT/EX program of Ludwig (1999). For both samples, forced Model 1 regressions were performed as the analytical points were either concordant or nearly concordant with little spread in the data. Uncertainties in concordia intercept ages are given at the 2s level (Fig. 5).

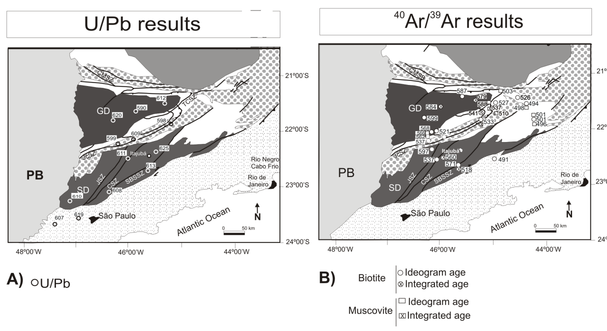
$^{40}Ar/^{39}Ar$ analyses

Transmitted- and reflected-light microscopy of polished thin sections were used to determine the mineralogy and textures of datable samples. Samples were then crushed and suitable minerals (well-formed biotite and muscovite grains) were concentrated and hand-picked under a binocular microscope. The mineralogical study was conducted at the Geochronology Laboratory of the State University of São Paulo (USP) and at the Department of Geology of the Federal University of Rio de Janeiro (UFRJ), Brazil. The $^{40}Ar/^{39}Ar$ geochronology (see Vasconcelos et al., 2002) was carried out at the Geochronological Research Center (CPGeo) at the University of São Paulo, Brazil. The laboratory facility comprises two major units: a home built fully automated noble gas stainless steel ultra-high vacuum gas extraction and purification system, coupled with a continuous laser, and the MAP-215-50 mass spectrometer. The argon routine is limited to grains smaller than 2.1 mm, since this is the maximum diameter of the wells in the sample aluminum disks used for irradiation. Five to ten grains from each sample were loaded into these disks along with Fish Canyon sanidine standards (28.02 ± 0.28 Ma; Renne et al., 1998). The disks were wrapped in aluminium-foil, sealed in silica glass tubes and irradiated for 30 hours at the IPEN/CNEN IEA-R1 nuclear reactor, São Paulo, Brazil.

The samples were analyzed after cooling by the laser incremental heating, following procedures detailed by Vasconcelos et al. (2002). Argon isotope ratios ($^{40}Ar/^{39}Ar$, $^{38}Ar/^{39}Ar$, $^{37}Ar/^{39}Ar$, $^{36}Ar/^{39}Ar$, $^{40}Ar^*/^{39}Ar$), the percentage of radiogenic argon ($^{40}Ar^*$), the age obtained for each incremental heating step (identified with a letter after the grain number), J factors, laser beam intensity, $^{40}Ar/^{36}Ar$ discrimination, correction factors, and full system blanks are shown in the Appendix 1. The calculation of $^{40}Ar/^{36}Ar$ discrimination (McDougall and Harrison, 1999), was obtained by the measurement of the ^{40}Ar and ^{36}Ar isotopes from the air pipette of the extraction line, in order to account correcting factors for the production of interfering isotopes (^{36}Ar, ^{37}Ar, ^{38}Ar, ^{39}Ar, and ^{40}Ar) from Ca and K salts and glasses during sample irradiation. Full system blanks correspond to the masses of ^{40}Ar, ^{39}Ar, ^{38}Ar, ^{37}Ar, and ^{36}Ar present in the extraction line and mass spectrometer. The $^{40}Ar/^{39}Ar$ incremental heating analyses on three single grains from each sample (triplicate analysis) have provided plateau, ideogram and integrated ages (see Table 4). The plateau ages represent continuous steps (more than 50%) of the total ^{39}Ar released from a sample and for which no difference in age can be detected between any two fractions at the 95% confidence level (Fleck et al., 1977). All uncertainties in plateau, integrated, and weighted mean ages are given at 2s level. When the plateau ages showed comparable individual results within error, the resulting age-probability ideogram is taken as a robust estimate of the samples' age (weighted mean age). Figure 3B contains some examples of weighted mean age corresponding to ideograms. Contrastingly, when the plateau ages are significantly different they indicate a complex thermal history of the sample. In these cases the range between the single grain ages has been considered realistic (Table 4 ; H693C and HFT361), as additionally supported by the new U-Pb monazite ages and the regional geochronologic background.

The $^{40}Ar/^{39}Ar$ ages (Ideogram/Integrated) are plotted in Fig. 3B which presents the different domains of the Brasília and Ribeira belts, north and south of the Jacutinga shear zone. Figure 6 shows four selected $^{40}Ar/^{39}Ar$ analyses for each domain distinguished in the area, whereas Table 4 presents the age variation of the ideograms for the selected group of samples. These ideograms display the thermal history against time within the selected domains.

Figure 3. Geologic map of SE Brazil



Geologic map of SE Brazil (modified after CPRM, 2002) showing: A) U-Pb monazite ages; B) $^{40}Ar/^{39}Ar$ biotite and muscovite ages (bold numbers). Symbols as in Figure 2. Compare with Fig. 2 for sample numbers.

Samples and radiometric results

The timing of late collisional stages of the southern Brasília belt have been derived from U-Pb analyses of monazite grains and $^{40}Ar/^{39}Ar$ analyses of muscovite and biotite of high-grade paragneisses, schists, migmatites and late-tectonic pegmatites from the Reworked Cratonic Border, Socorro-Guaxupé Nappe System and the

Metasedimentary Succession Domains of the Brasília and Ribeira belts (Heilbron et al., 2004). Monazite age is used to date peak metamorphism (De Wit et al., 2001; Foster et al., 2004; Gibson et al., 2004; Guillaume-Seydoux et al., 2002) interpreted to be related to the southern Brasília belt evolution, as supported by petrography and field inferences. Ar-Ar is used to date thermal episodes (Noce et al., 2004).

All samples studied were taken from locations far from the recognized late sub-vertical shear zones (Jacutinga, Jundiuvira, Camanducaia, São Bento do Sapucaí, Campo do Meio and Três Corações shear zones; Fig. 2) to avoid local tectonic effects. These shear zones are related to the Socorro-Guaxupé Nappe System of the Brasília belt or to the younger escape tectonic at the Central Ribeira belt. Twenty nine samples were analyzed by the $^{40}Ar/^{39}Ar$ method whilst eleven of them by U-Pb method as well (sample locations and descriptions are in Figs 2, 3 and Table 2). U-Pb monazite analyses are summarized in Table 3 , and concordia diagrams are shown in Fig. 5. The $^{40}Ar/^{39}Ar$ ages are listed in Table 4 , whilst the complete analytical data are shown in Appendix 1. Four plots of the $^{40}Ar/^{39}Ar$ dates illustrate the history of uplift and cooling for the studied domains (Fig. 6A-D).

Figure 4. Field photographs

Field photographs. A) Paragranulite of the Guaxupé Domain, sample H693; B to D) paragneisses of the Socorro Domain (samples HFT353, HFT349, H704 respectively); E) Schist interlayered with quartzites of the Metasedimentary Succession Domain, sample H687.

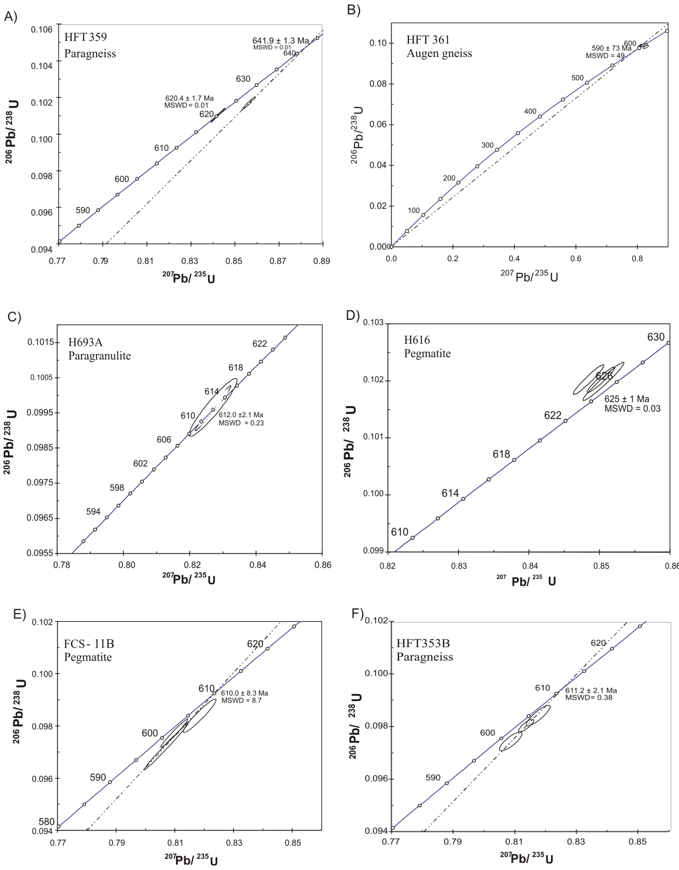
Table 2. Sample Description

Sample	Lithology	Provenance	Coordinates	Analysis
Guaxupé Domain				
HFT359	Banded, biotite paragneiss	road between Poços and Machado Minas Gerais State- MG	21º 42' 0.6''S, 46º 22' 56''W	gneissic banding (122/09) composed of narrow bands of quartz, plagioclase, biotite , K-feldspar and prismatic monazite crystals
HFT361	Augen gneiss	road between Machado and Pouso Alegre-MG	21º 42' 52''S, 45º 55' 35''W	gneissic banding (80/10) and thrust sense to west composed by K-feldspar porphyroblasts in a quartz-feldspathic matrix, biotite and well formed monazite as accessory mineral
H693	Paragranulite (Fig. 4A) alternating with kinzigite and metabasite	road Varginha-Carmo Cachoeira-MG, at the Santo Antônio quarry	21º 33' 25''S, 45º 22' 07''W	gneissic banding (232/11) and stretching lineation (252/8) with transport sense to northeast. It is

U-Pb results

The oldest populations of monazite were found in the Guaxupé Domain. U-Pb age determinations of monazite grains from a single sample of migmatite (HFT 359, Figs 3A, 5A and Table 3) yield a discordant age of around 642 ±1 Ma. This age represents an early generation of monazite growth related to an early metamorphic event. This event is roughly contemporaneous to that in the Socorro Domain, associated with the pre-collisional granites of Hackspacher et al. (2003).

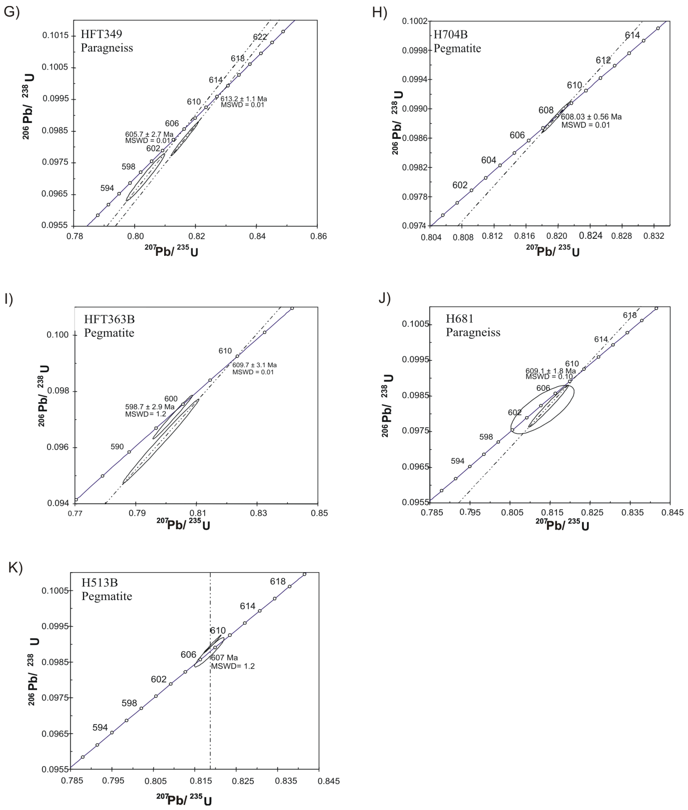
Figure 5a. U-Pb concordia diagrams



U-Pb concordia diagrams of monazite data from paragneisses. migmatites and pegmatites in the southern part of the: Brasília belt, Guaxupé Domain:

a. HFT359
b. HFT361
c. H693A.
d. Socorro Domain: H616,
e. FCS-11B,
f. HFT353B,

Figure 5b. U-Pb concordia diagrams



U-Pb concordia diagrams of monazite data from paragneisses. migmatites and pegmatites in the southern part of the: Brasília belt, Guaxupé Domain:

g. HFT349,
h. H704B.
i. Reworked Cratonic Border: HFT363B,
j. H681.
k. Ribeira belt: H513B.

Granulites, migmatites and paragneiss leucosomes of both the Guaxupé and Socorro Domains (Brasília belt) yield concordant ages between of 620±2 Ma, sample HFT 359, Guaxupé Domain, and 625±1 Ma, sample H616, Socorro Domain (Figs 3A, 5D and Table 3). Nearly concordant U-Pb monazite ages between 613 and 607 Ma were also found (samples H693A, H361, FCS 11B, HFT 353, H 704, H 681, H513B in Figure 3 a, Figure 4 , Figure 5a and Table 3). Geological and textural evidence, such as monazite inclusions in garnet, suggest that these old monazite grains grew during peak metamorphism (e.g., De Wit et al., 2001; Foster et al., 2004; Gibson et al., 2004; Guillaume-Seydoux et al., 2002). In the Brasília belt these early-formed monazite grains were found in high-grade rocks associated with low angle shear zones, syn-collisional granites, which may have re-homogenized the monazite ages of older migmatites and paragneisses.

One sample of pegmatite was dated. Pegmatites are mostly undeformed except for local boudinage and are interpreted to be late tectonic. They are intrusive into garnet-schists of the Andrelândia Group (Metasedimentary Succession Domain), in the southern edge of the Brasília belt. This monazite sample yielded an almost concordant U-Pb age of 598±2 Ma (Fig. 5I, sample HFT363B).

Table 3. U-Pb monazite data from the southern Brasília belt

Sample				Pb206	Pb207*	±	Pb206*	±	Correl.	Pb207*	±	Pb206*	±	Pb207*	±	Pb207*	±
Fraction	Wt.	U	Pb	Pb204	U235	2σ	U238	2σ	Coeff.	Pb206*	2σ	U238	2σ	U235	2σ	Pb206*	2σ
	(mg)	ppm	ppm	(obs.)		%		%	(rho)		%	Age	(Ma)	Age	(Ma)	Age	(Ma)
Guaxupé Domain HFT359																	
M(0.4A)2	0.018	4643	2459	12496	0.8564	0.28	0.1017	0.27	0.974	0.06108	0.06	624	2	628	2	642	1
M(0.5A)2	0.018	13357	6811	18461	0.8423	0.32	0.1010	0.32	0.994	0.06047	0.03	620	2	620	2	620	1
H																	

$^{40}Ar/^{39}Ar$ results

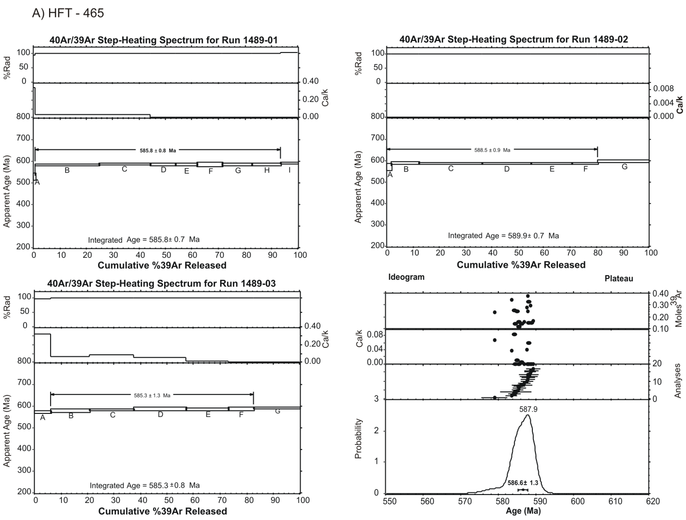
The study of monazite growth ages marking thermal peak is complemented by the study of Ar-Ar cooling ages. This thermochronometer was used here to identify the overprinting of the Ribeira belt deformation on the Brasília belt. In the northern portion of the Nappe System, north of the Jacutinga shear zone, in the Guaxupé Domain, $^{40}Ar/^{39}Ar$ data from biotite (Group 1 in Table 4 , Figure 3 B), yield a fairly tight cluster of cooling ages (plateau and ideogram), between 599±1 and 587±3 Ma (Fig. 6A, sample HFT465). Muscovite sample (H559: 588±2 Ma) yields similar ages to biotite. This indicates that the northern part of the Nappe System cooled to ~350 oC some 20-30 myr after peak metamorphism.

In the southern portion of the Nappe System, south of the Jacutinga shear zone, $^{40}Ar/^{39}Ar$ biotite data show a varied cooling history. The oldest ideogram biotite ages yielded a value of 597±1 Ma (sample HFT355), similar to the northern part of the Nappe System, and interpreted to represent a relict of that cooling phase. The next oldest sample obtained in this region is younger, ranging between 571±1 to 566±1 Ma (Group 2 in Table 4, Figs 3B, 6B sample HFT358), and include muscovite age between 566-562 Ma (Group 2 in Table 4 , sample HFT356).

A third group of samples south of the Jacutinga shear zone is associated with transpressional structures of the Central Ribeira belt, such as the NE-SW trending sub vertical strike-slip Jacutinga and Três Corações shear zones, which separate the Guaxupé and Socorro Domains. They yield $^{40}Ar/^{39}Ar$ biotite ideogram ages from 527±1 to 521 ±1 Ma (Group 3 in Table 4, e.g. samples HFT353 H681 and LUME, Figs 3B, 6C). The $^{40}Ar/^{39}Ar$ systematics in this area has been perturbed, as indicated by age spectra of the sample H687B that vary from 557±2 to 527±1 Ma. The youngest group of ages south of the Jacutinga shear zone yield biotite/muscovite ideogram ages from 510±2 to 491 ±1Ma (group 4 in Table 4, Figs 3B and 6D sample FDA). Six $^{40}Ar/^{39}Ar$ cooling age determinations in the eastern sector, near the boundary to the Ribeira Belt, show an age distribution between 501±2 and 491±1 Ma (see for example FDA, ANDT in Table 4).

Thus, the age patterns in the Nappe System south of the Jacutinga shear zone (Groups 2, 3 and 4), show that group 3 samples from the Jacutinga and Três Corações shear zones are younger than elsewhere (group 2), while group 4 probably reflects a new tectonic event. Their geographical distribution, closer to the Ribeira belt boundary, suggests a possible late overprint. The cooling ages of groups 3 and 4 are interpreted to have been reset by motion on vertical shear zones south of the Jacutinga and Três Corações shear zones producing a range of younger ages.

Figure 6. Incremental heating analysis of single grains



$^{40}Ar/^{39}Ar$ incremental heating analysis of single grains with plateau ideogram and integrated graphics.

a. North of Jacutinga shear zone, sample HFT 465. View Figure 6a [fullsize] (above).
b. South of the Jacutinga shear zone, sample HFT 358. View Figure 6b [fullsize].
c. South of Jacutinga shear zone, sample HFT 353. View Figure 6c [fullsize].
d. South of Jacutinga shear zone, sample FDA. View Figure 6d [fullsize].

See Table 4 for details.

Table 4. ^{40}Ar-^{39}Ar data (single grains; triplicate) from the southern Brasília belt. See Table 2 for sample details. Errors are given in 2s.

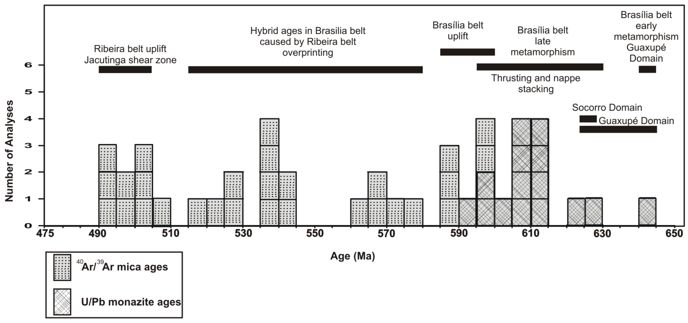
Sample	Rock /Mineral	Lab #	Plateau 1	Plateau 2	Plateau 3	Ideogram	Integrated
		USP	Ages (Ma)	Ages (Ma)	Ages (Ma)	Ages (Ma)	Ages (Ma)
Group 1- North of Jacutinga shear zone: northern part of the Socorro-Guaxupé domains							
HFT359	paragneiss/biotite	1512	601 ±1	598 ±1	598 ±1	599 ±1	
HFT361	augen gneiss/biotite	1513	588 ±1	586 ±1	591 ±1		584 ±1
H693C	paragranulite/biotite	1485	574 ±1	578 ±1	586 ±1		579 ±1
H465	schist/biotite	1489	586 ±1	589 ±1	585 ±1	587 ±1	
H559	schist/muscovite	1491	591 ±1	587 ±1	587 ±1	588 ±2	
Group 2- South							

Discussion and Conclusions

The U-Pb and $^{40}Ar/^{39}Ar$ ages presented above can be divided into different groups which define the tectonic history of different blocks related to the collision and amalgamation of the Neoproterozoic around the southern limit of the São Francisco Craton. These final stages occur at different times and overprint differently the Brasília and Ribeira belts (Figure 7). The older U-Pb monazite ages between 642±1 and 620±1 Ma (H359) from migmatites and high-grade paragneisses of the Guaxupé Domain in the southern Brasília belt, are considered to date the main metamorphic phase associated with granitic plutonism, collision and a tangential tectonic regime (Figure 7). This is supported by U-Pb data and geologic constraints from the Socorro Domain indicating pre- to syn-collisional processes between 650 and 628 Ma (Hackspacher et al., 2003; Piuzana et al., 2002; Pimentel et al., 2004).

The U-Pb monazite ages from the Guaxupé and Socorro Domains between 613±1 and 607±3 Ma represent late stage metamorphism of the Brasília belt associated with eastward thrusting and nappe stacking. Pegmatites intruding upper crustal level have concordant monazite ages of around 598 Ma (Fig. 5I). They were associated with the final magmatic evolution, popossibly the same event reported by Janasi et al. (2001) in the Guaxupé Domain, between ca. 610 and 580 Ma. This late magmatism is interpreted to represent the post-orogenic uplift of the Brasília belt (Wernick, 1998) and marks the final closure of the Goianides Ocean (Fischel et al., 1998; Pimentel et al., 2000; Piuzana et al., 2002). Magmatic ages between 595 and 560 Ma record the main period of tectonic activity in the Ribeira belt (Machado et al., 1996) suggesting that magmatism in the easternmost part of the Brasília belt could be a response to tectonic and possibly magmatic activity in the Central Ribeira belt. Biotite $^{40}Ar/^{39}Ar$ cooling ages of 599±1 and 587±1 Ma from the paragneisses of the Guaxupé Domain indicate that the nappe system cooled from the 700 oC closure temperature of monazite to 350 oC over 10-20 myr, possibly as a result of exhumation of the southern Brasília belt.

Figure 7. Biotite and muscovite age-histogram



U-Pb monazite and $^{40}Ar/^{39}Ar$ biotite and muscovite age-histogram of the Southern Brasília and Central Ribeira belts. See text for details.

The $^{40}Ar/^{39}Ar$ ages in the range between 580 – 520 Ma, defining groups 2 and 3, include rocks south of the Jacutinga shear zone (Socorro Domain) and reflect a complex history of exhumation of the Nappe System. Transpressional structures in the Brasília belt characterize deformation during this time and are interpreted to be related to the tectonic evolution of the Central Ribeira belt (Figure 7) as described in the regional geology. At that time the main tectonic activity in the Ribeira belt changed from a compressive to an extensional regime where ductile shear zones evolved to brittle systems.

In the Socorro Domain, the $^{40}Ar/^{39}Ar$ ages from 571±1 and 560±1 Ma down to 537±1 and 521±1 Ma, are significantly younger than those north of the shear zone. This delayed cooling reflects either different times of exhumation, or partial resetting due to reheating during transpressional tectonics related to the Ribeira belt. Supported by a component of vertical displacement along the strike-slip shear zones, and contrasting metamorphic conditions on either side of Jacutinga shear zone (greenschist and amphibolite facies), we favour a later exhumation for this domain, but further interpret the variability of apparent ages of single samples as representing overprinting by tectonic activity related to the Ribeira belt. The apparent cooling ages around 520 Ma from samples located along the NE-SW trending sub-vertical strike-slip Jacutinga and Três Corações shear zones between the Guaxupé and Socorro Domains (Fig. 3) define both the latest time and the westernmost limit of the effects of the Ribeira belt tectonic on the Brasília belt. The youngest group of $^{40}Ar/^{39}Ar$ ages, between 505 and 490 Ma, is limited to the Metasedimentary Succession Domain (see Fig. 3A-B), south of the Jacutinga shear zone, are identical to typical cooling ages in the Ribeira belt along the Atlantic coast further to the east. Thus, we interpret these ages to reflect final uplift.

The $^{40}Ar/^{39}Ar$ cooling ages of samples ANDT, DIT, FDA, ITM TR and TI45 (Group 4, Table 4) are the youngest and suggest a trend ageing to the NW within the Metasedimentary Succession Domain. Although more data is required to establish this trend, the data suggest progressive partial reheating related to exhumation of the Central Ribeira belt.

In summary, integration of U-Pb and $^{40}Ar/^{39}Ar$ ages, supported by geologic documentation, indicates that the southern Brasília belt was reactivated by the younger Central Ribeira belt. Such interaction took place from the end of the Neoproterozoic to early Phanerozoic, during the assembly of West Gondwana. The southern margins of the Brasília belt reached the main collision phase with the São Francisco Craton at 620 Ma (Table 1) and peak metamorphism at 610-590 Ma as indicated by monazite ages. This was followed by exhumation and cooling before a late overprinting as a result of collision with the Central Ribeira belt and subsequent transpression. This late event caused the resetting of cooling ages to between 580 and 520 Ma. Late cooling ages recorded by samples from the Jacutinga shear zone marks the northwestern limit of a progressive regional cooling, associated to the Ribeira belt transpressional tectonics.

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A. $^{40}Ar/^{39}Ar$ analytical data

Table A.1. $^{40}Ar/^{39}Ar$ analytical data (single grains; triplicate) from the southern Brasília belt

Sample	Material	Lab#	Laser	40/39	38/39	37/39	36/39	40*/39	Ar40	%Rad	Age	±
			(W)						(mols)		(Ma)	(Ma)
		SPA0104-46										
DIT	muscovite	0918-01A	0.20	34.99554	0.03762	0.00000	0.05417	18.98691	3.73E-16	54.3	528.38	99.59
		0918-01B	0.35	22.02483	0.06764	0.13530	0.06565	2.63582	3.57E-16	12.0	83.27	78.50
		0918-01C	0.50	21.07184	0.01166	0.00000	0.00250	20.33110	6.75E-16	96.5	560.52	27.11
		0918-01D	0.70	19.36441	0.01606	0.00000	0.00677	17.36386	2.28E-15	89.7	488.79	9.80
		0918-01E	0.90	20.62366	0.01391	0.00000	0.00878	18.02889	7.72E-15	87.4	505.12	3.90
		0918-01F	1.20	18.13211	0.00925	0.00000	0.00123	17.76869	5.43E-14	98.0	498.75	3.28
		0918-01G	1.50	17.88917	0.01015	0.00000	0.00037	17.77886	1.75E-13	99.4	499.00	1.48
		0918-01H	1.80	17.58880	0.01107	0.00000	0.00004	17.57570	8.51E-14	99.9	494.01	2.70
		09	2.2	17.	0.0	0.0	0.0	17.	1.2	98.	48	3.4