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Tectonic implications of Precambrian Sm–Nd dates from the southern São Francisco craton and adjacent Araçuaí and Ribeira belts, Brazil

Hannes K. Brueckner [a,b,*], Dickson Cunningham [c], Fernando F. Alkmin [d], Stephen Marshak [e]

[a] School of Earth and Environmental Sciences, Queens College and the Graduate Center of CUNY, Queens College, Flushing, NY 11367, USA
[b] Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[c] Orogenic Processes Group, Department of Geology, University of Leicester, Leicester LE1 7RH, UK
[d] Depto. de Geologia, Univ. Federal de Ouro Preto, Ouro Preto M.G. 35.400, Brazil
[e] Department of Geology, University of Illinois, Urbana, IL 61801, USA

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Abstract

The Archean and Paleoproterozoic São Francisco craton of eastern Brazil is surrounded on all sides by Brasiliano (= Pan African) orogens. The N–NE trending orogen that separates the eastern edge of the southern São Francisco craton from the Atlantic coast can be divided into the largely greenschist and amphibolite facies Araçuaí belt on the west and the largely granulite facies Ribeira belt on the east. A pronounced linear gravity and magnetic anomaly, the Abre Campo discontinuity, defines the boundary between these two belts. We obtained Sm–Nd mineral ages and whole-rock Sm–Nd model ages for garnet-bearing metamorphic rocks along an E–W transect across the southern São Francisco craton, the southern Araçuaí belt, and the Ribeira belt at about latitude 20°S. A recrystallization age of 2.1 Ga from metasediments recrystallized during the development of the classic dome-and-keel province of the southern São Francisco craton (the 'Quadrilátero Ferrífero') indicates that dome emplacement occurred during the waning stages (extensional collapse) of the Transamazonian collisional orogeny. Seven mineral ages from the southern Araçuaí and Ribeira belts date the thermal peak of metamorphism at between 538 and 589 Ma, confirming that these belts were pervasively remobilized during the Brasiliano event. Samples from the Araçuaí belt yield either Archean (>2.6 Ga) or Transamazonian (2.1–2.3 Ga) T_{DM} model ages, indicating that the protoliths were either fragments of the São Francisco craton crust or were sediments derived from that craton, which presumably had been stretched to form a thinned continental margin during Meso- and Neo-Proterozoic rifting events. Notably, a mixed meta-pelite and metabasite sequence in the southern Araçuaí belt, the Dom Silvério Group, has Transamazonian ancestry and thus may represent oceanic sediments deposited on or east of this stretched margin and then thrust back onto the continent to mark a collisional suture between the São Francisco block and an Archean (?) crustal sliver to the east. The rocks of the Ribeira belt (i.e. the region east of the Abre Campo discontinuity) have younger model ages (T_{DM} = 1.6–2.0 Ga), indicating that this belt was not originally part of the São Francisco craton — it may represent an accreted Transamazonian terrane. Therefore, the Abre Campo discontinuity marks an important crustal boundary, possibly a suture. Brasiliano shear zones appear to steepen and root into the Abre Campo discontinuity, suggesting that it formed in Brasiliano time. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Araçuaí belt; Brasiliano event; Brazil geology; Ribeira belt; São Francisco craton; Sm–Nd geochronology

* Corresponding author. Fax: +1-914-365-8150.
E-mail address: hannes@ldeo.columbia.edu (H.K. Brueckner)

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1. Introduction

South America today consists of a Precambrian core bordered by active orogens to the north and west, and by a Mesozoic–Cenozoic passive margin to the east. The Precambrian core is divided into four Archean to late Proterozoic 'cratons' (Almeida et al., 1981; Brito Neves and Cordani, 1991) by a network of 'Brasiliano' (=Pan African) orogens that developed during the final assembly of Gondwana near the end of the Proterozoic. One of these cratons, the São Francisco craton (Almeida, 1977), lies within the eastern part of the Brazilian Highlands (Fig. 1). The northeastern lobe of this craton was continuous with the Congo craton of western sub-Saharan Africa (Fig. 1),

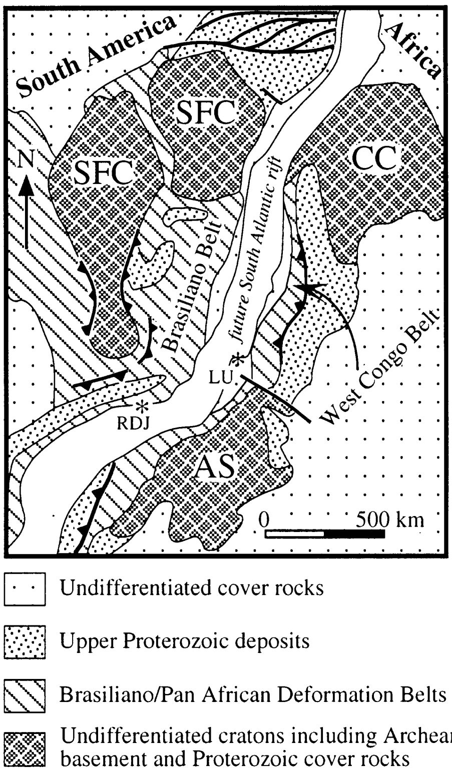

Fig. 1. West Africa–eastern Brazil Gondwana reconstruction showing location of cratons and Brasiliano/Pan African belts. Adapted from Porada (1989) and Cunningham et al. (1996). AS: Angola Shield; CC: Congo Craton; SFC: São Francisco Craton; RDJ: Rio de Janeiro; LU: Luanda.

prior to the Cretaceous opening of the South Atlantic (e.g. Trompette, 1994). The crust between the São Francisco craton and the Atlantic coast was mobilized and/or remobilized by Brasiliano tectonism and metamorphism (e.g. Almeida, 1977; Almeida and Hasui, 1984) to form an orogen that was continuous with the West Congo fold belt of western Africa prior to the opening of the South Atlantic (Porada, 1989; Brito Neves and Cordani, 1991; Pedrosa-Soares et al., 1992; Maurin, 1993; Trompette, 1994; Fig. 1). Despite considerable previous work concerning the petrological evolution of the region between the São Francisco craton and the Atlantic coast (e.g. Söllner et al., 1991; Figueiredo and Campos Neto, 1993; Wiedemann, 1993; Costa et al., 1995) there is no unified and generally accepted geological subdivision for this region. Recent work (e.g. Costa et al.; 1995; Cunningham et al., 1998; Alkmim and Marshak, 1998; Fischel et al., 1998) suggests that it can be divided into two distinct ~N–S-trending tectonic belts (Fig. 2): the largely amphibolite-facies Araçuaí belt on the west, and the largely granulite-facies Ribeira belt [also referred to as the 'Coastal Mobile belt' or 'Atlantic belt'; see Cunningham et al. (1996, 1998) for discussion of nomenclature] on the east. These belts are separated by a pronounced gravity and magnetic anomaly (Haralyi and Hasui, 1982): the Abre Campo discontinuity.

Previous dates on metamorphic and igneous rocks from the Araçuaí and Ribeira belts indicate that Brasiliano tectonism in this region occurred around 0.6–0.5 Ga (Teixeira, 1982; Söllner et al., 1991; Campos Neto and Figueiredo; 1995; Machado et al., 1996b). However, many questions remain concerning the precise timing of tectonism and the ancestry of the crust affected by this tectonism. For example, did the Ribeira and Araçuaí belts form separately or simultaneously? Is there any Brasiliano juvenile crust in either belt or are both belts composed of remobilized Archean and/or Proterozoic crust? Is there a Brasiliano suture in the region, or are there any older sutures? How much of the Archean crust of the São Francisco craton was affected by the 2.1 Ga Transamazonian orogeny? Did any crust in the

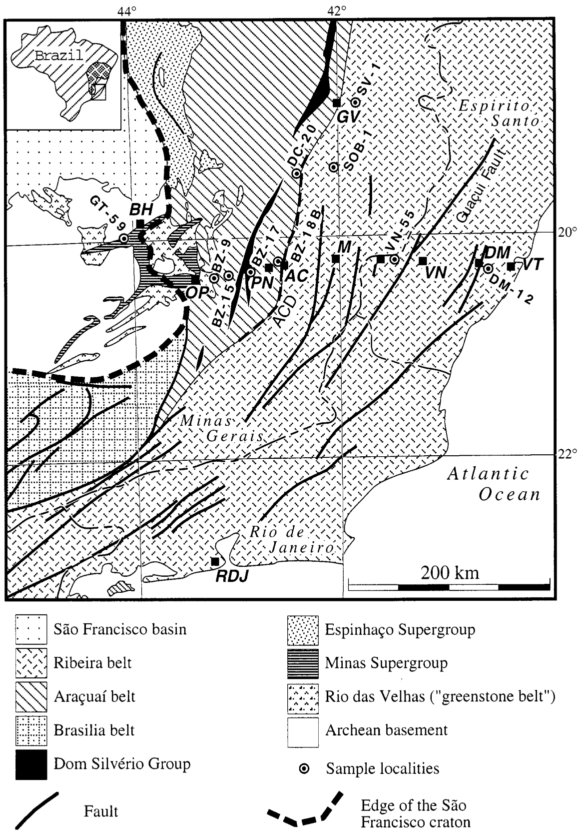

Fig. 2. Simplified regional map of southeastern Brazil showing sample localities and the southern São Francisco craton, the Quadrilátero Ferrífero, and the Araçuaí and Ribeira belts separated by the Abre Campo discontinuity (ACD). BH: Belo Horizonte; GV: Governador Valladares; OP: Ouro Preto; PN: Ponta Nova; AC: Abre Campo; M: Manhuaçu; I: Ibatiba; DM: Domingo Martins; VN: Venda Nova; VT: Vitória; RDJ: Rio de Janeiro.

Araçuaí and Ribeira belts form during the Transamazonian event, and, if so, is there a boundary between Transamazonian juvenile crust and Archean crust?

We undertook a combined structural and geochronological study of the southern São Francisco craton and the Brasiliano belts along its eastern margin in order to address these questions. We concentrated our efforts in the region between Belo Horizonte and Vitória, at about 20°S, in the states of Minas Gerais and Espirito Santo (Fig. 2). The results of our structural analyses are presented elsewhere (Marshak et al., 1996; Cunningham et al., 1996, 1998; Alkmim and Marshak, 1998). Here we report Sm–Nd mineral and whole-rock geochronologic results on garnet-bearing metamorphic rocks. These results confirm that the rocks of the Araçuaí and Ribeira Belt were intensely recrystallized and deformed between 550 and 600 Ma ago. They provide evidence for Transamazonian tectonism in the southern São Francisco craton, and suggest that the basement of the Araçuaí belt contains relics of the Transamazonian orogen. Finally, the results suggest that most of the Araçuaí belt consists of remobilized Archean rocks of the São Francisco craton whereas the Ribeira belt appears to consist of remobilized post-Archean crust, implying that the boundary between these two belts may be a suture.

2. Geologic setting

The southern São Francisco craton and its margins initially formed during the Archean in several discrete events between 3.2 and 2.7 Ga (Carneiro et al., 1998). Between 2.1 and 1.9 Ga, the Transamazonian orogeny left its imprint on the southern and eastern parts of the craton (Machado et al., 1992, 1996b), creating a NNW-verging fold-and-thrust belt that was later incorporated in a dome-and-keel province (Alkmim and Marshak, 1998). The eastern margin underwent rifting at 1.75 Ga (Machado and Abreu-Bentivi, 1989) to form a deep basin that filled with the largely quartzitic Espinhaço Supergroup (Dussin and Dussin, 1995; Brito Neves et al., 1996). Another rifting event occurred along the eastern margin between 1050 and 900 Ma, resulting in the deposition of the Macaúbas Group, and the generation of mafic dike swarms (Machado and Abreu-Bentivi, 1989; Pedrosa-Soares et al., 1992, 1998; Correa-Gomes and Oliveira, 1996). All margins of the craton were subjected to Brasiliano deformation during the Neoproterozoic and earliest Phanerozoic (Cambrian), creating fold-thrust belts that generally verge towards the interior of the craton (Fig. 1).

Four principal stratigraphic units occur in the southern São Francisco craton in the region around Belo Horizonte (Fig. 2): Archean basement [granitoid intrusives, gneisses, and migmatites that range in age from 3.2 to 2.7 Ga (Machado et al., 1992; Carneiro et al., 1998)]; an Archean (ca. 2.7 Ga) supracrustal assemblage (the Rio das Velhas 'greenstone' and associated sedimentary sequences); two Paleoproterozoic supracrustal assemblages, the Minas Supergroup [platformal and deep marine strata including quartzite, phyllite, carbonate, and Lake Superior type banded iron formations, deposited between 2.1 and 2.4 Ga (Babinski et al., 1991; Machado et al., 1992, 1996b)] and the Itacolomi Group (quartzite and conglomerate). The basement occurs in dome-shaped bodies separated by deep keels (troughs) containing deformed supracrustal rocks — i.e. the region is a dome-and-keel province (Marshak et al., 1992). This dome-and-keel province is known as the Quadrilátero Ferrífero (QF), or 'iron quadrangle', because of the abundant iron ores of the Minas Supergroup (Dorr, 1969). Alkmim and Marshak (1998) postulated that the last dome emplacement event occurred after the NNW-verging deformation attributed to the Transamazonian orogeny, but before Brasiliano west-vergent thrusting. Typically, a metamorphic 'aureole', where temperatures reached 625°C at 3 kbar (Jordt-Evangelista et al., 1992; Marshak et al., 1992), occurs in supracrustal strata at the contact between supracrustal strata and basement along the margins of the domes (Marshak et al., 1996). We collected material from this aureole to date the dome-emplacement event.

The eastern two-thirds of the QF is overprinted by west-verging structures attributed to the Brasiliano orogeny (Chemale et al., 1994; Alkmim and Marshak, 1998). The intensity of deformation and the degree of associated metamorphism increases eastward, culminating in the intensely deformed, dominantly amphibolite-facies schists and gneisses of the southern Araçuaí belt. The rocks in the eastern part of the southern Araçuaí belt are dominantly biotite–amphibole orthogneisses and migmatites of felsic-intermediate composition of the Mantiqueira gneiss and Piedade Gneiss complexes (Jordt-Evangelista and Müller, 1986; Schulz-Kuhnt et al., 1990; Brandalise, 1991; Herbert et al., 1991; Müller et al., 1991). There is also a structural contrast between the eastern and western halves of the southern Araçuaí belt. The eastern half is characterized by moderate to steep foliations and is cut by numerous shear zones that consistently verge west and, therefore, can reasonably be attributed to Brasiliano tectonism. In contrast, much of the western half of this belt contains a shallow east-dipping foliation (Cunningham et al., 1998) that gradually steepens eastwards towards a structural root zone near Abre Campo. The southern Araçuaí belt contains numerous mappable lithologic units (Costa et al., 1995; Cunningham et al., 1996, 1998). One of the most distinct units is the Dom Silvério Group, a sequence of pelitic metasedimentary and metabasic rocks that occurs just west of the town of Ponte Nova (Fig. 2). This unit contains pelitic schists, talc schists, serpentinites, manganese-rich metasediments (gondites) and other metabasites including rare ultramafic units (Brandalise, 1991; Jordt-Evangelista, 1992). Cunningham et al. (1996, 1998) suggested that the Dom Silvério Group may represent a former subduction complex that marks a collisional suture between a Paleoproterozoic continent to the west (which encompasses the São Francisco craton and the basement to the southern Araçuai belt) and Transamazonian basement terrane to the east.

The Araçuaí belt terminates to the east at a pronounced gravity and magnetic anomaly called the Abre Campo discontinuity (Haralyi and Hasui, 1982; Fischel et al., 1998). A narrow, discontinuous belt of amphibolite, the Santo Antônio do Grama amphibolite, is exposed along the discontinuity (Brandalise, 1991) and a band of migmatite lies just east of it (Jordt-Evangelista and Müller, 1986). The Ribeira Belt occupies the region east of the Abre Campo discontinuity and extends to the Atlantic coast. Previously, this region has been divided into the Juiz to Fora Gneiss Complex on the west, the Paraíba do Sul Complex in the center, and the Costeiro Gneiss Complex on the east (Almeida and Hasui, 1984; Söllner et al., 1991). The Ribeira belt consists of dominantly granulite-facies gneisses and charnockites that contrast markedly in metamorphic grade with the amphibolite facies rocks of the Araçuaí belt. The granulites are separated by numerous narrow, highly deformed, quartz mylonite and metasedimentary belts and are cut by an array of steep NNE-striking shear zones along which there has been dextral strike-slip and transpressive movement (Costa et al., 1995; Cunningham et al., 1998). In addition, the Ribeira belt is intruded by calk-alkaline granitoids that may define a Brasiliano magmatic arc (Wiedemann, 1993; Pedrosa-Soares et al., 1998).

3. Sm–Nd geochronology

Garnets generally develop much higher Sm/Nd ratios than most other metamorphic minerals in high-grade metamorphic rocks and can be used to define mineral isochron ages (Griffin and Brueckner, 1980). These ages usually approach the time of the thermal peak of metamorphism more closely than do K–Ar, Ar–Ar and Rb–Sr mineral ages. In addition, the tendency for the REEs to be relatively immobile during metamorphism means that Sm–Nd model ages calculated from whole-rock samples reasonably constrain the time the protoliths of the metamorphic rocks were extracted from the mantle (DePaolo and Wasserburg, 1976). Garnet-bearing metamorphic rocks were collected from nine localities with the goal of obtaining Sm–Nd recrystallization ages and whole-rock model ages.

4. Sample collection localities

Here, we describe the sample localities (shown in Fig. 2), in sequence from west to east, and provide the reasons for collecting the samples.

4.1. Sample GT-59

This garnet–sillimanite–muscovite schist is from the Sabará Formation (Dorr, 1969) exposed in a roadcut near the town of Ibirité, 10 km west of Belo Horizonte, in a portion of the QF that escaped subsequent Brasiliano overprinting. The collection locality lies within the contact aureole 200 m from the contact with basement gneiss of the Belo Horizonte 'dome' (Fig. 2). Therefore, a mineral age from this rock dates the time of contact metamorphism, and hence the time of dome emplacement in the dome-and-keel province. The whole-rock model age provides constraints on the provenance of the metasediment. Further information on the petrography of this zoned contact aureole is given by Herz (1978) and Jordt-Evangelista et al. (1992).

4.2. Sample BZ-9

This sample is a garnet–chlorite–muscovite schist from the Nova Lima Group (Dorr, 1969), within the southern Araçuaí belt, from a railroad cut 15 km east of Ouro Preto at the southeastern corner of the QF. The unit lies at the west edge of the southern Araçuaí belt and is thought to be an Archean greenstone recrystallized during Brasiliano metamorphism. The outcrop displays a strong E-dipping foliation with top-to-the-west kinematic indicators suggesting Brasiliano deformation. Snowball-like inclusion trails within garnets indicate syntectonic metamorphism.

4.3. Sample BZ-15

This garnet–biotite gneiss was collected from a roadcut on MG262 where it crosses the Gualaxo River about 32 km east of Ouro Preto. The gneiss is traditionally mapped as the Mantiqueira Complex and corresponds to the basement of the Dom Silvério Group, a metasedimentary unit discussed below. The foliation dips 60°E. The sample was analyzed for whole-rock model age.

4.4. Sample BZ-17

This biotite–garnet–muscovite–kyanite schist is mapped as part of the Dom Silvério Group within the Araçuaí belt, and was collected from a roadcut 12 km west of the town of Ponte Nova. In addition to metasedimentary schists, the Dom Silvério Group contains metabasalts, ultramafites, gondites, and marble (Jordt-Evangelista, 1992) along strike to the north, suggesting deposition in an oceanic environment. Also, the unit may correlate with a belt of tectonized greenstone in the northern

Araçuaí belt that has been interpreted as the remnant of an ophiolite (Pedrosa-Soares et al., 1992, 1998). Thus, the Dom Silvério Group may mark a Transamazonian or Brasiliano suture. However, the unit may be allochthonous; if so, its present position does not necessarily define the position of a suture. We collected the sample to determine its metamorphic age and possibly to constrain the age of the provenance source.

4.5. Sample BZ-18B

A sample of garnet–biotite gneiss was collected from a narrow slot-like roadcut along highway MG262 12 km east of the town of Ponte Nova, in the Araçuaí belt. Garnet-bearing gneisses of the Mantiqueira Complex are exposed as lenses with a relict steeply dipping foliation, surrounded by garnet-free, biotite-rich gneiss that developed in association with an anastamosing shallow-dipping foliation. If the shallow-dipping foliation is a Brasiliano fabric, the relict garnet-bearing gneiss lenses may record pre-Brasiliano metamorphism. This sample comes from one of these lenses. The sample also contains abundant magnetite and amphibole that may be of secondary origin, related to the shallow dipping foliation.

4.6. Sample DC-20

This sample is a garnet-bearing charnockitic gneiss from a roadcut along BR 458 where it crosses the Santo Estevão River, 15 km southwest of the town of Dom Cavati. The largely massive outcrop displays an east-dipping foliation. The sample was taken about 100 km northeast of sample BZ-18B near the boundary between the Araçuaí belt and Ribeira belt where granulite and amphibolite-grade lithologies are intermixed [the boundary is not well defined in this region (Cunningham et al., 1996)]. It was collected to determine whether it contains a record of pre-Brasiliano metamorphism. This gneiss is believed to be a thrust slice that correlates with charnockitic rocks of the Juiz de Fora complex further to the south.

4.7. Sample SOB-1

This sample comes from strongly deformed biotite-garnet gneiss exposed in a roadcut on BR 116 about 8 km southeast of the town of Sobralia (i.e. 30 km south of Governador Valadares), in the westernmost Ribeira belt. The sample comes from outcrops that expose large (hundreds of meters across) west-vergent sheath folds and mylonitic shear zones. We collected this sample to determine its history of metamorphism and to try to constrain the timing of west-directed deformation.

4.8. Sample SV-1

This rock is from a roadcut 25 km east of the city of Governador Valadares within the Ribeira belt. The sample is a foliated granodiorite, and is from a metamorphosed intrusive suite of tonalite, granodiorite, and diorite called collectively the Galiléia Batholith. da Silva et al. (1987) determined an Rb–Sr whole-rock isochron age of 650 Ma from a diorite within this complex and interpreted this date as the time of crystallization of a Brasiliano intrusive complex. Nalini et al. (1998) obtained a somewhat younger U–Pb crystallization age of 595 Ma from zircons in a granodiorite. However, Sm–Nd model ages (T_{DM}) for these rock range between 2.26 and 1.80 Ga (Nalini et al., 1998), with ϵ_{ND} values ranging between -8.9 and -9.3. These values suggest that the complex is Brasiliano in age and was generated by melting older Precambrian crustal rocks. The collected sample is foliated and contains a metamorphic mineral assemblage, including garnet. We collected this sample to determine the time of metamorphism and associated deformation.

4.9. Sample VN-55

This garnet-bearing migmatite was collected from a roadcut along BR 262, 14 km northwest of the town of Venda Nova (120 km west of Vitoria) in the central Ribeira belt. The rock is part of a wide migmatite belt associated with small granite bodies included in the Juiz de Fora complex, that lies just to the west of the Guaçui fault. A Rb–Sr whole-rock isochron age of 580–590 Ma

(Signorelli, 1993) was obtained from migmatites within this unit. We collected this sample to determine the age of recrystallization, and to determine from the model age whether this rock had an earlier crustal history.

4.10. Sample DM-12

This sample comes from a roadcut along BR 262, 5 km east of the town of Domingos Martins, not far from Vitoria, in the eastern Ribeira belt. The rock consists of kinzingite, part of a 20 km wide belt of biotite–garnet–sillimanite–cordierite gneiss that is variably migmatized. The belt is involved in a very large west-vergent nappe. We collected this sample to determine its metamorphic history.

5. Methodology

We collected approximately 5 kg of each sample, making sure that the sample was unweathered. Initial processing was carried out at the Federal University of Ouro Preto. Samples were crushed in a jaw crusher. A fraction of the resulting fragments was further pulverized in a disk mill to provide material for whole rock analysis. A second fraction was passed through a jaw crusher to yield fragments less than 1 mm in diameter. We obtained concentrates of heavy minerals (garnet, biotite, amphibole) and light minerals (primarily feldspars and quartz) using a shaker table. The concentrates and whole-rock powders were sent to the isotope geochemistry lab at Lamont–Doherty Earth Observatory for further processing. There, the concentrates were further processed into pure mineral separates using standard heavy liquid, magnetic separation and hand-picking techniques. Garnet, biotite, muscovite, amphibole and quartz/feldspar mixtures (QF) and whole-rock powders were prepared for Sm–Nd analyses using laboratory methods described by Brueckner et al. (1991). Procedural blanks for Nd are 30–140 pg. Sm and Nd analyses were performed on a VG 54-30 mass spectrometer at Lamont–Doherty Earth Observatory using a dynamic, multicollector program. Repeated runs of standards gave an average $^{143}Nd/^{144}Nd$ ratio of $0.511\,857 \pm 42$ for the La Jolla Nd standard (2σ, standard deviations) at the time most of the samples were being analyzed. The $^{143}Nd/^{144}Nd$ ratios were corrected for machine fractionation by normalizing to $^{146}Nd/^{144}Nd$ of 0.721 90.

The data are shown in Table 1. Isochrons were calculated by applying York-fit regressions to the data from each sample using the ISOPLOT program of Ludwig (1988). The $^{147}Sm/^{144}Nd$ errors were taken to be 0.5%, the errors in $^{143}Nd/^{144}Nd$ were estimated using the relationship $(X^2+Y^2)^{1/2}$ where X is the standard deviation (2σ) of replicate analyses of the standards (i.e. 0.000 042, see above) and Y is the standard deviation of the mean (2σ) of each individual run (shown on Table 1). The calculated ages are Model 1 (Ludwig, 1988) unless otherwise noted. T_{CHUR} and T_{DM} model ages are calculated from the whole-rock analyses and represent extraction ages from the mantle assuming the rocks had been derived from an undepleted and depleted mantle respectively.

6. Results and interpretation

6.1. São Francisco craton

The date for sample GT-59 [Fig. 3(A)] indicates that metamorphism at a dome/keel (i.e. basement/supracrustal) contact in the western QF occurred at 2098 ± 33 Ma — i.e. during late stages of the Transamazonian event. As discussed in earlier papers (Marshak et al., 1996; Alkmim and Marshak, 1998), this date constrains the timing of final dome emplacement. Pomerene (1964) mapped the sampled unit as the Sabará Formation, the youngest unit of the Minas Supergroup. U–Pb studies by Machado et al. (1992) indicate that the Sabará contains Transamazonian zircons (2125 ± 4 Ma), leading them to interpret the Sabará as a Transamazonian foreland basin deposit. Alkmim and Marshak (1998) argue that the unit was deformed shortly after deposition by incorporation in NW-verging folds, part of the foreland fold-thrust belt of the Transamazonian orogen, and that immediately following thrusting the unit downfaulted into keels between basement

Table 1
Sm–Nd whole-rock and mineral results from garnet-bearing metamorphic rocks form the São Francisco craton, the Araçuaí belt, and the Ribeira belt, eastern Brazil

		Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Error 2σ	ϵ_{Nd}		T_{CHUR} (Ga)	T_{DM} (Ga)
							today	@575		
São Francisco craton										
GT-59	WR	7.20	40.0	0.110	0.511 368	0.000 014	−24.8	–	2.22	2.37
	Ms	4.60	26.1	0.107	0.511 319	0.000 012				
	Ms	4.07	23.0	0.107	0.511 320	0.000 016				
	Grt	2.19	4.22	0.313	0.514 171	0.000 012				
	Grt	2.43	4.89	0.301	0.513 999	0.000 017				
Araçuaí belt										
BZ-9	WR	8.84	33.5	0.160	0.511 452	0.000 045	−23.1	−20.4	4.8	4.0
	QF_1	1.28	6.30	0.123	0.511 229	0.000 007				
	QF_2	0.98	16.63	0.0897	0.511 205	0.000 011				
	Chl	5.57	30.5	0.110	0.511 273	0.000 008				
	Grt	1.11	4.28	0.157	0.511 479	0.000 008				
BZ-15	WR	7.89	43.7	0.109	0.510 999	0.000 005	−32	−25.6	2.83	2.83
BZ-17	WR	6.08	35.6	0.103	0.511 323	0.000 003	−25.7	−18.8	2.14	2.29
	Grt	1.55	2.22	0.422	0.512 467	0.000 014				
BZ-18B	WR	58.9	356	0.100	0.510 879	0.000 008	−34.3	−27.3	2.76	2.78
	Amp_1	68.4	198	0.209	0.512 236	0.000 009				
	Amp_2	65.7	194	0.205	0.512 200	0.000 006				
	Mag	17.2	71.6	0.145	0.511 602	0.000 015				
	QF	8.50	28.8	0.178	0.512 048	0.000 010				
	Grt_1	12.3	44.8	0.166	0.511 902	0.000 009				
	Grt_2	10.4	36.3	0.173	0.511 913	0.000 009				
Ribeira belt										
SOB-1	WR	6.51	40.9	0.09601	0.511 548	0.000 015	−21.3	−13.9	1.65	1.89
	Bi	1.30	6.19	0.127	0.511 635	0.000 012				
	QF	0.631	3.82	0.0999	0.511 561	0.000 009				
	Grt	4.19	2.44	1.04	0.515 183	0.000 014				
SV-1	WR	3.11	17.6	0.106	0.511 901	0.000 009	−14.4	−7.74	1.24	1.60
	QF	0.301	0.705	0.258	0.512 449	0.000 014				
	Grt	2.07	0.631	1.98	0.518 804	0.000 020				
DM-12	WR	15.7	82.6	0.115	0.511 916	0.000 006	−14.1	−8.08	1.34	1.70
	QF	2.89	16.8	0.104	0.511 874	0.000 010				
	Grt	3.78	13.6	0.168	0.512 101	0.000 012				
DC-20	WR	8.04	46.4	0.105	0.511 598	0.000 007	−20.3	−13.5	1.72	1.96
	QF	0.642	3.97	0.0977	0.511 545	0.000 019				
	Grt	7.03	7.69	0.553	0.513 239	0.000 013				
VN-55	WR	2.08	11.8	0.106	0.511 607	0.000 010	−20.1	−13.4	1.72	1.97
	QF	2.19	15.9	0.0833	0.511 492	0.000 010				
	Grt	1.82	1.85	0.591	0.513 417	0.000 016				

domes during orogenic collapse. The 2098 Ma date reported here is consistent with that interpretation. The model ages of 2.2 Ga (T_{CHUR}) to 2.3 Ga (T_{DM}) are consistent with the U–Pb zircon data (Machado et al., 1996b) and indicate that the Sabará Formation could not have been derived from an Archean source. The model ages and the small negative ϵ_{Nd} value (−1.0) at the time of recrystallization indicate that the source rock had a short residence time in the crust before it was eroded and re-deposited as the Sabará formation, as would be expected if the source terrain contained a major Transamazonian igneous component.

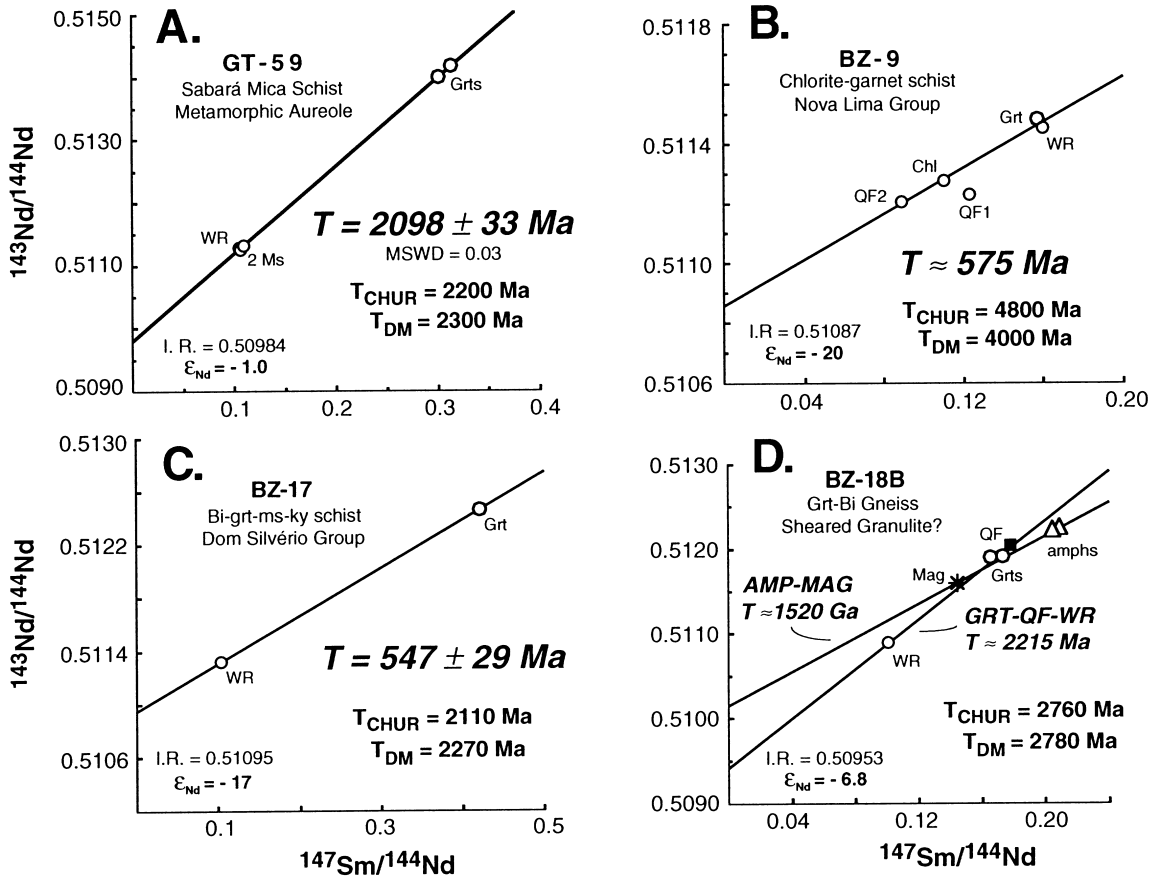

Fig. 3. Sm–Nd mineral isochrons from the São Francisco Craton and the Araçuaí belt, eastern Brazil. Best-fit line for sample BZ-9 (B) excludes QF1.

6.2. Araçuaí belt

The data for Sample BZ-9, the metamorphosed chlorite–garnet schist from the Nova Lima Group [Fig. 3(B)], yield a very poorly defined scatterchron of ca. 575 Ma. The minerals in this relatively low-grade (greenschist) metamorphic rock do not appear to have equilibrated for Sm, Nd and Nd isotopes. The snowball-like inclusions in the garnet suggest it formed under changing *P–T* conditions, so a lack of equilibration is not surprising. The crude best-fit age of ca. 580 Ma (QF 1 is arbitrarily deleted from the age calculation) suggests that the rock was metamorphosed during the Brasiliano event. If confirmed, this date would be significant because it would mark the westernmost dated mineral assemblage attributable to the Brasiliano orogeny and would suggest that the west-verging fabric found throughout the eastern part of the QF, particularly in the western Araçuaí belt, formed during the Brasiliano. The unrealistically old model age for the whole rock ($T_{DM}=4.0$ Ga!) is based on a whole rock with an unusually high Sm/Nd ratio, but is nevertheless consistent with the interpretation of the Nova Lima as an Archean Greenstone Belt.

The biotite–muscovite–garnet–kyanite schist from the Dom Silvério Group (BZ-17) defines a garnet–whole-rock mineral age of 547 Ma [Fig. 3(C)], demonstrating that this unit was metamorphosed during the Brasiliano event. In addition, the model ages of ca. 2.1 Ga (T_{CHUR}) to

2.3 Ga (T_{DM}) indicate that the unit was derived from a Paleoproterozoic (Transamazonian) source terrane. The apparent large negative ϵ_{Nd} ratio for this rock (−16.6) at the time of the metamorphism indicates that the source rock and/or the detritus from the source rock comprising the sediments had a long residence time in the crust before Brasiliano metamorphism, as would be expected if the rock was derived from a Paleoproterozoic source.

As previously mentioned, the protoliths of the Dom Silvério Group were probably deep oceanic sediments and possibly ophiolitic rocks. The model ages suggest that this oceanic setting existed to the east of the São Francisco craton and that the protolith sediments were either derived from a Paleoproterozoic terrane to the east (arc/subduction complex?) or from rocks affected by the Transamazonian (Paleoproterozoic) deformation to the west in the São Francisco craton. In other words, the Dom Silvério Group could represent rocks caught between a colliding terrane to the east and the São Francisco craton thus representing a suture. Because Archean rocks lie immediately east of the Dom Silvério outcrop belt (see results for sample BZ-18B), this offshore terrane is probably a continental basement fragment that rifted off of the eastern margin of the São Francisco craton. The present position of the Dom Silvério group within the Araçuaí belt (Fig. 2) does not necessarily constrain the original position of this possible suture, because the degree of allochthoneity of the unit has not been determined. However, structural data of Cunningham et al. (1998) suggest that the Dom Silvério Group is not derived from the boundary between the Araçuaí and the Ribeira Belts some tens of kilometers to the east of the present outcrop belt (Fig. 2).

The scattered mineral data for sample BZ-18B [Fig. 3(D)], a high-grade gneiss that occurs in lenses surrounded by shallowly dipping lower-grade shear zones, provide a complex and interesting story. The model ages for the whole rock suggest that the protolith of this rock formed in the Archean, between 2.7 and 2.8 Ga. This age range is typical of the basement rocks in the southern São Francisco craton region and has been associated with a major crust formation event in the craton known as the Rio das Velhas event (Carneiro et al., 1998). However, sample BZ-18B comes from east of the Dom Silvério Group, suggesting that if the Dom Silvério Group represents a Transamazonian or Brasiliano suture then there is Archean basement on either side of it. The model age is consistent with other Sm–Nd whole-rock model ages determined for rocks in the region (Fischel et al., 1998), although these ages tend to cluster at Early Archean (3.02–3.06 Ga) and Late Archean (2.53–2.64 Ga) and thus bracket the model age determined for BZ-18B.

The primary minerals of sample BZ-18B, garnet and the quartz–feldspar mixture (QF), and the whole rock, define a linear array with an age that implies the rock was subjected to Transamazonian metamorphism at about 2.2 Ga [Fig. 3(D)]. The ϵ_{Nd} value of −6.8 for this rock during recrystallization is consistent with the notion that Transamazonian metamorphism remobilized older (Archean) crystalline rocks. The secondary minerals of sample BZ-18B, amphibole and magnetite, which may have formed later, appear to define a younger age of about 1.5 Ga. This young age matches model ages of about 1.5 Ga for rocks nearby to the east, in the Ribeira belt, as discussed below. Thus one interpretation of the data is that sample BZ-18B represents Archean basement rocks that were recrystallized during the Transamazonian orogeny and then later during a ca. 1.5 Ga event. However, other Sm–Nd mineral isochrons in the same general region as sample BZ-18B (i.e. the area immediately west of the Abre Campo discontinuity) range from 528 to 672 Ma (Fischel et al., 1998), clearly reflecting Brasiliano recrystallization but showing no evidence of a 1.5 Ga event. Therefore, another interpretation of the data is that sample BZ-18B represents Archean basement rocks that were recrystallized during the Brasiliano event, but either recrystallization did not result in complete equilibration between minerals for the Sm–Nd system, or shearing or some other event subsequent to recrystallization caused open system behavior for the Sm–Nd system, resulting in the scattered data array in Fig. 3(D). In either case, the unit sampled by BZ-18B appears to differ from the other dated units of the region. Perhaps the gneisses represent a basement complex that escaped pervasive Brasiliano recrystallization and therefore records important pre-Brasiliano events.

6.3. Ribeira belt

All five samples analyzed from the Ribeira belt, the region east of the Abre Campo discontinuity, define Brasiliano Sm–Nd recrystallization ages (Fig. 4) between 538 and 589 Ma. These ages confirm previous K–Ar and Rb–Sr mineral ages (Teixeira, 1982; da Silva et al., 1987). They also agree with other Sm–Nd mineral ages from garnet-bearing metamorphic rocks (528–600 Ma) determined by Fischel et al. (1998) for the area east of Abre Campo (Fig. 2), U–Pb zircon ages of 570–580 Ma for rocks of the Juiz de Fora complex, in the western Ribeira belt (Söllner et al., 1991), U–Pb zircon, monazite and titanite ages between 565 and 590 Ma for different lithotectonic domains within the Ribeira belt (Machado et al., 1996a), an Rb–Sr whole-rock isochron age of 580–590 Ma (Signorelli, 1993) from migmatites collected near our sample VN-55 (Fig. 2), and a U–Pb crystallization age of 595 Ma from zircons from the Galiléia batholith (Nalini et al., 1998). Taken

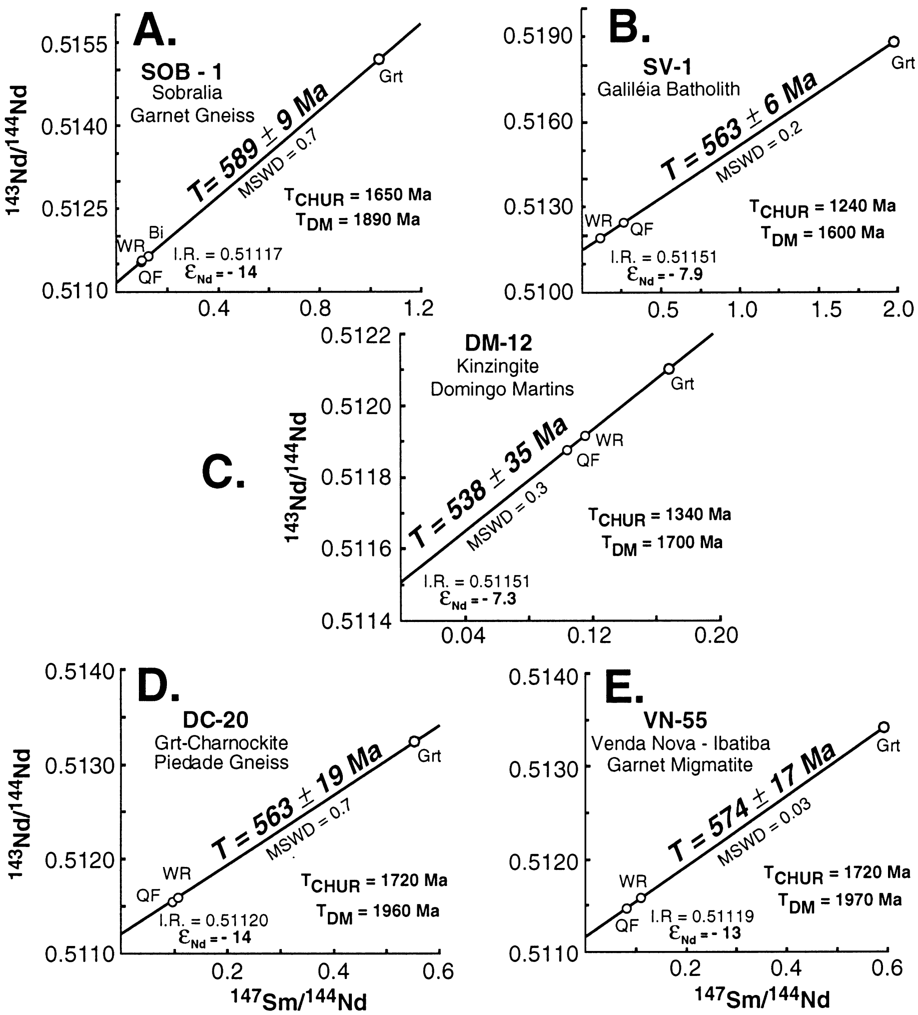

Fig. 4. Sm–Nd mineral isochrons from the Ribeira belt, eastern Brazil.

together, these ages suggest that Brasiliano granulite-facies metamorphism accompanied by large-scale migmatization and anatectic melting occurred at about 575±20 Ma.

The whole-rock model ages for samples from the Ribeira belt are between 1.2 and 1.7 Ga if it is assumed the rock protoliths were derived from non-depleted mantle (i.e. T_{CHUR}) and 1.6–2.0 Ga if it is assumed the protoliths were derived from a depleted mantle source (i.e. T_{DM}). Our results are in broad accordance with model ages determined by Fischel et al. (1998) from rocks from the western Ribeira belt, although their T_{DM} values tend to fall into two groups: Paleoproterozoic (2.2–2.1 Ga) and Mesoproterozoic (1.5–1.4 Ga). They also agree with those of Söllner et al. (1991), who carried out a U–Pb study of zircons from the Juiz de Fora complex (i.e. the western Ribeira belt) and found all ages were 2.1 Ga or younger. Similarly, an Rb–Sr whole-rock isochron from the Piedade Gneiss yielded an age of 2.16 Ga (Teixeira, 1982). The lack of Archean model ages from the Ribeira belt distinguishes it from the Araçuaí belt and implies that it is not remobilized unmodified São Francisco cratonic material, but rather a separate terrane. The Abre Campo discontinuity is, therefore, a reasonable candidate for a major terrane boundary. Fischel et al. (1998) determined a model age (T_{DM}) of 897 Ma from an amphibolite (the Santo Antônio do Grama amphibolite) that lies along the Abre Campo discontinuity near our transect. This age and the basaltic nature of the amphibolite protolith suggest the Abre Campo discontinuity may represent a Brasiliano suture.

The ca. 1.95 Ga (T_{DM}) model ages for samples DC-20 and VN-55 [Fig. 4(D) and (E)] and the 2.1–2.2 Ga T_{DM} model ages determined by Fischel et al. (1998) and 2.26–1.80 Ga T_{DM} model ages determined by Nalini et al. (1998) may indicate that portions of the Ribeira belt were generated initially during the Transamazonian event. It should be remembered that T_{DM} ages are model ages that give the oldest possible time of extraction from the mantle. If the rocks of the Ribeira terrane had been extracted from a less depleted, or even undepleted mantle, the model ages would be significantly younger and approach the T_{CHUR} ages. T_{DM} and T_{CHUR} ages from the remaining samples analyzed from the Ribeira belt (SOB-1, SV1 and DM-12) are significantly younger than Transamazonian [Fig. 4(A)–(C)] and many of them approach the younger (1.4–1.5 Ga) T_{DM} ages obtained by Fischel et al. (1998) for rocks of the Ribeira belt just east of Abre Campo. These younger model ages hint at episodes of crust formation during the very long interval (ca. 1500 m.y.) between the Transamazonian and Brasiliano events. Among these possible events is the 1.75 Ga Espinhaço rifting event that occurred along the eastern margin of the São Francisco craton (Machado et al., 1992; Brito Neves et al., 1996) and the 0.9 Ga rifting and mafic extrusive event documented by Pedrosa-Soares et al. (1992) 200 km to the north. The only evidence for either rifting event at the latitude of our study is the model age (T_{DM}) of 897 Ma from the Santo Antônio do Grama amphibolite (Fischel et al., 1998) noted above. We suggest that the model ages may point towards post-Amazonian anorogenic magmatism at ca. 1.6±0.2 Ga (Cunningham et al., 1998). However, this possible interpretation must be judged with caution, as samples SOB-1, SV-1 and DM-12 are from penetratively sheared and locally migmatized gneisses that may not have remained closed Sm–Nd systems during peak Brasiliano metamorphism.

7. Conclusions

Our dates indicate the following.

(1) Transamazonian (~2.1 Ga) metamorphism accompanied juxtaposition of basement domes with supracrustal keels in the southern tip of the São Francisco craton, confirming structural evidence that a Transamazonian event occurred within the southern margin of the craton at this time.

(2) The region between the eastern edge of the southern São Francisco craton and the east coast of Brazil was metamorphosed to amphibolite and granulite facies, migmatized and anatectically melted during the Brasiliano orogeny between 589 and 538 Ma.

(3) The protoliths of the largely amphibolite to greenschist facies metamorphic rocks of the southern Araçuaí belt either formed during the Archean or were derived as sediments from an Archean terrane. Thus, the southern Araçuaí belt represents the stretched eastern margin of the São Francisco craton that was closed and thrust westward during the Brasiliano orogeny and possibly previously during the Transamazonian orogeny.

(4) The Dom Silvério Group, an oceanic metasedimentary and metaigneous unit exposed near the east edge of the southern Araçuaí belt, was derived from a Transamazonian source and was metamorphosed during Brasiliano deformation. This unit could represent ocean crust and marine sediments that formed between an offshore Transamazonian terrane (e.g. a magmatic arc constructed on an Archean continental basement sliver — perhaps similar to modern-day Japan) to the east and the São Francisco craton to the west.

(5) Model ages for the largely granulite-facies rocks of the Ribeira belt are late- to post-Transamazonian to Mesoproterozoic. The older protoliths may represent remobilized Transamazonian crust; the Mesoproterozoic protoliths in this belt may have formed during one or more post-Transamazonian/pre-Brasiliano orogenic/magmatic events.

(6) The Abre Campo discontinuity separates the southern Araçuaí belt of São Francisco craton derivation to the west from the Ribeira Belt of Transamazonian and younger affinity to the east and thus also appears to be a major boundary between terranes of different ages. Thus the strong possibility exists that there are two separate Precambrian sutures within the Araçuaí and the Ribeira Belts: the Dom Silvério Group and the Abre Campo anomaly. Unfortunately, determining whether one suture is Brasiliano and the other Transamazonian is difficult because of the strong Brasiliano amphibolite–granulite-grade recrystallization and structural overprint. Cunningham et al. (1998) suggested that the Abre Campo discontinuity represents a Brasiliano suture because Brasiliano thrust faults appear to steepen towards and root into that zone. However, the structural significance of the Dom Silvério Belt is uncertain and more work is needed to resolve the issue.

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