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New geochronological constraints on the geological evolution of Espinhaço basin within the São Francisco Craton—Brazil

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ABSTRACT

The São Francisco Craton, in the central-eastern region of Brazil, is a cratonic fragment stabilized after the Rhyacian tectono-metamorphic event (2.25–2.05 Ga). Volcanic and sedimentary rocks of the Espinhaço (Paleo- to Mesoproterozoic) and São Francisco (Neoproterozoic) basins crop out on this craton. In the northern sector of the craton, the Espinhaço basin crops out in two domains: the Northern Espinhaço Range and the Chapada Diamantina, that are separated by the Paramirim Corridor, a Brasiliano/Pan African (650–500 Ma) deformation zone, which crosses the craton in NNW–SSE direction. The stratigraphic framework of the Northern Espinhaço is characterized by eight synthems that comprise units bound by unconformities, or stratigraphic discontinuities with regional extent over the Espinhaço basin. These synthems are: Algodão, São Simão, Sapiranga, Pajeú and Bom Retiro (lower interval), São Marcos and Sítio Novo (intermediate interval) and Santo Onofre (upper interval). For each interval the sedimentary processes, the depositional systems, the filling style of the basin and the tectonic settings were evaluated, based mainly on the facies association characteristics and their lateral/vertical changes. Zircon U–Pb SHRIMP and basin analysis studies carried out along the eastern border of the Northern Espinhaço Range provide a few new or improved anchors upon which the tectonic evolution of the Espinhaco basin can be pinned. We identified Statherian rifting in the São Simão Synthem, by dating volcanic rocks at 1.73 Ga. This is followed by a previously unknown, minor intracratonic rift phase within the São Francisco Craton, dated at circa 1.57 Ga through a volcanic unit within the Pajeú Synthem. The entire lower interval is cut by mafic intrusive dykes of which we dated one at 850 Ma, which we correlate with a Tonian rifting phase affecting the eastern part of the São Francisco craton, and related to the break-up of the Rodinia Supercontinent. Our data show that the development of the Northern Espinhaço Range spans a large time interval, and comprises a discontinuous series of tectonic events that gave rise to the formation of the various synthems and are punctuated by the extrusion of minor volcanic units and emplacement of dykes within the eastern part of the São Francisco Craton.

1. Introduction

The Espinhaço basin occurs in the northern portion of the São Francisco Craton, occupying two physiographic domains: the Chapada Diamantina and the Northern Espinhaço Range (Fig. 1), as well as the western margin of the Araçuaí orogen at the eastern border of the craton. The basin records a polycyclic depositional history, with alternating episodes of distinct tectonic regimes over time. The rocks related to these various episodes have been ascribed to the Espinhaço Supergroup, which has a geological evolution spanning the Paleo- and Mesoproterozoic eras. The Espinhaço Supergroup underwent metamorphism and deformation during the Neoproterozoic Brasiliano Event, between 650 and 550 Ma (Schobbenhaus, 1996; Danderfer, 2000), providing a minimum age of deposition.

In the Northern Espinhaço Range, several stratigraphic models have been proposed, based on the characterization and interpretation of the various lithostratigraphic units (Schobbenhaus, 1972; Portela et al., 1976; Moutinho da Costa and Silva, 1980; Fernandes et al., 1982; Inda and Barbosa, 1978; Mascarenhas et al., 1984; Inda et al., 1984; Mascarenhas, 1990; Barbosa and Domingues, 1996; Schobbenhaus, 1993, 1996). Based on the recognition of regional unconformities or stratigraphic discontinuities, eight unconformity-bounded units (the synthems sensu Salvador, 1994) were recognized (Danderfer, 2000; Danderfer and Dardenne,

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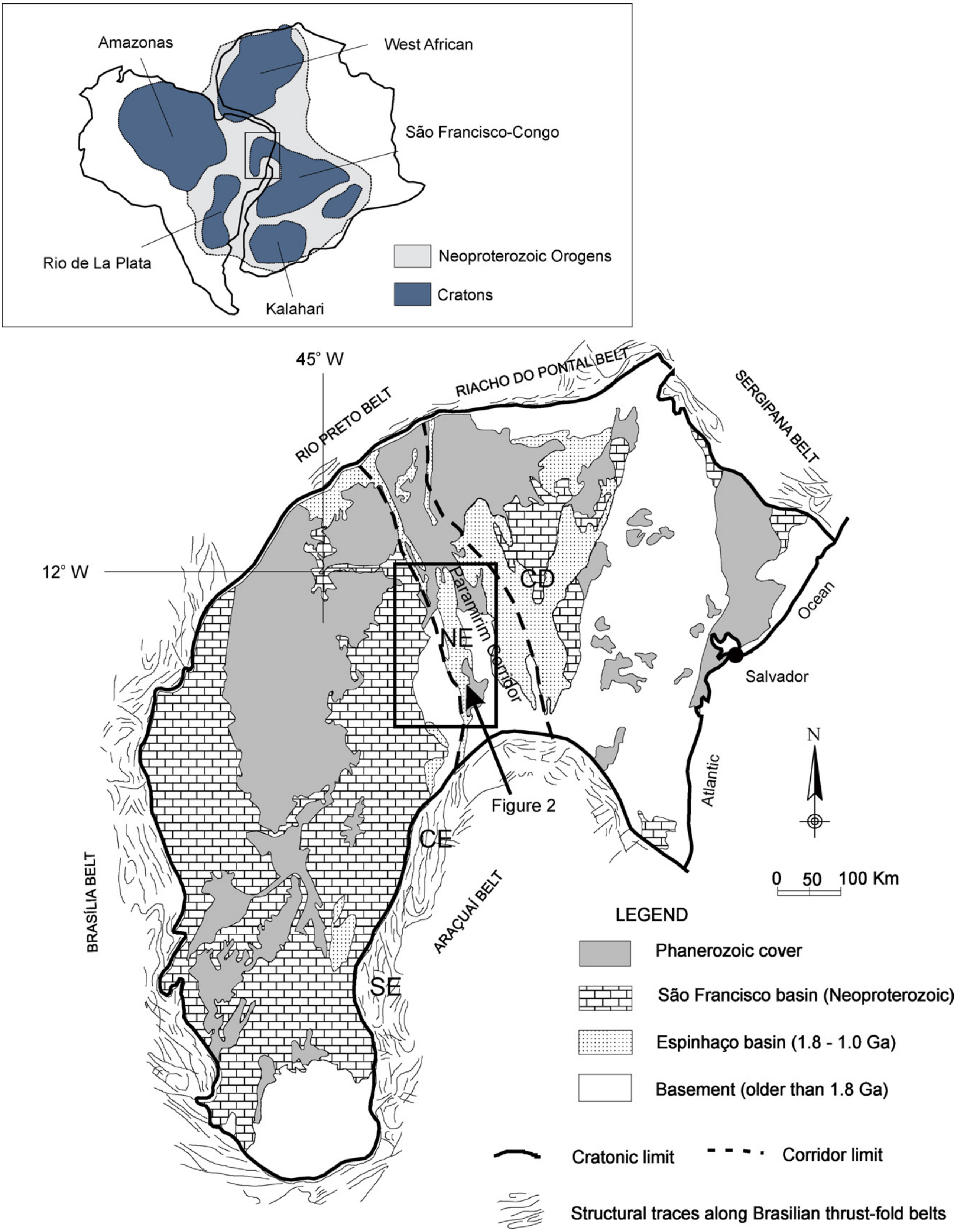

Fig. 1. São-Francisco Craton (modified after Almeida, 1977 and Alkmim et al., 1993). SE: Southern Espinhaço; CE: Central Espinhaço; NE: Northern Espinhaço; CD: Chapada Diamantina.

2002) within the Northern Espinhaço Range. These comprise from bottom to top: the Algodão, São Simão, Sapiranga, Pajeú and Bom Retiro of the lower interval, the São Marcos and Sítio Novo of the middle interval, and the Santo Onofre of the upper interval.

However, the rocks of the Northern Espinhaço basin still lack a chronostratigraphic framework, largely due to the absence of units suitable to date (i.e. felsic tuffs, cross-cutting intrusions and so forth). In this work we present new radiometric age data, obtained by the zircon U–Pb Sensitive High Resolution Mass Spectrometry (SHRIMP) method, for volcanic rocks that occur in the lower interval of the Northern Espinhaço and for a mafic intrusive cutting it. These new ages directly constrain the timing of extension and deposition in the Northern Espinhaço.

2. Geological setting

The Northern Espinhaço Range occurs in the northern portion of the São Francisco Craton (Fig. 1), which comprise several Archean and Paleoproterozoic terrains. This craton is considered to have stabilized after the Rhyacian tectono-metamorphic event between 2.2 and 2.0 Ga (Almeida, 1977) and is surrounded by Neoproterozoic thrust-fold belts resulting from the Brasiliano/Pan-African Orogeny (climax ranges from ca. 680 to 550 Ma; Teixeira et al., 2000). Alkmim et al. (1993) proposed the existence of a Brasiliano-aged deformation zone (the Paramirim Corridor), which crosses the craton in a NNW–SSE direction. This corridor is flanked by the Northern Espinhaço in the west, and by the Chapada Diamantina in the east (Fig. 1). There are many radiometric K–Ar dates through the Paramirim Corridor that indicate the thermal influence of the Brasiliano tecono-metamorphic event (e.g. Távora et al., 1967; Jardim de Sá et al., 1976a; Cordani et al., 1992), but there is no record of associated granite magmatism. Several zircon U–Pb lower intercept dates for rocks in the Paramirim Corridor further attest to the occurrence of a Brasiliano-aged event (e.g. Turpin et al., 1988; Pimentel et al., 1994; Schobbenhaus et al., 1994). The Paramirim Corridor divides the São Francisco Craton into two domains of opposing vergence, related to intracratonic inversion (Trompette et al., 1992; Alkmim et al., 1993; Danderfer, 2000).

In the Northern Espinhaço Range, four tectonic blocks have been defined based on NNW–SSE oriented faults that extend from the basement into the cover sequences. These are: (a) the Guanambi-Correntina Block, bound to the east by the Muquém fault; (b) the Ibotirama Block, bound by the Muquém fault and the Santo Onofre fault; (c) the Boquira Block, situated between the Santo Onofre and Carrapato faults and (d) the Paramirim Block to the east of the Carrapato Fault (Fig. 2, Danderfer, 2000). Tectonic inversion, dominated by compression along ENE–WNW axes, is best registered in the Ibotirama, Boquira and Paramirim blocks, which are part of the Paramirim Corridor (Fig. 2). A sinistral transpressive effect occurred during the last stages of basin inversion, and is recorded in all blocks, except fot the Guanambi-Correntina block, which is not involved in overall deformation.

The basement of the São Francisco Craton records a complex geological history. The main event, of Rhyacian age (approximately correlated in time to the Transamazonian Orogeny in the Northeast Amazonian Craton), is marked by widespread magmatism, migmatisation and medium- to high-grade metamorphism. The basement also contains sedimentary and volcano-sedimentary sequences, known as the Boquira and Riacho de Santana complexes (Fig. 2). Several authors regard this event to record the amalgamation of Archean and Paleoproterozoic crustal fragments older than 2.4 Ga, with associated metamorphism, deformation and magmatism in the interval between 2.2 and 2.0 Ga, and cooling extending up to 1.9 Ga (Barbosa and Sabaté, 2002, 2004; Barbosa et al., 2003, among others). Widespread alkalipotassic plutonism, dated around 2.05 Ga (U–Pb and Pb–Pb), would mark the last activities of the Rhyacian event in the São Francisco Craton (Conceição et al., 2002, 2003; Paim et al., 2002; Rios et al., 2005, 2007).

Along the Paramirim Corridor two contemporary and co-genetic felsic igneous events stand out: (a) the volcanism of the Rio dos Remédios Formation (along the western Chapada Diamantina) and (b) granite intrusions generally known as the São Timóteo Granite (in the south of the Paramirim block). Both have been dated by U–Pb and Pb-evaporation methods, yielding ages that vary between 1.75 and 1.71 Ga (Babinski et al., 1994, 1999; Pimentel et al., 1994; Schobbenhaus et al., 1994; Cordani et al., 1992; Turpin et al., 1988). This magmatism has been considered to be of anorogenic character and related to the evolution of an intracratonic extensional event, marking the beginning of the sedimentation of the Espinhaço Supergroup. In several other places of the South American platform there are granitoids with ages around 1.75 Ga, interpreted to indicate a continent-wide period of rifting (Brito Neves, 1995).

3. Northern Espinhaço tectonostratigraphy

According to Danderfer and Dardenne (2002), the Espinhaço basin is defined as: (a) polycyclic, characterized by several stratigraphic cycles related to stages of basin formation, (b) multitemporal, each cycle developed during a defined time-slice, and (c) polyhistoric, each cycle translates in a response to a certain geodynamic process.

In what follows, we present the synthems that make up the tectonostratigraphy of the Northern Espinhaço, from the oldest to the youngest, broadly from east to west (Fig. 3, see also Danderfer, 2000):

(a) The Algodão Synthem defines the first rifting episode in the region. The base of this synthem is characterized by conglomerates, rich in clasts of basement rocks, marking the basal unconformity. The sedimentation was mainly of alluvial fans, braided fluvial and "dry" aeolian systems. There is evidence of syn-sedimentary mafic volcanism. The maximum thickness of the synthem is 4000 m and some paleocurrent data suggest a source area situated to the east. It is possible that this unit is older than the felsic magmatism dated at 1.75 Ga, as we did not find felsic rock clasts in its sedimentary package.

(b) The São Simão Synthem is characterized by volcanic acid rocks that occur directly in unconformity on the crystalline basement. Its minimum thickness was evaluated at 250 m. The São Simão Synthem shows no contact relationships with the other units of the Espinhaço basin. Nevertheless, Danderfer (2000) suggested that the São Simão Synthem postdates the Algodão Synthem and is older than the Sapiranga Synthem. It is, however, possible that the São Simão Synthem forms part of the extensive acid magmatic record of the Rio dos Remédios Formation.

(c) The Sapiranga Synthem occurs directly on top of the Algodão rocks, and defines the evolution of a second rift basin. Its basal limit is marked by conglomerates containing pebbles of acid volcanic rocks similar to those in the São Simão Synthem. In the Sapiranga Synthem, sedimentary facies is similar to that in the Algodão Synthem, mostly alluvial fans, fluvial and aeolian "dry" systems. The whole succession measures more than 3000 m of thickness. In places volcanic rocks occur within the synthem.

(d) The Pajeú Synthem is characterized by the onset of renewed rifting. The base of this synthem is defined by an unconformity separating it from the underlying crystalline basement, except in the southern segment were it directly overlies the Sapiranga Synthem; it is marked in several areas by basal conglomerates. Sedimentary characteristics allow the distinction of two half-grabens, with fault borders striking E–W. In these sub-basins, the basal successions (Riacho Fundo Formation) were deposited by alluvial fans, braided fluvial and "dry" aeolian systems and

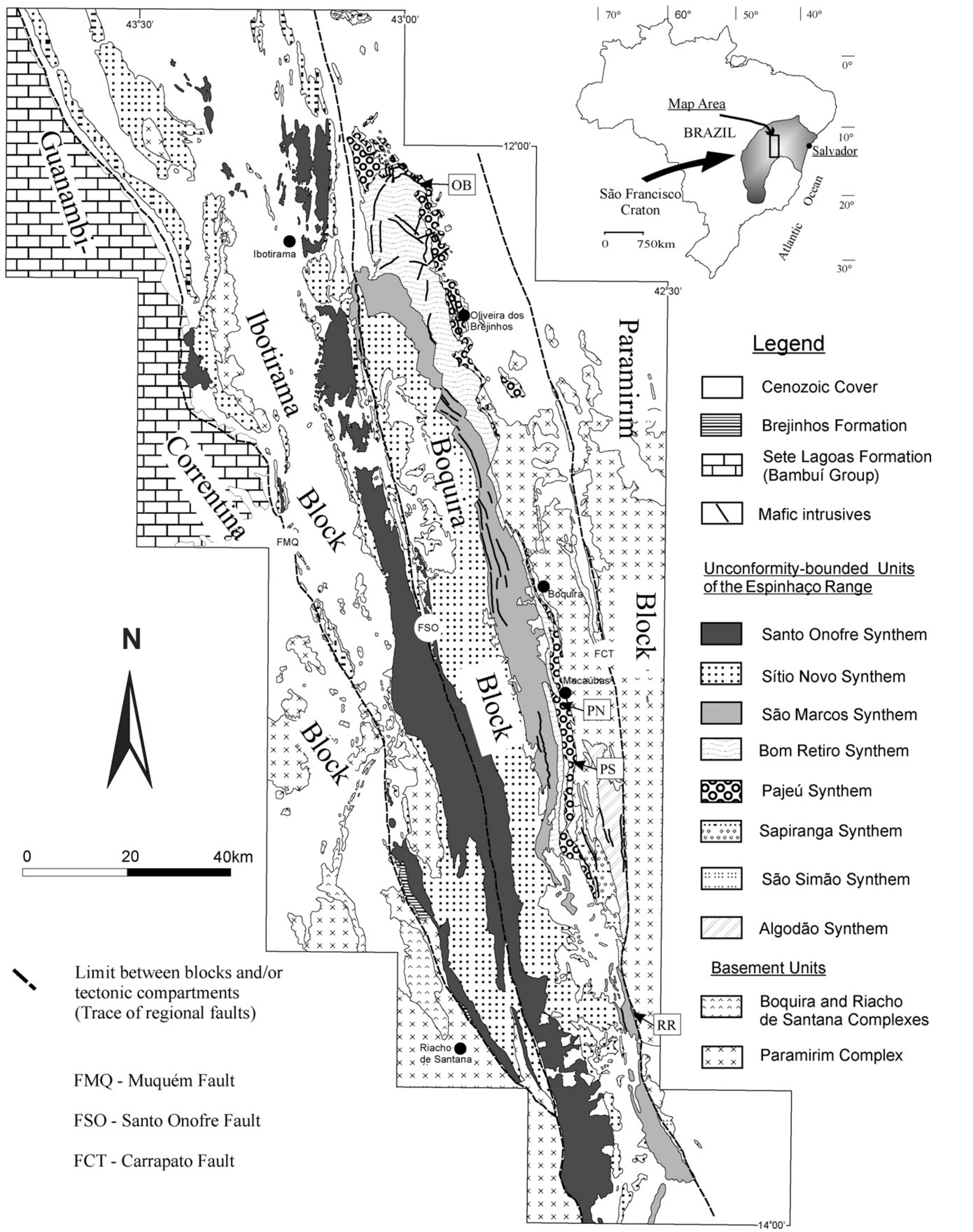

Fig. 2. Detailed map of the Northern Espinhaço, showing the location of the dated samples (OP: basic intrusive rocks; PN and PS: volcanic rocks from Pajeú Synthem; RR: volcanic rocks from São Simão Synthem).

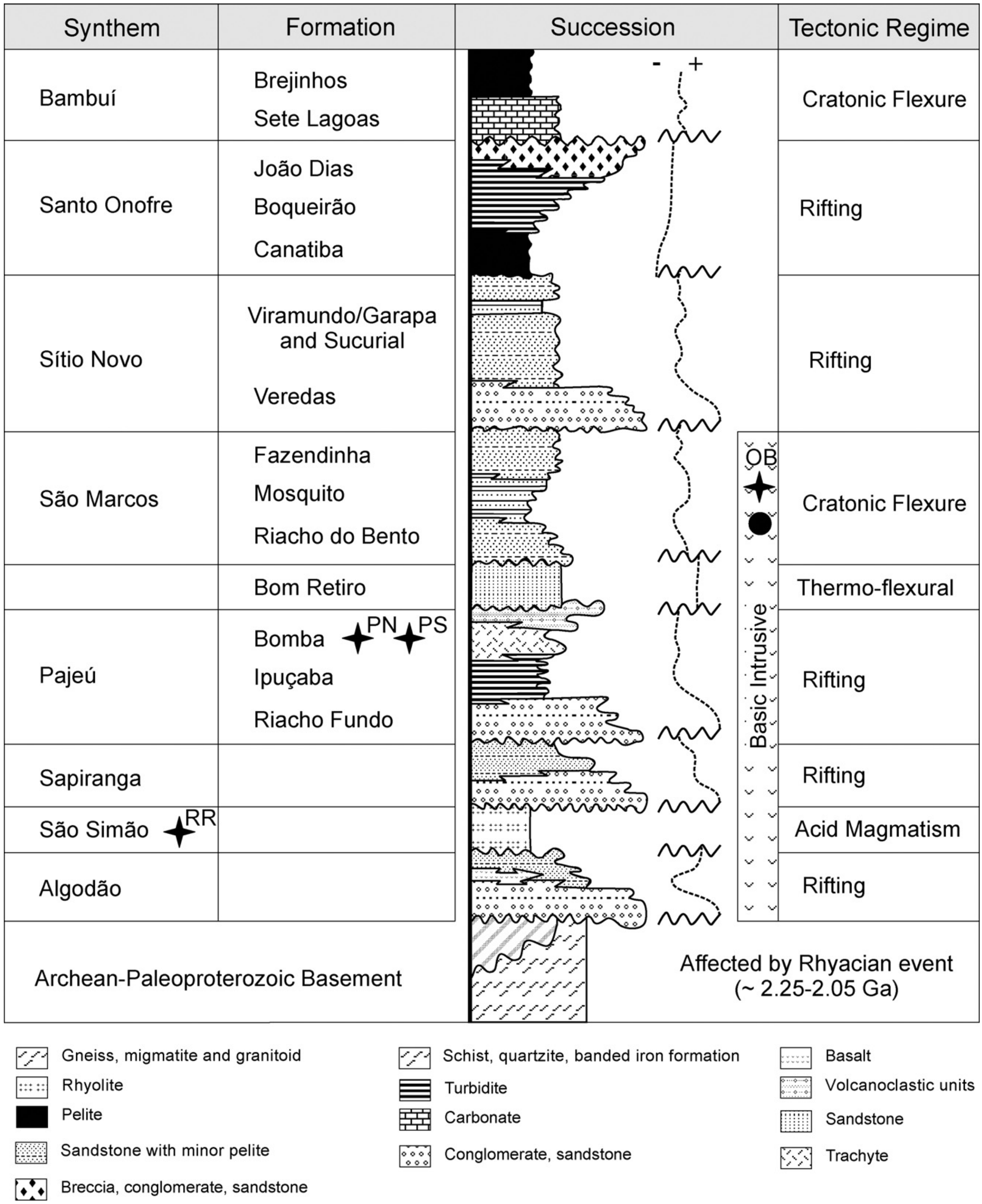

Fig. 3. Synthetic tectono-stratigraphic column of the Northern Espinhaço. The star symbols indicate dated samples: OB: basic intrusive rocks; PN and PS: volcanic rocks from Pajeú Synthem; RR: volcanic rocks from São Simão Synthem (tectono-stratigraphic columns adapted from Danderfer and Dardenne, 2002). The circle symbol indicate a K/Ar age of 1204 ± 58 age dated by Távora et al. (1967).

afterwards covered by a deltaic-lacustrine retrogradational system (Ipuçaba Formation); in the southern halfgraben, the top of the basin is characterized by intermediate volcanism of the Bomba Formation. The overall sequence that defines the Pajeú Synthem starts with gravely and sandy sediments with low degrees of textural and mineralogical maturity that fine upward into pelitic deposits. This succession is characterized by rapid facies variations, both lateral and vertical. The thickness in the depocenter, close to the fault borders, measures up to 2500 m. A hydrothermal phase is recorded during the final rift stage. The equivalent units to the Pajeú Synthem in the Chapada Diamantina are the Ouricuri do Ouro and the Lagoa de Dentro formations, both cut by basic intrusive rocks dated at 1514 ± 22 Ma (U–Pb; Babinski et al., 1999).

(e) The Bom Retiro Synthem rests in stratigraphic discontinuity above the Pajeú sequence and registers the development of a monotonous, texturally mature sedimentary succession, composed above all of quartz-sandstone, with only very subtle faciologic variations. It has a thickness varying about 500–4000 m, and comprises exclusively "dry" aeolian sedimentation. The succession occupies a continental interior sag, without associated tectonism. This basin stage is interpreted to be due to a thermoflexural process occurring soon after the initiation of the Pajeú rifting. The Bom Retiro Synthem can be correlated with the Mangabeira Formation in the Chapada Diamantina, which was deposited before 1.5 Ga (Babinski et al., 1999).

(f) The São Marcos Synthem fills in another wide sag basin, originated during a passive subsidence event. Its maximum thickness is registered around 9000 m. The thickness decreases to the north and to the south of the central depocentre, down to 2000 m on average. The evolution of this synthem can be interpreted by means of three depositional systems tracts, from base to top the Riacho do Bento, Mosquito and Fazendinha formations. The first, in direct contact with the Bom Retiro Synthem through a stratigraphic discontinuity, comprises a transgressive-gradational tract deposited in coastal and platformal shallow marine systems. The Mosquito Formation was deposited in marine-dominated deltaic conditions, and records a period of high sea-level. The Fazendinha Formation marks the return to a transgressive-gradational tract, with coastal and platformal shallow marine systems. The observed vertical profiles within these units vary depending on the sedimentary environment that originated them and, usually, do not contain coarse facies, nor sedimentary processes related to rift settings, such as mass flows of high density. The synthem is instead dominated by very fine to medium-grained sandstones. Given the thicknesses observed, sedimentation appears to have occurred under slow rates of subsidence in association with eustatic variations. The São Marcos Synthem could be correlated to the undated upper succession of the Paraguaçu Group (Ipupiara, Guiné and Açuruá formations) in the Chapada Diamantina (Table 2; Danderfer, 2000)

(g) The Sítio Novo Synthem is characterized by the in-filling of a north–south striking asymmetric rift, with the fault of Santo Onofre defining its western limit—a master border fault. Within this halfgraben geometry, its thickness is estimated up to 12,000 m. The base of this unit is marked by profound erosion of the upper parts of the São Marcos Synthem and characterized by basal conglomerates as well as depositional discontinuities. In-filling of this rift starts with the Veredas Formation, above all in the Boquira block, with deposits of alluvial plain, observed in the succession base, and of coastal zone in the top, these last with evidence of having occurred in conditions of high evaporation rates (paleoevaporites were interpreted in this stratigraphic interval by Danderfer, 2000). The remaining halfgraben fill (the more voluminous), defining the Viramundo Formation, is distinguished by deposits originated by systems that vary from littoral to shallow marine (siliciclastic ramp), with some deltaic influence in parts of the basin. Input processes range from those dominated by normal waves, tidal action and storms. The equivalent of this succession in the footwall is marked by the Garapa Formation rocks, in which littoral, platformal and shallow marine facies are identified. Locally carbonate rocks with stromatolites are recognized (Sucurial Member). The Sítio Novo Synthem can be correlated with the Chapada Diamantina Group of the Chapada Diamantina, deposited somewhere between 1.35 and 0.95 Ga (Jardim de Sá et al., 1976a; Brito Neves et al., 1979, 1980; Macedo and Bonhomme, 1984; Buchwaldt et al., 1999; Babinski et al., 1993; Rocha, 1997).

(h) The Santo Onofre Synthem registers the last basin formation event in the Northern Espinhaço. Its sedimentary signature is compatible with the development of a strike-slip basin under transtensional conditions. The successions occur in erosive and angular unconformity, or mark a clear depositional discontinuity with the underlying Sítio Novo Synthem rocks. Along the Muquém fault, the main border of this basin, halfgrabens formed that were infilled mainly by very coarse facies in fandeltaic systems (João Dias Formation). Along the main axis of the basin, interpreted as a hanging wall quill developed to the east of the halfgrabens, the infilling is marked by both rapid vertical and lateral faciologic variations, with very fine to very thick facies originating from gravitational flows of sediments of high and low densities, or hyperconcentrated flows. This succession, defined as the Boqueirão Formation, is interpreted to result from slope and slope-rise submarine fans. Part of the succession is comprised of very fine-grained deposits (the Canatiba Formation), mainly in the lower interval of the Santo Onofre Synthem, and corresponds to the slope-rise and basin floor deposits. The Santo Onofre Synthem measures more than 4000 m thick, although it is difficult to propose a precise value because of a high degree of tectonic shortening and erosion of the upper parts of this succession. This unit corresponds to the south to the upper sequence of the Macaúbas Group, in the Central Espinhaço, and probably to the Bebedouro Formation, in Chapada Diamantina, both interpreted to result from rifting of Tonian age, between 900 and 850 Ma. The minimum age of the Bebedouro Formation was estimated around 900 Ma (Macedo and Bonhomme, 1984), by K–Ar and Rb–Sr methods. Buchwaldt et al. (1999) dated detrital zircons extracted from diamictites of the Jequitaí Formation (a facies of the Macaúbas Group), using the Pb evaporation method, and they obtained three age populations: (a) 1.75 and 1.60 Ga, with larger frequency input at 1.70 and 1.75 Ga, (b) 1.20 and 1.15 Ga and (c) 0.9 and 1.0 Ga. These authors, and Toulkeridis et al. (1999) therefore suggested that deposition took place in the time interval 0.9–0.7 Ga.

Within the Northern Espinhaço and the Chapada Diamantina domains, countless bodies of mafic intrusive rocks (doleritic dykes and gabbro) occur, that exclusively crosscut the lower and middle units of the supracrustal successions. In the Northern Espinhaço range specifically, we do not observe intrusive rocks in the Sítio Novo and Santo Onofre synthems. Radiometric age data on these basic intrusive rocks point to several magmatic events occurring in the São Francisco Craton context, as follows: (a) 1714 ± 5 Ma (U–Pb; Silva et al., 1995); (b) 1514 ± 22 Ma (U–Pb; Babinski et al., 1999); (c) 1.2–1.0 Ga (K–Ar; Jardim de Sá, 1976b, Távora et al., 1967. Ar/Ar; Renne et al., 1990); (d) 906 ± 2 Ma (U–Pb; Machado et al., 1989); (e) 190–170 Ma (K/Ar; Dussin et al., 1995).

The Bambui Synthem represents a Neoproterozoic pelitic-carbonate sequence, part of the São Francisco basin (Fig. 1), that rests on the western part of the São Francisco Craton along the Guanambi-Correntina block; it does not occur in the Espinhaço range. It also occurs in the northern and eastern part of the Chapada Diamantina (locally known as the Salitre Formation). This sequence has been interpreted as foreland basin deposits related to the Brasília thrust-fold belt (e.g., Martins-Neto and Alkmim, 2001). In accordance with the works of Macedo and Bonhomme (1984) and Toulkeridis et al. (1999), the carbonates of the Salitre Formation would have been deposited between 850 and 750 Ma, as suggested by Rb–Sr dates from autigenic clay-minerals.

4. Materials and methods

4.1. Location and description of samples

We collected one sample of volcanic rock in the São Simão Synthem (sample RR), two from the Pajeú synthem (samples PN and PS), as well as a sample of a mafic intrusive in these successions (sample OB). The acid volcanic rocks of the São Simão Synthem crop out in three locations in the extreme southeast part of the Northern Espinhaço Range in a NNW-oriented shear zone. In general these units register strong deformation and are marked by a pervasive mylonitic fabric. Sample RR was collected in a roadcut between Igaporã and Tanque Novo, a few kilometers east of Caldeiras (Fig. 2). The rock is a rhyolite to rhyodacite, generally transformed into quartz-muscovite schist, with a porphyroclastic texture, containing phenocrysts of blueish quartz, disseminated in a very fine felsic matrix (Portela et al., 1976; Moutinho da Costa and Silva, 1980).

Samples PN and PS of the Pajeú Synthem were collected in two localities of the Bomba Formation, in the vicinity of Macaúbas and close to Pajeú (Fig. 2). They are volcanic rocks with trachytic composition and affinity varying from alkaline to peralkaline, as determined by Moutinho da Costa and Silva (1980), Jardim de Sá (1978) and Fernandes et al. (1982). They have textures varying from aphanitic, with a microcrystalline matrix, to porphyritic, containing prismatic phenocrystals of K-feldspar dispersed in the matrix. The rock is massive, and usually grayish in colour. Sometimes the rocks show trachytic texture, with feldspar crystals aligned along a preferential direction. Locally volcanic rock levels, rich in spherical or elliptic amygdales in-filled by quartz, were found. In some parts autobrecciation and hyaloclastic breccias were recognized. Some breccias have a fine-grained sandy matrix (i.e. peperite).

The mafic rock sample OB was collected in the NNE extremity of the Northern Espinhaço Range, near a place called Serra Negra, along a roadcut of the BR-242 highway (Fig. 2). In this locality a large mafic intrusive body cuts the rocks of the Pajeú Synthem, emplaced part as a dyke, part as sill. Metamorphism and deformation are low or absent in this part of the range. The rocks show coarse isotropic fabric constituted of pyroxene, amphibole and saussuritised plagioclase; biotite, ilmenite, titanite and quartz are accessory minerals.

5. Dating methods

The field samples were treated in the Sample Preparation Laboratory for Geochemistry and Geochronology of the Federal University of Ouro Preto. Each sample (40 kg) was crushed and milled. Afterwards, the heavy mineral fraction was separated by density using a pan. All steps of the process were done under clean conditions to avoid contamination. Zircon grains within the heavy fraction were picked and mounted in a custom-size epoxy mount, and polished mid-section to expose the grains. The mount was imaged using a camera system on a binocular microscope, and further imaged using SEM fitted with a Cathodo-Luminescence (CL) detector to better reveal internal zoning (Fig. 4). SHRIMP analysis follows standard methodologies similar to those elaborated upon by Nelson (1995). We calibrated our analyses to the BR266 standard (Stern, 2001), and monitored precision and accuracy by analysing the TEMORA2 standard as an unknown two times during

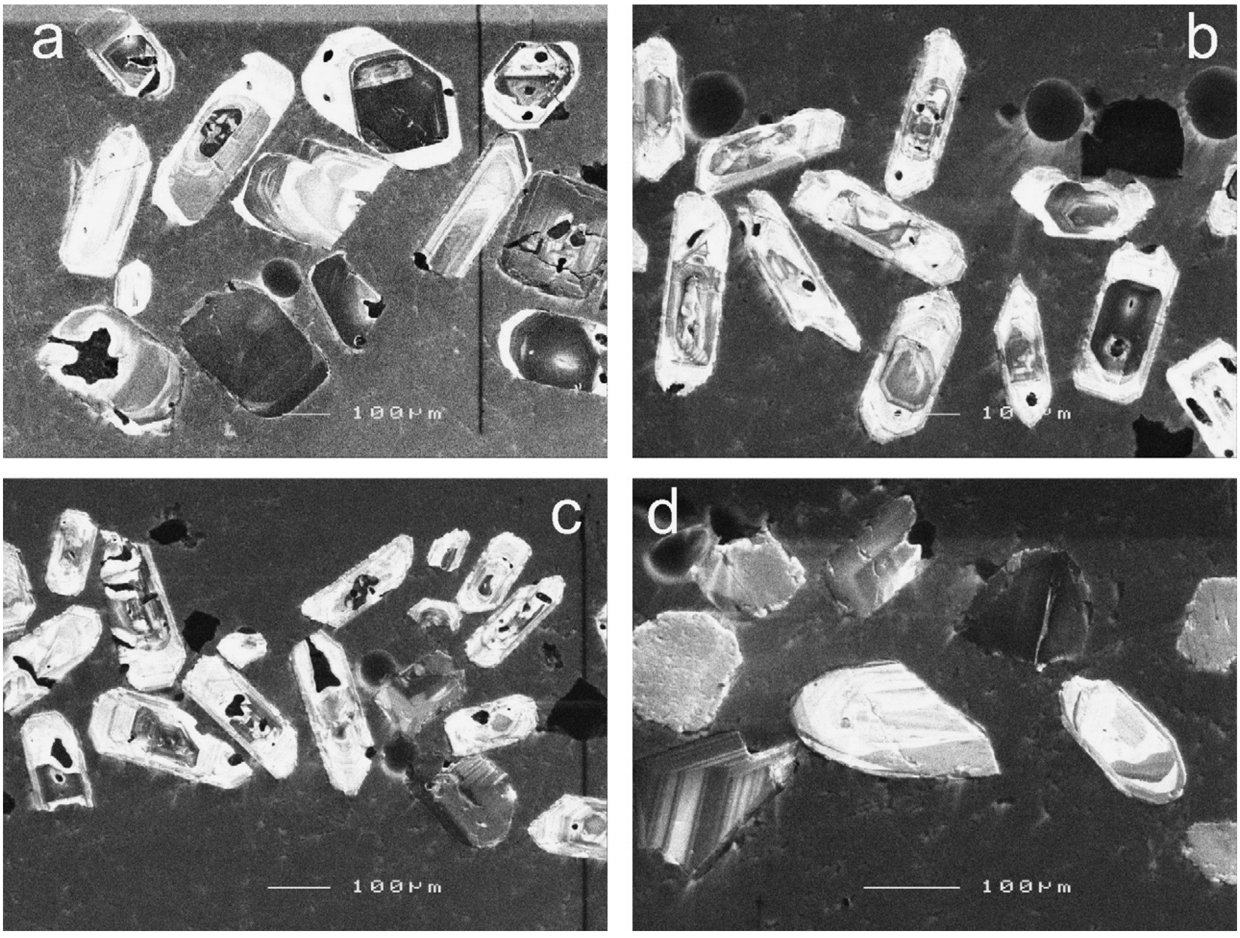

Fig. 4. Cathodo-luminescence imagery from typical zircon of samples (a) RR, (b) PS, (c) PN and (d) OB.

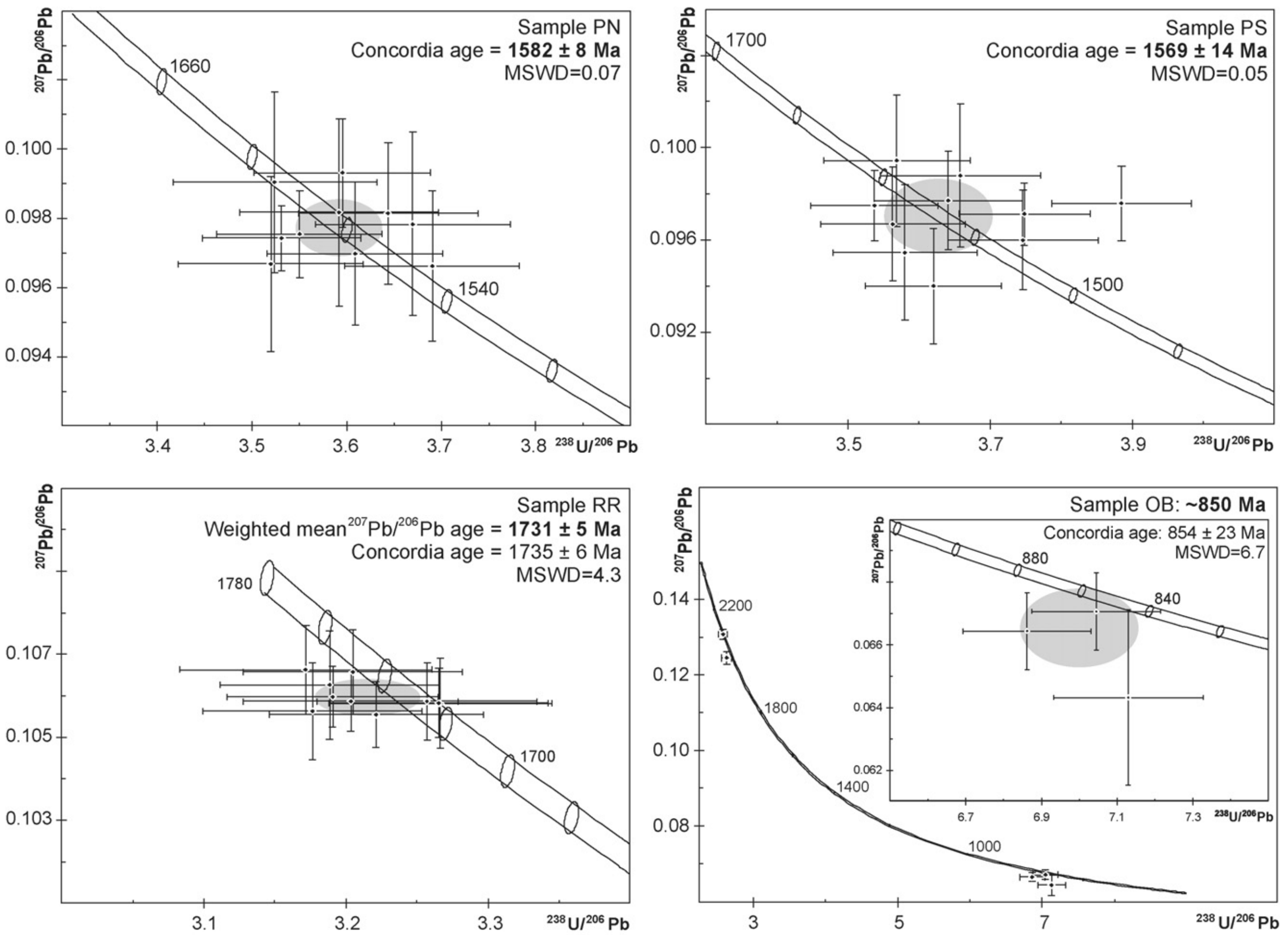

Fig. 5. Concordia plots of SHRIMP U–Pb isotopic analyses of zircon for samples OB: basic intrusive rocks; PN and PS: volcanic rocks from Pajeú Synthem; RR: volcanic rocks from São Simão Synthem. Error crosses are at 2 sigma confidence level; grey ellipse indicated the concordia age at 2 sigma confidence. All $^{206}Pb/^{238}U$ ratios include the error on the standard during the session.

the session. TEMORA2 yielded a concordia age of 414 ± 10 Ma (95% confidence, MSWD = 0.62), within error of its reported age of 416.8 ± 1 Ma (Black et al., 2004). SHRIMP data were reduced using Excel add-in Squid, and the data interpreted using Isoplot 3.53 (Ludwig, 2001a,b). The error of the decay constant was propagated during data reduction, as well as the error on the primary standard (BR266, 2σ error 0.68%). The error on standard is reported in the data table. Common Pb correction was based on measured ^{204}Pb using a common Pb composition appropriate for the age of the sample, calculated after Stacey and Kramers (1975). All pooled data are reported at 95% confidence level, while single analyses are reported at 1σ confidence level (Fig. 5 and Table 1). All data plots are shown at the 2σ confidence level.

6. Results

6.1. Sample RR

Zircon grains picked from sample RR range in size from 250 to 500 μm and have aspect ratios between 1:1 and 6:1. The crystals are euhedral and have well-developed crystal faces and terminations. The zircon grains range in colour from pale to dark yellow, and have small amounts of inclusions and cracks. CL imaging brings out well-developed internal zoning patterns interpreted to indicate crystallization from magmatic melt.

Ten concentrically zoned sectors from ten zircon crystals were analysed and indicate very low *f*206 values (proportion of non-radiogenic ^{206}Pb in total ^{206}Pb) below 0.03%. U and Th are in the ranges 317–849 and 145–588 ppm, respectively, giving Th/U ratios between 0.36 and 0.72, typical for magmatic zircon (Rubatto and Gebauer, 2000). Because there is a modest correlation between reverse discordance and *f*206 in some analyses, the slight amount of excess reverse discordance (outside 2σ analytical error) could be a result of overcorrection for common Pb component, due to either slight inaccuracy in measurement of ^{204}Pb or inappropriate common Pb composition. The data define a concordant cluster with a concordia age of 1735 ± 6 Ma and corresponding to a weighted mean $^{207}Pb/^{206}Pb$ age of 1731 ± 5 Ma (MSWD = 0.55). We interpret the latter to represent a reasonable estimate for crystallization of zircon in sample RR and emplacement of the rhyolite.

6.2. Sample PN

Zircon crystals from sample PN range in size from 50 to 250 μm, and have aspect ratios between 1:1 and 4:1. The zircon crystals are yellow to colourless, clear and contain minor inclusions and cracks. All crystals display well-developed crystal faces and most have bipyramidal terminations interpreted to reflect an igneous origin. CL imaging reveals clear concentric zoning patterns, with luminescence ranging from medium to high. All zircon crystals display single growth, and no inherited cores are recognized.

Ten zircon crystals were analysed and yielded U and Th contents in the ranges 61–466 and 27–368 ppm, respectively, giving Th/U

Table 1
Zircon U–Pb data.

Spot	^{204}Pb (cps)	*f*206 (%)	U (ppm)	Th	Th/U	^{206}Pb/^{238}U (±1σ)	^{207}Pb/^{206}Pb (±1σ)	^{206}Pb/^{238}U age (±1σ Ma)	^{207}Pb/^{206}Pb age (±1σ Ma)	C (%)
PN1-1	0.06	0.030	257	170	0.68	3.55995 ± 0.04392	0.09755 ± 0.00063	1596 ± 21	1578 ± 12	101.2
PN1-2	0.06	0.102	80	37	0.48	3.60191 ± 0.05252	0.09817 ± 0.00136	1579 ± 23	1590 ± 26	99.4
PN1-3	0.09	0.111	100	61	0.63	3.52944 ± 0.04887	0.09669 ± 0.00127	1608 ± 23	1561 ± 25	103.1
PN1-4	0.75	0.417	216	166	0.79	3.70041 ± 0.04592	0.09662 ± 0.00108	1542 ± 20	1560 ± 21	98.9
PN1-5	–	–	147	79	0.56	3.60551 ± 0.04677	0.09932 ± 0.00078	1578 ± 21	1611 ± 15	98.0
PN1-6	–	–	466	368	0.82	3.54113 ± 0.04196	0.09742 ± 0.00047	1603 ± 20	1575 ± 9	101.8
PN1-7	0.37	0.269	174	114	0.68	3.61892 ± 0.04630	0.09698 ± 0.00104	1573 ± 21	1567 ± 20	100.4
PN1-8	0.03	0.042	96	47	0.51	3.67994 ± 0.05133	0.09784 ± 0.00132	1550 ± 22	1583 ± 25	97.9
PN1-9	–	–	61	27	0.45	3.53373 ± 0.05379	0.09906 ± 0.0013	1606 ± 24	1606 ± 25	100.1
PN1-10	0.34	0.250	170	111	0.68	3.65383 ± 0.04725	0.09815 ± 0.00103	1559 ± 21	1589 ± 20	98.2
PS1-1	0.11	0.081	202	144	0.74	3.89563 ± 0.04932	0.09758 ± 0.0008	1473 ± 20	1578 ± 15	93.4
PS1-2	0.04	0.058	100	50	0.52	3.7564 ± 0.05289	0.09599 ± 0.00108	1522 ± 22	1548 ± 21	98.4
PS1-3	–	–	94	47	0.51	3.5782 ± 0.05152	0.09944 ± 0.00143	1589 ± 23	1614 ± 27	98.5
PS1-4	–	–	84	41	0.50	3.65119 ± 0.05222	0.09771 ± 0.00106	1560 ± 23	1581 ± 20	98.8
PS1-5	0.13	0.067	271	192	0.73	3.75831 ± 0.04622	0.09714 ± 0.00068	1521 ± 20	1570 ± 13	96.9
PS1-6	0.06	0.152	60	26	0.44	3.66816 ± 0.05635	0.09879 ± 0.00155	1554 ± 24	1601 ± 29	97.1
PS1-7	0.29	0.289	136	74	0.56	3.62995 ± 0.04790	0.09401 ± 0.00126	1569 ± 21	1508 ± 25	104.1
PS1-8	0.20	0.289	91	43	0.49	3.58982 ± 0.05083	0.09545 ± 0.00147	1584 ± 23	1537 ± 29	103.1
PS1-9	–	–	199	131	0.68	3.54688 ± 0.04486	0.09748 ± 0.00076	1601 ± 21	1577 ± 15	101.6
PS1-10	0.14	0.207	85	41	0.50	3.57246 ± 0.05090	0.0967 ± 0.00124	1591 ± 23	1561 ± 24	102.0
RR1-1	0.10	0.017	628	404	0.66	3.2301 ± 0.03767	0.10555 ± 0.00039	1739 ± 21	1724 ± 7	100.9
RR1-2	–	–	387	172	0.46	3.18038 ± 0.04457	0.10663 ± 0.00054	1762 ± 25	1743 ± 9	101.2
RR1-3	0.04	0.013	395	203	0.53	3.21362 ± 0.03854	0.10657 ± 0.0005	1746 ± 22	1742 ± 9	100.3
RR1-4	0.08	0.012	740	308	0.43	3.19924 ± 0.03712	0.10598 ± 0.00037	1753 ± 21	1731 ± 6	101.3
RR1-5	0.09	0.027	371	229	0.64	3.27544 ± 0.03931	0.10582 ± 0.00054	1718 ± 22	1729 ± 9	99.4
RR1-6	0.07	0.028	382	235	0.64	3.1851 ± 0.03861	0.10563 ± 0.00058	1760 ± 22	1725 ± 10	102.1
RR1-7	–	–	317	145	0.47	3.19716 ± 0.03873	0.10626 ± 0.00065	1754 ± 22	1736 ± 11	101.1
RR1-8	–	–	460	275	0.62	3.26592 ± 0.03866	0.10586 ± 0.00047	1722 ± 21	1729 ± 8	99.6
RR1-9	0.07	0.015	544	191	0.36	3.2744 ± 0.03840	0.10583 ± 0.00042	1718 ± 21	1729 ± 7	99.4
RR1-10	0.17	0.022	849	588	0.72	3.21213 ± 0.03784	0.10586 ± 0.00036	1747 ± 22	1729 ± 6	101.1
OB1-1	–	–	331	250	0.78	6.88133 ± 0.08439	0.06644 ± 0.00061	875 ± 12	820 ± 19	106.8
OB1-2	0.00	0.000	184	214	1.20	2.64024 ± 0.03325	0.12453 ± 0.00081	2070 ± 26	2022 ± 11	102.4
OB1-3	0.07	0.025	245	141	0.59	2.59022 ± 0.03179	0.13082 ± 0.00064	2105 ± 26	2109 ± 9	99.8
OB1-4	0.10	0.062	375	504	1.39	7.06405 ± 0.08556	0.06707 ± 0.00061	853 ± 12	840 ± 19	101.7
OB1-5	0.10	0.205	128	128	1.03	7.14877 ± 0.09863	0.06433 ± 0.0014	844 ± 13	752 ± 46	112.3

*f*206: the proportion of common ^{206}Pb in the total ^{206}Pb; Th/U: ^{232}Th/^{238}U; C: percentage of concordance. All ratios and ages corrected for common Pb using measured ^{204}Pb and composition appropriate to the age of the zircon (Stacey and Kramers, 1975). Standard error has been added in quadrature to Pb/U ratios. Analyses conducted during a single session (30/09/2002). 13 BR266 standard analyses yielded a 2σ error of the mean of 0.68%.

ratios between 0.45 and 0.82 typical for igneous zircon (Rubatto and Gebauer, 2000). *f*206 values are low, up to 0.42%. The data plot in a concordant cluster for which a concordia age of 1582 ± 8 Ma can be calculated which we consider a good estimate for the crystallization age of zircon in sample PN, and thus the extrusion age of the volcanic unit.

6.3. Sample PS

Zircon grains picked from sample PS range in size from 150 to 450 μm and have aspect rations between 2:1 and 5:1. The crystals are yellow in colour, and contain small numbers of inclusions and cracks. Most grains show a euhedral shape, with well-developed crystal faces and sharp tips, indicative of an igneous origin. CL imaging reveals well-developed oscillatory zoning patterns, in keeping with crystallization from a magmatic melt. Some crystals show a dark CL central sector, overgrown by concentrically zoned medium-CL zircon.

Ten analyses were conducted on ten zircons crystals, targeting the concentrically zoned sectors interpreted to have grown during magmatic crystallization. The data indicate low *f*206 values not exceeding 0.29%, and a narrow range of U and Th contents, 60–271 and 41–192 ppm, respectively. Th/U ratios are between 0.49 and 0.74, consistent with a magmatic character. Apart from data point 1, the data plot on concordia, allowing the calculation of a concordia age of 1569 ± 14 Ma, interpreted to date crystallization of zircon in the sample and extrusion of the rhyolite.

6.4. Sample OB

Few zircons crystals were recovered from sample OB. They range in size from 50 to 300 μm and have low aspect ratios no greater than 2:1. Most zircons crystals are subrounded in shape, while a few zircons crystals, although broken, display well-developed crystal faces and a euhedral shape. The zircons crystals range in colour from colourless to dark yellow, with the subrounded grains showing darker shades and a larger number of inclusions. CL imaging reveals a wide variety of response. The subrounded grains range from high CL to low CL, and show faint oscillatory zoning patterns. They are interpreted to represent various xenocrystic components, either detrital zircons derived from the metasedimentary succession, or zircon crystals derived from an underlying crystalline basement. The euhedral grains have low- to medium CL response, but show broad well-developed concentric zoning patterns consistent with magmatic crystallization.

Only five analyses were conducted, three on euhedral grains (analyses 1, 4 and 5) and two on subrounded grains (2 and 3). *f*206 values are low, up to 0.20%, and U and Th in the ranges 128–375 and 141–504 ppm, respectively. Th/U ratios are between 0.59 and 1.39 consistent with a magmatic character of all zircon. The subrounded zircon grains define concordant ^{207}Pb/^{206}Pb ages of 2108 ± 17 and 2022 ± 23 Ma (95% confidence), which can be interpreted as the minimum age of crystallization of these crystals, which are interpreted as xenocrystic components. The three data points from euhedral crystals define a loose cluster for which a concordia age of 854 ± 23 Ma can be calculated. The most concordant data point defines an identical $^{206}Pb/^{238}U$ age of 854 ± 23 Ma, while the inversely discordant data were taken on the zircon crystals with the highest U + Th content. We conclude that zircon in the mafic dyke crystallized around 850 Ma, dating the emplacement of the dyke within the succession.

7. Discussion

One of the big challenges in the study of Precambrian sedimentary basins relates to the difficulty in obtaining reliable age estimates. This is largely due to the total reliance on radiometric methods to date key stratigraphic units, whereas in Phanerozoic sequences one can also rely on biostratigraphic indicators to date lithologies and allow correlations. A sparsity of dateable marker lithologies in many basins, hamper a full appreciation of the time intervals associated with the deposition of the various sedimentary packages, as well as the time registered in the bounding unconformities. In fact, it is recognized that a regional unconformity can accumulate much more time than that spent to deposit the bounding units (the synthem).

In the Northern Espinhaço Range, Danderfer and Dardenne (2002) proposed several stratigraphic events, based on the recognition of synthems, each one related to basin tectonics. In addition, Danderfer (2000) tried to correlate the synthems of the Northern Espinhaço Range with the several lithostratigraphic units along de full Espinhaço Range (north, central, and south; see Fig. 1) and with the Chapada Diamantina, establishing at least six large stratigraphical cycles (Table 2). Our new and previously published age data allow to place some time constraints on the evolution of the Northern Espinhaço basin and provide grounds for some tentative correlations across the various physiographic domains (Northern, Central, and Southern Espinhaço and Chapada Diamantina).

The first geologic activity recorded after the Rhyacian orogeny comprises a series of rifting and extensional magmatic phenomena at ca. 1.8–1.7 Ga (Event I, Table 2). This includes the acid magmatism of the Rio dos Remédios Formation in the Chapada Diamantina, and the emplacement of São Timóteo Granite, in the southern Paramirim block (see Figs. 1 and 2). In the Southern Espinhaço this event is recognized in the Borrachudos Granite and the Conceição do Mato Dentro Metaigneous Unit (see Fig. 1). All these show ages between 1.77 and 1.71 Ga (Babinski et al., 1994, 1999; Pimentel et al., 1994; Schobbenhaus et al., 1994; Cordani et al., 1992; Turpin et al., 1988; Brito Neves et al., 1979; Machado et al., 1989; Dussin and Dussin, 1995; Buchwaldt et al., 1999). In addition to that, intrusive mafic rocks in the southern basement of São Francisco Craton were dated at ca. 1.71 Ga (Silva et al., 1995). In the Northern Espinhaço many of the basal sequences were thought to have been formed during Event I rifting, including the Pajeú Synthem. Our ages of 1582 ± 8 and 1569 ± 14 Ma for volcanic units within the Pajeú Synthem, however, clearly discount the attribution of this sedimentary package to Event I rifting. Our age of 1731 ± 5 Ma for a volcanic unit within the São Simão Synthem, on the other hand, proves that this unit was deposited during the same time-frame of the Event I extension. In the absence of age data for the under- and overlying synthems, we can only suggest that deposition of the Algodão Synthem occurred very early in the rift phase, while a rifting event post-dating 1.73 Ga gave rise to the Sapiranga Synthem (events IA, IB and IC, Table 2). Whether these various rifting stages correspond to widely spaced tectonic activity, or to various pulses of a single tectonic event remains unclear at present.

Table 2
Stratigraphical correlations between the various units of the Central and Northern Espinhaço and Chapada Diamantina (modified from Danderfer, 2000); NRI: unrecognized interval). Note that the events (tectonic units) are separated by unconformities (broken lines).

Event	Northern Espinhaço		Chapada Diamantina		Central Espinhaço
	Synthem	*Formation*			
VI	Santo Onofre	João Dias	Bebedouro Formation (Basal part of Una Group)		Chapada Acauã, Nova Aurora and Serra do Catuni Formations (Upper part of Macaúbas Group)
		Boqueirão			
		Canatiba			
V	Sítio Novo	Garapa	Morro do Chapéu and Caboclo Formation	Chapada Diamantina Group	Domingas, Rio Peixe Bravo and Duas Barras Formations (lower part of Macaúbas Group)
		Viramundo			
		Veredas	Tombador Formation		
IV	São Marcos	Fazendinha	Açuruá Formation	Paraguaçu Group (upper part)	NRI
		Mosquito	Guiné Formation		
		Riacho do Bento	Ipupiara Formation		
III	Bom Retiro	...	Mangabeira Formation	Paraguaçu Group (intermediate part)	NRI
II	Pajeú	Bomba	NRI	Paraguaçu Group (lower part)	NRI
		Ipuçaba	Lagoa de Dentro Formation		
		Riacho Fundo	Ouricuri do Ouro Formation		
IC	Sapiranga	...	NRI		NRI
IB	São Simão	...	Rio dos Remédios Formation (or Group)		
IA	Algodão	...	NRI		

After this first series of rifting events (Events IA, IB and IC), a long period of non-deposition, and thus profound erosion, occurred, as evidenced by our ages of 1582 ± 8 and 1569 ± 14 Ma for volcanic units within the Pajeú Synthem. The volcanism of the Pajeú rift (Bomba Formation) defines a hitherto unreported geological event in the São Francisco Craton, which we interpret to represent renewed rifting at ca. 1.57 Ga. The only exception concerns a generation of anorogenic tin granites dated at 1.56 Ga (Pimentel et al., 1991, 1999; Pimentel and Botelho, 2001) in the Brasília belt at the western border of São Francisco Craton (see Fig. 1). The wide age-gap between Event 1 and Event 2 rifting is supported by profound erosion of the sequences deposited during Event I, mainly of the Rio dos Remédios Formation in the Chapada Diamantina. The base of the Pajeú Synthem in the Northern Espinhaço as well of the Ouricuri do Ouro Formation in the Chapada Diamantina is marked by conglomerates containing clasts interpreted to have been derived from the Rio dos Remédios Formation. Although no volcanism has been reported for the Chapada Diamantina, precluding a chronostratigraphic correlation with the Northern Espinhaço, the Ouricuri do Ouro and Lagoa de Dentro formations of the Chapada Diamantina represent part of Event II rifting, being well correlated with the Riacho Fundo and Ipuçaba formations of the Espinhaço Range, respectively. Equivalent units have not been reported from the southern prolongation of the Espinhaço range.

Event III includes aeolian deposits formed on formations correlated to the Pajeú Synthem, namely the Bom Retiro Formation (or synthem) in the Northern Espinhaço, and Mangabeira Formation in the Chapada Diamantina. In the latter, mafic sills were dated at ca. 1514 ± 22 Ga (Babinski et al., 1999). Event III deposition therefore occurred soon after Event II, supporting the interpretation of Danderfer (2000) of the Bom Retiro Synthem to reflect a thermo-flexural phase in response to Pajeú rifting.

No direct time constraints can be proposed for Events IV and V, but it has been suggested that these events took place between 1.5 and 0.9 Ga. Danderfer (2000) has related these events to flexural (or thermo-flexural) and rifting process, respectively.

Event IV was responsible for deposition of the São Marcos Synthem in Northern Espinhaço and the top of Paraguaçu Group (Ipupiara, Guiné and Açuruá Formations) in the Chapada Diamantina. Unfortunately neither unit has any dateable material.

Event V is related to the NNW striking rifting and deposition of Sítio Novo Synthem in Northern Espinhaço and Chapada Diamantina Group in the Chapada Diamantina, the first occupying the basin depocenter along the Santo Onofre master fault. Also here, no suitable material for dating has been identified. However, in the Sucurial Member (included in the Garapa Formation, top of the Sítio Novo Synthem) stromatolites were found that could be correlated to the stromatolite horizons occurring in the Caboclo Formation (intermediate succession of Chapada Diamantina Group), which provided ages of 1140 ± 140 Ma (Babinski et al., 1993). Srivastava (1989, in Rocha, 1997) has estimated an interval of 1.35 to 0.95 Ga for the formation of these stromatolites. Diagenetic ages obtained in illite present in shales of the Caboclo Formation suggest a minimum age of 950 Ma (Jardim de Sá et al., 1976a,b; Macedo and Bonhomme, 1984; Buchwaldt et al., 1999). In contrast, Battinlani et al. (2005) and Battilani et al. (2007) reported an Ar/Ar age of 1515 ± 3 Ma for metasomatic muscovite in NNW–SSE-striking dykes and sills crosscutting or intercalated within the Chapada Diamantina Group, interpreted as the minimum age of intrusion. Providing a robust age for the deposition of the Chapada Diamantina Group would help define the timing of rifting related to event V.

In the Northern Espinhaço, a network of several generations of mafic intrusive rocks have been recognized, emplaced as dykes and sills in the São Marcos Synthem and units below. A similar network of mafic intrusions occurs in the Chapada Diamantina, where the mafic rocks occur only below the base of the Chapada Diamantina Group, without cutting this unit. In addition Danderfer (2000) has described dark, lithic wacke to lithic arenites (graywackes in the older classifications) in the base of the Sítio Novo Synthem, probably derived from rocks of mafic composition. A few ages were reported for mafic rocks in the northern São Francisco Craton. In the Northern Espinhaço Távora et al. (1967) reported a K/Ar age of 1204 ± 58 Ma (whole rock; recalculated by Brito Neves et al., 1980) for a mafic intrusive in the basal sedimentary interval (in Pajeú and Bom Retiro Synthems). In the Chapada Diamantina Jardim de Sá et al. (1976b) reported a K/Ar age of 1111 ± 56 age (plagioclase; recalculated by Brito Neves et al., 1980) for a gabbro stock intrusive in the Mangabeira Formation (equivalent to Bom Retiro Synthem). Both of these sample locations are characterized by Danderfer (2000) to record very low metamorphic grades, below the closing temperature for Ar in plagioclase, so these determinations may possibly be related to the crystallization ages of the intrusions. These ages might be related to event V in the Northern Espinhaco, but more data are needed to confirm them.

In our study we report for the first time a robust emplacement age of 854 ± 23 Ma for mafic igneous rocks in the Northern Espinhaço. However this dyke was observed intruding only rocks of the Bom Retiro and Pajeú Synthems, and the age does not help to constrain the deposition of the younger events and units. In fact it suggests a much younger minimum age of development of the São Marcos Synthem at 0.85 Ga. Related to this intrusion age, Machado et al. (1989) obtained an age of 906 ± 2 Ma (U–Pb) for mafic intrusions (Pedro Lessa Metabasic Suite) in the lower interval of the succession in the Southern Espinhaço. Pedrosa-Soares et al. (1998) reported a Sm–Nd age of 816 ± 72 Ma for orthoamphibolites in the central Espinhaço, and interpreted these rocks as ophiolites. Moreover, along the northeastern basement of the Araçuaí Belt a series of anorogenic granites intrude into Paleoproterozoic orthogneisses that comprises the Salto da Divisa Granite Suite. These anorogenic plutons have been related to the initial rifting and dated around 875 ± 9 Ma (U–Pb) by Silva et al. (2008). During Event VI, deposition of the Santo Onofre Synthem occurred along the northern Espinhaço segment. This unit has been correlated to the south to the Macaúbas Group with similar interpretation (Schobbenhaus, 1996; Danderfer, 2000). Some detrital zircons with ages between 1.0 and 0.9 Ga were found in the sediments of this unit (Buchwaldt et al., 1999; Pedrosa-Soares et al., 2000), placing a maximum depositional age at 0.9 Ga. We suggest that the 0.85 Ga dyke set could reflect a rifting phase, marking the last basin formation stage in the Northern Espinhaço.

After event VI, tectonic inversion of the whole basin took place, between 650 and 500 Ma—the Brasiliano Orogeny (Távora et al., 1967; Jardim de Sá et al., 1976b; Brito Neves et al., 1979, 1980; Cordani et al., 1992; Pimentel et al., 2001; Toulkeridis et al., 1999, among others).

8. Conclusions

The new geochronological data obtained for the Northern Espinhaço allows for some age constraints on the basin formation stages, with new tectonic implications for the evolution of the São Francisco Craton. Although very restricted in occurrence, we confirm the existence of acid volcanism of Statherian age, related to the São Simão Synthem, which shows an age of 1.73 Ga. The São Simão Synthem, together with the Algodão and Sapiranga synthems occurring respectively below and above it, could be related to an important extensional event recorded throughout the São Francisco Craton, about 250 Ma after the Rhyacian event.

The volcanic rocks of the Bomba Formation, mapped in the top of the Pajeú Synthem, give an age around 1.57 Ga, which represents renewed rifting and a second cycle of sedimentation in the cratonic segment. In fact, this is a new paradigm for the São Francisco Craton evolution, because until now, similar ages have not been reported for the Southern Espinhaço Range nor the Chapada Diamantina.

Previous work has attributed the opening of the Espinhaço basin to Statherian rifting alone. The difference of ca. 160 Ma between the São Simão and Bomba volcanic events suggest that we cannot relate all sequences to a unique rifting process, but that instead the northern Espinhaço basin developed during at least three different rifting events (∼1.73, ∼1.57 and ∼0.85 Ga). Another event of rifting, not yet dated and related to the sedimentary succession of Sítio Novo Synthem must have happened at some time between 1.57 and 0.85 Ga, with some fragile evidence for 1.2 Ga.

Our newly reported age of 0.85 Ga relates to a previously unrecognized stage of rifting in the northern São Francisco Craton. Our data support the idea of a NNW–SSE trending aulacogen related to the breakup of a supercontinent (the São Francisco–Congo paleocontinent), called the Santo Onofre Aulacogen (e.g., Schobbenhaus, 1996; Danderfer, 2000; Silva et al., 2008).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2009.01.002.

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