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Constraints on the Statherian evolution of the intraplate rifting in a Paleo-Mesoproterozoic paleocontinent: New stratigraphic and geochronology record from the eastern São Francisco craton

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ABSTRACT

An integrated approach of stratigraphic analysis and U–Pb age dating reveals some information on the tectono-sedimentary evolution of the Statherian cover of the São Francisco craton in the so-called Espinhaço basin (Atlantic shield in eastern Brazil). Here, continental sedimentation patterns, such as alluvial fan, braided-plain and lacustrine facies associations, with associated volcanic rocks are documented in two superposed basin fill-successions, which are defined as the Algodão and Sapiroanga Synthem and grouped in the Botuporã Supersynthem. Both studied units consist mainly of conglomerates and cross-bedded sandstones and minor amounts of mudstones, sedimentary breccias, volcanic lava beds and volcanoclastic rocks, which were deposited in a rift basin – the Botuporã rift – during two syn-rifting phases. The Algodão Synthem represents the first rifting phase. The basal synsedimentary conglomerates of this unit were deposited mainly by subaerial debris flows, most likely along and near a rift border fault. The framework of this rock consists of only crystalline rock clasts from the basement and no fragments of volcanic rocks. Detrital zircon grains that were extracted from this facies show ages older than 2.05 Ga. The remainder of the section is dominated by fluvial sandy lithofacies with minor conglomerate lenses and sandstone–mudstone heterolithic lithofacies, which represent distal, waning-flood deposits in a lacustrine environment. The upper section also contains hummocky cross-stratified sandstone lithofacies, which are related to a storm-influenced deposition. On top of the Algodão succession, the volcanic rocks were dated at 1775 ± 7 Ma, which was interpreted as the near final age of the first rift-phase. Representing the second rift-phase, the Sapiroanga Synthem shows similar sedimentation patterns to the Algodão Synthem. The Sapiroanga Synthem rests directly on the volcanic rocks of the Algodão Synthem, and its basal conglomerates (which are most likely also related to a master fault) contain voluminous clasts of volcanic rocks, sandstones and crystalline rocks. The detrital zircon grains that were extracted from this facies show ages of 1741 ± 14 and 1766 Ma as well older than 2.05 Ga. The volcanic rocks on the upper succession of the Sapiroanga Synthem record ages of 1740 ± 10 Ma, which finalized the Botuporã rift evolution. A preliminary geochemical study of volcanic rocks from the Botuporã Supersynthem showed that these rocks are alkaline rocks with high K_2O/Na_2O ratios, which belong to an ultrapotassic suite. The low concentrations of MgO wt.% suggest a felsic ultrapotassic character. The Botuporã Supersynthem is unconformably covered by a volcano-sedimentary rift-succession of EoCalymmian age – the Pajeú Synthem, which represents the second rifting stage of the Espinhaço basin. Several Statherian-related volcano-sedimentary sequences and anorogenic granitoids occur dispersed in the São Francisco block, which requires a regional geologic model to explain the extensional and magmatism process during this time. We used the last Columbia paleocontinental reconstruction to constrain these processes by relating them to far-field continental extensional and magmatic record as part of a silicic LIP, which was triggered by the convection-driven tectonic-plate motion on the western border of the Atlantica block inside of the Columbia supercontinent.

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1. Introduction

One of several major continental blocks in the West Gondwana assembly is the São Francisco–Congo paleocontinent (SFCP) (Fig. 1). It comprises two main cratonic areas (the São Francisco craton and the Congo craton) and the surrounding Neoproterozoic orogens (Trompette, 1994). The basement of this paleocontinent was consolidated after the

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Fig. 1. Geological configuration of the Espinhaço aulacogen in the northern São Francisco craton that is bordered by Brasiliano fold-and-thrust belts: Araguaia (AB), Rio Preto (RB), Riacho do Pontal (RPB), Sergipano (SB), Araçuaí (ArB), and Brasília (BB). The inset caption indicates the location of the map in the tectonic scenario of West Gondwana (modified from Alkmim et al., 1993; Bizzi et al., 2003; Peres et al., 2004; Alkmim et al., 2006, 2007). The cover related to the so-called Espinhaço basin occurs in the following physiography domains: Chapada Diamantina (CD), Northern Espinhaço (NE), Central Espinhaço (CE) and Southern Espinhaço (SE).

Rhyacian orogeny and included Archean terranes, Paleoproterozoic sedimentary basins and magmatic rocks (older than 2.0 Ga). The consolidation of this basement was followed by several episodes of intraplate basin formation and related magmatism (e.g., Danderfer et al., 2009; Chemale et al., 2012; Santos et al., 2013), which must have occurred in a Paleo-Mesoproterozoic supercontinent, which is currently defined in the literature as the Columbia supercontinent (Rogers and Santosh, 2002; Zhao et al., 2002). However, although this subject has

been discussed in the literature, there remains no consensus about the position of the SFCP in this huge landmass, and several hypotheses have been proposed since its definition (e.g., Rogers and Santosh, 2004; Zhao et al., 2004; Hou et al., 2008a; Yakubchuk, 2010; Meert, 2012; Zhang et al., 2012). A probable reason is the lack of reliable geological, geochronological and paleomagnetic data for the SFCP from the interval of 1.8–1.3 Ga, during which the Columbia supercontinent is believed to have existed.

The Espinhaço basin in the eastern SFCP comprises a thick basin-fill succession of Paleo-Mesoproterozoic sedimentary and volcanic rocks (Schobbenhaus, 1993, 1996). The northern extension occurs in the São Francisco craton as the Espinhaço aulacogen (Moutinho da Costa and Inda, 1982) and includes the Northern Espinhaço and Chapada Diamantina physiographic domains, which are separated by the Paramirim valley (Fig. 1). The southern segment includes the Southern and Central Espinhaço ranges and integrates the western fold–thrust belt of the Neoproterozoic Araçuaí orogen (Alkmim et al., 2006, 2007). The generation of the Espinhaço basin has been attributed to a Statherian rifting based on U–Pb ages of acid volcanic rocks (e.g., Brito Neves et al., 1979; Machado et al., 1989; Cordani et al., 1992; Babinski et al., 1994; Pimentel et al., 1994; Schobbenhaus et al., 1994; Dussin and Dussin, 1995; Babinski et al., 1999) and the related anorogenic granitoids (Turpin et al., 1988; Cordani et al., 1992; Dussin et al., 1993; Pimentel et al., 1994; Silva et al., 2002a, 2002b; Delgado et al., 2003; Noce et al., 2007; Costa, 2013).

Martins-Neto (2000, 2009) and Martins-Neto et al. (2001) considered the tectonics and the sedimentation of the Southern Espinhaço in one Paleo-Mesoproterozoic rift-sag basin evolution. Recently, based on U–Pb detrital zircon ages, Chemale et al. (2012) interpreted that two basin-fill successions formed in this domain under intraplate conditions: (i) the older succession is marked by the Statherian volcano-sedimentary sequence; and (ii) the overlying sequence characterizes a Stenian rift-sag basin. With respect to Northern Espinhaço, Danderfer and Dardenne (2002) characterized several unconformity boundary units (synthems), each of which is related to a tectono-stratigraphic stage of basin formation. Aside from the Statherian volcanism (São Simão Synthem), which occurred on the basement rocks south of the Paramirim valley, Danderfer et al. (2009) have dated the volcanic rocks (Bomba Formation, uppermost unit of Pajeú Synthem) in the Northern Espinhaço domain that is related to a Calymmian rift stage, which was not detected in the Southern Espinhaço. Under the Pajeú Synthem, two other unconformity boundary units, namely Algodão (basal) and Sapiranga Synthems, occurred, which certainly marked the early-stage rifting in the Espinhaço aulacogen (Fig. 2). Both units are characterized by a thickness of hundreds to thousands of meters and sedimentary–volcanic successions that are well exposed on the east side of Northern Espinhaço with uncertain temporal relationships to the volcanism of both the São Simão and Pajeú Synthems (Danderfer, 2000; Danderfer and Dardenne, 2002).

The imprint of the Statherian rifting and acid magmatism on the São Francisco crustal block has also been documented in the northern basement of the Brasília belt (e.g., Pimentel et al., 1991). Other records could have occurred and scattered across this block, but younger cover precludes their observation. Moreover, further characterization and better temporal resolution of the events that are related to the Statherian rifting are necessary to clarify the geological evolution of the SFCP. The elucidation of this question is relevant for understanding the Espinhaço basin and the context of the SFCP in a possible Paleo-Mesoproterozoic supercontinent during Statherian.

The focus of this investigation is to describe the stratigraphic successions from the Algodão and Sapiranga Synthems, present new geochronological data that constrain the ages of both units and present geochemical data for volcanic rocks. The objectives of this study are to understand the older-than-Calymmian basin-fill successions and to compare similar volcano-sedimentary sequences and the related magmatism that occurs in the eastern São Francisco crustal block. The ultimate goal is to examine the context of the SFCP in the reconstruction of Columbia.

2. Geological setting

The São Francisco block corresponds to the western continental crust part of the SFCP (Fig. 1), which was believed to be totally individualized from the fragmentation of a Rodinian supercontinent between

1.1 Ga and 750 Ma (e.g., Dalziel, 1991; Moores, 1991; Hoffman, 1991; Dalziel, 1995; Torsvik et al., 1996; Meert, 2001; Torsvik, 2003; Meert and Torsvik, 2003; Rino et al., 2008; Bybee et al., 2010). The oceanic crust that was originally part of this paleoplate was totally consumed during the Brasiliano–Pan African orogeny at the end of the Neoproterozoic (i.e., mainly during the Ediacaran), which produced marginal magmatic arcs and fold–thrust belts and finally integrated into the Gondwana paleocontinent (e.g., Pedrosa-Soares et al., 2001; Alkmim et al., 2007; Meert, 2003). The São Francisco block in Fig. 1 schematically represents the limit of the deformed and undeformed cover and basement rocks, which in turn would be part of the western portion of SFCP, serving only as an initial reference framework. Brasiliano granites (related mainly to the consumption of a Neoproterozoic oceanic lithosphere) predominate within the crystalline cores, which in part may also contain recycled crust. In addition, tectonic nappes and accretion of terranes mainly along the south and southwestern Brasília belt greatly complicate this reconstruction (e.g. Fuck et al., 2014).

The São Francisco craton delimits the area of basement rocks preserved from Brasiliano–Pan African orogeny (Almeida, 1977). All marginal belts show tectonic vergence to cratonic areas with basement rocks involved on the cover deformation (Alkmim et al., 1993). The sedimentary cratonic cover shows only thin-skinned deformation near the marginal belts (Alkmim et al., 1993; Alkmim et al., 1996). In the northern Espinhaço aulacogen (Moutinho da Costa and Inda, 1982; others call it Santo Onofre – Schobbenhaus, 1996, or Paramirim aulacogen – e.g., Alkmim and Martins-Neto, 2012), an intracontinental deformation partly with basement-involved tectonics occurred along the so-called Paramirim Corridor (Fig. 2; Alkmim et al., 1993; Cruz and Alkmim, 2006).

As postulated by Danderfer and Dardenne (2002), the Espinhaço aulacogen records a polycyclic depositional history, which alternated episodes of distinct tectonic regimes along time. Therefore, this setting serves as an ideal place to uncover the “black box” of the craton and aid in the understanding of geological events that were recorded by the São Francisco block in the time the supercontinent existed and afterwards. According to several authors, the first record of this history is related to a rifting episode in the Statherian. The stratigraphic framework of the Espinhaço aulacogen was systematically documented along the Northern Espinhaço by recognizing and characterizing eight synthems that are equivalent to unconformity-bounded units (Danderfer, 2000; Danderfer and Dardenne, 2002): Algodão, São Simão, Sapiranga, and Pajeú (lower interval), Bom Retiro, São Marcos, and Sítio Novo (intermediate interval) and Santo Onofre (upper interval). According to the authors, the Bom Retiro and São Marcos Synthems correspond to intracontinental sag basins. The Pajeú, Sítio Novo and Santo Onofre Synthems are related to the evolutionary stages of the rifting; the first two basins were generated by extensional tectonics, and the last one was generated by transtensional tectonics. The Algodão and Sapiranga Synthems are interpreted as rift basins. Finally, the São Simão Synthem is related to intracontinental volcanism, which was directly dispersed on the basement rocks. Danderfer et al. (2009) identified the Statherian rifting in the São Simão Synthem by dating the volcanic rocks at 1.73 Ga but without more direct relations with the other basal units (Algodão and Sapiranga Synthems). They dated the volcanic rocks in the Pajeú Synthem at circa 1.57 Ga (Calymmian), which represented a much younger rifting event.

For the lithostratigraphic mapping, the lower units of the Northern Espinhaço, including Algodão, São Simão e Sapiranga Synthems, have been grouped by Danderfer and Dardenne (2002) in the Botuporã Group at the basal portion of the Oliveira dos Brejinhos Supergroup (Schobbenhaus, 1996, revisited by Danderfer and Dardenne, 2002). Some regional investigations previously studied the basal units of Northern Espinhaço (Schobbenhaus, 1972; Moutinho da Costa and Silva, 1980; Fernandes et al., 1982; Barbosa and Domingues, 1996; Schobbenhaus, 1996). This article will address the geological evolution of Algodão and Sapiranga Synthems based on new stratigraphic and

Fig. 2. (A) Simplified geological map showing the study area in the southern portion of the Paramirim corridor, within the Espinhaço aulacogen – northern portion of São Francisco craton (modified from Alkmim et al., 1993). (B) Geological map showing sample localities in this study – stars depict samples selected for U–Pb geochronology (modified from Danderfer, 2000).

geochronological data. The São Simão Synthem does not occur in the same stratigraphic stacking besides being composed only of a monotonous succession of volcanic rocks to the south of the studied area. Although there are no direct obvious contact relationships with São Simão, Danderfer and Dardenne (2002) considered that the São Simão was younger than the Algodão Synthem and older than the Sapiranga based only on the lack or the presence of volcanic rock fragments in the basal conglomerates, respectively. This issue will be discussed later. In this study, some starting points must be considered. Were the Algodão and Sapiranga Synthems the same age as Pajeú, older than Pajeú and/or with distinct records? Did they have some relationship with the Statherian volcanism of the São Simão Synthem? If so, what is the tectonic significance of these rifts?

3. Stratigraphic framework

The Algodão and Sapiranga Synthems occur along the east margin of the Northern Espinhaço (Fig. 2). We grouped them in the Botuporã Supersynthem based on geochronological data presented here that favor evolution in a single rifting event (Fig. 3). Both units define a thick siliciclastic succession that was dominated by sandstone and conglomerates with minor mudstone and volcanic rocks. In general, the rocks that compose them show weak penetrative deformation, which is marked by a west vergence cleavage; exceptions occur along the contact with the crystalline basement rocks, where the shearing was more intense (Carrapato fault). Locally, narrow, highly deformed zones can be found throughout the units, with kinematic indicators suggesting

Fig. 3. Stratigraphic sketch chart of the Botuporã Supersynthem (modified from Danderfer and Dardenne, 2002 and Danderfer et al., 2009, and based on data from this work). The stars indicate the collected samples used for geochronological investigation.

overturning reverse faulting. The sedimentary succession composed by the two units exhibits general tilting to WSW, which defines a regional homocline with high to medium values of dip. This structure is marked on a satellite image using a set of well-structured and aligned, small ridges in the NNW–SSE direction. Anticlines and synclines occur on the eastern border of this homocline, which most likely reflects the basement tectonics near the Carrapato fault.

The Algodão Synthem occurs directly above the basement crystalline rocks (older than 2.0 Ga), which reflects a significant hiatus before its deposition. The conglomerates that are rich in clasts of gneiss and granitic rocks at the base of the Algodão Synthem suggest prominent erosion of the basement. These deposits do not contain fragments of volcanic rocks. Furthermore, the lower boundary of the Sapiiranga Synthem over the Algodão Synthem is well marked by an extensive, thick coarse-grained siliciclastic rock deposit, which mainly consists of conglomeratic facies that are rich in clasts of sandstone and volcanic rocks derived from the basal unit and the basement rocks. There appears to be a slight angular unconformity between the layers located above and below the contact.

The research was conducted in a regional scale because further systematic sedimentary mapping was necessary to better define the lateral facies trends and the architectural geometry of the basin-filling

successions. Currently, the few outcrops and poor access throughout the region were the limiting factors to this goal. Because the geological map in Fig. 2 only simplifies the investigated stratigraphic framework, we focused our analysis on characterizing the facies, the associated facies and the process and interpreting them along the vertical successions.

The Algodão and Sapiiranga Synthems were each divided into two informal members based on the major lithofaciologic characteristics (Fig. 3). The lower members are mainly composed of coarse-grained lithofacies (conglomerates and sedimentary breccias) and moderately to poorly sorted sandy lithofacies (coarse- to very-coarse-grained up to microconglomeratic, quartz-feldspathic sandstones, which typically show trough and planar cross-laminations). The upper members consist of sandy and fine-grained lithofacies (medium to fine-grained quartz to feldspathic sandstones, rarely coarse-grained, massive or with internal cross-stratification besides subordinate intercalations of conglomerates and mudstones). Some volcanic lithofacies layers were found near and/or on the upper member of both the Algodão and Sapiiranga Synthems. The overall sedimentary trend in both the Algodão and Sapiiranga units is characterized by a fining upward succession, which is associated with a thinning of the layers toward the top; internally, there are portions with fining upward. The measured stratigraphic profiles

in the occurrence area of the Algodão Synthem revealed maximal thicknesses of 4600 m. A profile that was measured throughout the wider area of Sapiranga revealed a thickness of approximately 3.800 m. Nevertheless, all of these thicknesses may have been modified by faulting. Moreover, three sills of basic rocks occur along the sequence with unknown age.

4. Lithofacies associations and successions

The Algodão and Sapiranga Synthems show several comparable characteristics, such as stratigraphic organization, lithological composition, and sedimentary lithofacies associations or successions. Therefore, in this section, we describe the lithofaciologic characteristics of these units in a unified manner; the differences are highlighted when necessary. Both rock units currently show anchimetamorphism to low-grade metamorphism (chlorite zone), but deformation is notably weak and sometimes imperceptible. A penetrative slaty cleavage could be recognized in most places that are transversal to the bedding; under microscope, recrystallization is confined to the formation of aligned sericite. In general, we found well-preserved sedimentary structures and textures in several outcrops. Thus, we omitted the metamorphic terms for naming rocks.

Although a more detailed sedimentary mapping of the studied area is necessary, we present a preliminary interpretation of the possible depositional process and environment sites that are related to the

generation of the volcano-sedimentary successions of both Algodão and Sapiranga Synthems. This analysis was based on the principal features of individual lithofacies and facies association and/or succession that were previously described; Table 1 summarizes the results.

4.1. Clast- to matrix-supported conglomerate with minor sandstone lens association (A1)

4.1.1. Description

This association is predominantly composed of coarse-grained rocks, mainly of Cc lithofacies, sometimes with minor interbedded, graded or parallel-laminated, pebbly sandstone lenses (Sg and Shl lithofacies). Individual Cc lithofacies sets show a range of minimum thickness of 1–2 m, whereas the sandstone lithofacies occur as scattered lenses with a decimeter thickness (Figs. 4B and 5A). Thick conglomerate successions occur near the base up to two dozens of meters in thickness and show no distinguishable bedding, which most likely represents megabeds. Contacts between Cc and Sg or Shl lithofacies are usually sharp and non-erosive; sometimes, the Cc lithofacies quickly transforms into them. However, laterally, both lithofacies exhibit diffuse contacts. Association A1 is notably common along the lower members of the Algodão and Sapiranga Synthems and composes multistorey units that reach tens to hundreds of meters thick. The profile of this succession shows no clear textural trend, except in some places, for a volumetric growth of the sand fraction towards the top (which suggests a

Table 1
Summary of the main lithofacies identified in the Botuporã Supersynthem with its correspondent sedimentary process interpretations.

Code	Lithofacies	Description	Processes
<i>Coarse-grained lithofacies</i>			
Cc	Clast-supported conglomerate	Poorly to moderate sorted, clast-supported massive conglomerate (sometimes matrix-supported). Clasts rounded to well-rounded, sometimes elongated and crudely imbricated.	Debris flow deposit
Cm	Matrix-supported conglomerate	Disorganized matrix-supported conglomerate, with sandy or fine-grained matrix	Plastic to clast-rich debris flow
Cmg	Graded matrix-supported conglomerate	Unsorted, graded matrix-supported conglomerate in lenticular, thick layers	Plastic to clast-rich debris flow
Bs	Sedimentary breccia	Poorly sorted, chaotic, clast- to matrix-supported breccia, with very large, angular clasts of sandstone in a sandy matrix.	Mass gravity flow (avalanche or rock fall)
<i>Sandy lithofacies</i>			
Slc	Large-scale cross-stratified sandstone	Well-sorted fine to medium-grained sandstones with large-scale cross-stratification disposed in thick to very thick sets.	Migration of aeolian dune forms
St	Trough-cross bedded sandstone	Trough-cross bedded, medium to very coarse grained, moderate to poorly sorted sandstone. Medium to thick, irregular beds. Sometimes with lag of poorly sorted gravel to very coarse sand present at base of some sets.	Migration of 3D dune under lower flow regime
Sp	Planar-cross bedded sandstone	Planar-cross bedded, medium to coarse grained, moderately sorted sandstone. Medium to thick, regular tabular beds.	Migration of 2D dune under lower flow regime
Ss	Sigmoidal cross-bedded sandstone	Medium grained, moderate to well sorted sandstone with sigmoidal foresets (in general, upper part truncated by erosion). Medium to thick, tabular beds.	Migration of 2D dune under lower flow regime
Sh	Hummocky cross-bedded sandstone	Fine to medium grained, well sorted sandstone comprising medium sets with curving lamination (hummocks and swales forms).	Storm-waves
Slac	Low-angle cross-bedded sandstone	Well sorted, fine-grained sandstone with low angle cross-bedding	Oscillatory flow
Sg	Graded sandstone	Normal graded sandstone, with lenticular geometry	High density turbidity flow
Shl	Parallel-laminated sandstone lens	Parallel-laminated, poor to moderately sorted sandstone in lenticular, thin to medium layers.	Upper flow regime
Sm	Massive sandstone	Massive, poor to moderately sorted sandstone, with intraclasts.	High density turbidity flow
<i>Fine-grained lithofacies</i>			
M	Mudstone	Thin, gray to greenish mudstone layers singly interlayered at sandstone facies, sometimes as draping layers on the foresets of cross bedding within Ss lithofacies.	Product of low energy deposition (from suspension)
SP	Interlayered mudstone-sandstone	Thinly, tabular bedded, medium or fine to very fine grained sandstone with very thin interlamination of massive or laminated mudstone	Low density turbidity flow
<i>Volcanic lithofacies</i>			
Vm	Mafic volcanic rock	Massive, dark fine-grained rock in a single submetric layer interlayered to sandstone.	Lava flow (probably distal)
Vi	Intermediate volcanic rock	Massive, gray fine-grained rock varying in composition from trachyte to trachydacite. It is composed of a thick succession (> 100 m) with no visible bedding.	Proximal lava flow
Vp	Pyroclastic rock	Coarsely stratified, poorly sorted rock with variable lithic and crystal content. It is composed of a more than 2 m thick bed.	Distal, pyroclastic flow unit
Bv	Volcanic breccia (?)	Disorganized breccia with fragments of angular clasts of sandstone and volcanic rocks, over a thinner "rock mass" (fine-grained schistose matrix). Usually filling dike structures.	Fracturing and brecciation along dike intrusion (?)

Fig. 4. Lithofacies from the Algodão Synthem. (A) Graded conglomerate Cmg with massive sandstone Sm on top; (B) conglomerate Cc with a sandstone Shl lens; (C) conglomerate Cc with a sandstone Sm lens; (D) trough- and planar-cross bedded sandstone (St and Sp); (E) large-scale cross-stratified sandstone Slc; (F) breccia deposit (Bs); (G) hummocky cross-bedded sandstone Sh; (H) contorted strata of bedded sandstone–mudstone SP filling a channel (dashed line) into the matrix-supported conglomerate Cm (arrow points to a detail). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

sandier-upward sequence). The presence of sandstone lenses is less frequent along the package base and usually dominated by conglomeratic facies.

In general, the polymict conglomerate beds of the A1 association contain pebble- to cobble-grade, sub-angular to subrounded clasts in a disorganized framework; scattered boulders are also displayed in some beds. Some gradation or stratification is observed; the rare beds

show clast imbrications. In general, the fragments are rounded to well-rounded with high sphericity; minor proportion of subangular to subrounded clasts also occurs in scattered positions or forming layers. The matrix is moderately well sorted coarse to very coarse sandstone, sometimes granule sandstone; it contains quartz, feldspars, lithic clasts and some heavy minerals (Fig. 6A). Mega-bed boundaries and geometries are not always easy to observe, but in some outcrops, the thinner

Fig. 5. Lithofacies from the Sapiranga Synthem. (A) Graded conglomerate Cm with massive sandstone Sm layers; (B) detail view of rounded and sub-rounded volcanic rock clasts in Cm lithofacies; (C) interlayered mudstone–sandstone succession (SP); (D) low-angle tangential cross-stratification sandstone (Slac) separated by thin layers of undulated mudstone (M).

Fig. 6. Photomicrographs of siliciclastic lithofacies of the Botuporã Supersynthem (cross-polarized light). (A) Quartz and feldspar grains in conglomerate Cc; (B) volcanic rock fragment in conglomerate Cc; (C) feldspathic sandstone Sm; (D and E) well sorted sandstone Slc with minor feldspar grains; (F) outsized volcanic rock fragment in eolian sandstone Slc; (G and H) poorly sorted sandstone St with lithic grains; (I) well-rounded quartz grain with overgrowths in sandstone Sh.

individual beds show a gross tabular geometry with non-erosive boundaries. Conglomerates composed of granule to small pebbles are also found in some places, mainly along the north of the Sapiranga Synthem. In the Algodão Synthem, this association includes mostly fragments of crystalline rocks with minor proportions of quartzite, sandstone, and vein quartz clasts; steatite and ironstone clasts occur less frequently. In addition to the minor presence of the aforementioned fragments, the conglomerate from the Sapiranga Synthem contains large amounts of volcanic rock (mainly acid to intermediate nature) and sandstone clasts, which suggests a change of source area nature (Figs. 5B and 6B).

The sandstone forms well-confined lens-shaped units in the conglomerates of the Cc lithofacies, which is dominated by medium to very coarse-grained, arkose and lithic arkose terms with poor to moderate sorting. The grains are typically sub-angular to rounded, and the beds contain occasional isolated floating clasts. Horizontal-laminated sandstone beds (Shl lithofacies) dominate, although low-angle cross beds are also observed; the lamination is defined by the variation in grain size. Incipient normal graded sandstone (Sg lithofacies) occurs locally and sometimes shows soft-sediment deformation structures such as loads and clastic injection in the Cc lithofacies (Fig. 4C).

4.1.2. Interpretation

Association A1 is interpreted to have been deposited mainly by sub-aerial, sediment gravity-flow processes, particularly on steep slopes proximal to the source area. Lithofacies Cc (volumetrically most significant) features characteristics that suggest a deposition by a non-cohesive debris flow (sensu Lowe, 1982; Nemec and Steel, 1984), such

as a clast-supported framework with small content of matrix and poor textural sorting (polymodal), beds with non-erosive lower limits and rare clast imbrications and the absence of stratification and grading. The significant volume of relatively rounded pebbles could suggest the reworking of existing unconsolidated, better-sorted-gravel deposits by flows.

The sandstone lithofacies that were intercalated in this association display a clear lateral gradation to Cc lithofacies, which suggests that they originated from the transformation of a high flow (Fisher, 1983) or traction-carpet sedimentation (Sohn, 1997), or a waning flow (Nemec and Steel, 1984).

4.2. Breccia deposits

4.2.1. Description

Extensive and voluminous deposits up to tens of meters thick of sedimentary breccias (lithofacies Bs) occur along a unique preferential zone at the central north of the lower member of the Algodão Synthem. Although there are several exposures of breccia deposits, they are small and do not show clear bed forms. Thus, it was not possible to observe the relationships with other lithofacies but they are often found near association A1. They constitute disorganized, unstructured and without-gradation bodies of poorly sorted, coarse-grained and clast- to matrix-supported breccias with poorly sorted sandy matrix (Fig. 4F). There are randomly distributed pebbles, cobbles and boulders that are mainly of angular to subangular sandstone clasts; some subrounded fragments are also present in the framework. Rare fragments are of granitoid rocks.

4.2.2. Interpretation

The origin of this deposit is not readily deduced because the exposure does not reveal its form or its direct stratigraphic relationships with other sedimentary lithofacies. We can base the interpretation only on its inner characteristics and spatial positioning. Because the bulk of the breccia consists mainly of meter-sized to centimeter-sized angular sandstone clasts with a sandy-grained matrix, it was most likely formed in the same basin by the fragmentation of sandstone layers and the redeposition through gravity mass flow. It does not appear to be a product of tectonic fragmentation (fault breccias) because there are some subrounded corner clasts and a characteristically clastic matrix. Because they occur together with sedimentary successions, these breccia could be interpreted as an intraformational deposit, which was derived from the source rocks in the depositional basin itself. However, the angular character of most clasts and the absence of tractive structures and graded bed inner deposits (i.e., non-stratified) suggest short or practically nonexistent sedimentary transport for their fragments. In addition the monomictic character of the breccias, other features are marked by the absence of preferential orientation of the clasts and fine-grained lithofacies. Therefore, the breccia deposits could be originated by mass flow and/or mass-wasting processes that involved the collapse and fragmentation of a partially or fully consolidated lithic substrate at first, which was immediately followed by no cohesion debris avalanche or rock fall and subaerial redeposition inside a basin with steep local topography. Hence, they should be related to rapid and intense tectonic movements during basin infilling, which is compatible with the toe-of-slope setting where talus deposits accumulate. A similar process was described by Doreen and Jago (2008) for deposits related to extension pulses in a developing rift system. We do not observe the features that can support the glaciogenic interpretation that was provided by other authors (e.g., Hoffman et al., 2009).

4.3. Trough- to planar-cross bedded sandstone with minor conglomerate association (A2)

4.3.1. Description

Lithofacies association A2 generally occurs immediately over lithofacies association A1 and occupies the top of the lower successions of the Algodão and Sapiroanga Synthem. It makes up a succession of tens to hundreds of meters thick that is composed of interstratified, trough- to planar-cross bedded sandstones of the St and Sp lithofacies, respectively. Although the contact relationships between these two associations were not observed, layers or lenses of conglomerate (lithofacies Cm and Cc) occur interbedded to sandstone at some points. Lithofacies Cm was observed only in the lower member of the Algodão Synthem, whereas lithofacies Cc was observed in one outcrop of the lower member of the Sapiroanga Synthem.

The sandstone beds are decimeter to less than a meter thick and consist of medium to coarse-grained subarkose, arkose or lithic arkose (Figs. 4D and 6C). With certain frequency, the cross-lamination is well marked by heavy minerals. The St lithofacies predominantly formed in general multistory beds with generally sharp and erosive contacts. It is sometimes accompanied by centimeter thick, normal-graded (granule to pebbly) conglomerates at the base of the layers; rounded to subrounded clasts dominate, and siliciclastic fragments appear in its framework (Fig. 6G and H) beside a large amount of crystalline rocky clasts. The Sp lithofacies generally appears as isolated sets in this succession as tabular layers.

Characteristically, the matrix-supported conglomerate (lithofacies Cm) is disorganized, massive, and shows beds with a thickness of tens of decimeters to meters and poorly sorted, medium to coarse sandy matrix. It contains pebbles of sandstone, quartzite, crystalline rocks and vein quartz that are no more than 15 cm in size; they are equant, subrounded to well-rounded clasts. Lithofacies Cc shows characteristics that are similar to those described for association A1.

4.3.2. Interpretation

Lithofacies association A3 is interpreted as having been formed by the deposition from a high-power stream current, which is most likely related to the migration of two-dimensional (lithofacies Sp) and three-dimensional (lithofacies St) subaqueous dunes. Then, the lithofacies Cm is the result of unconfined and episodic cohesive debris flows (Lowe, 1982). Lithofacies Cc results from debris flow.

4.4. Large-scale cross-stratified sandstone succession (A3)

4.4.1. Description

Large-scale cross-stratified sandstone deposits are common and well exposed in several areas of both upper members of the Algodão and Sapiroanga Synthem. They rest on alluvial sediments of the lower members and are overlain by the upper volcanogenic lithofacies. This association is entirely formed of lithofacies Slc sets that compose a succession that is a dozen to hundreds of meters thick and hundreds to thousands of meters in extent.

In general, the lithofacies Slc shows a light pink color. The individual cross-bed sets are meters to tens of meter thick with steep, sharply truncated cross-bedding (Fig. 4E). Commonly, the cross-strata are long and tangential to their basal bounding surfaces (parallel to the paleoflow) with concave-upward surfaces; the foreset dips are greater than 20°. More rarely, a brecciation of part of the cross-bedding was observed along the individual sets, which is most likely not directly related to the tectonic deformation. The layers above and below the brecciated layer are intact. The sandstone is well to very well sorted, fine- to medium-grained and varies compositionally from quartzarenite, to subarkose, and to arkose (Fig. 6C and E). In the section, the grains are invariably recrystallized with rarely preserved shapes. It is sometimes possible to distinguish the textural bimodality along the thin to medium laminae; locally, layers of coarse to very coarse grains, including granules, were observed. Occasionally, we observe volcanic fragments in sandstone Slc from the Sapiroanga Synthem (Fig. 6F).

4.4.2. Interpretation

The good selection and high textural maturity of sedimentary particles and the common presence of large cross-beds with frontal high-angle cross-stratification suggest that this succession is the record of aeolian deposits. The bimodal character could be attributed to the selective reworking of the wind action after lamination, which was formed by either grain fall or grain flow, according to Kocurek and Dott (1981).

The lack of interdune facies suggests that these deposits were formed in dry conditions, possibly from the eolian reworking of distal alluvial sediments in an extensive eolian dune field in the basin. The presence of feldspars in the rock can be linked to arid or semi-arid climate types, which must have promoted the preservation of this mineral in the original eolian sediments. Such conditions have also been described in the Early Jurassic, circum-North Atlantic rift system of the Pangaea breakup (e.g., LeTourneau and Huber, 2006).

4.5. Graded conglomerate and massive sandstone association (A4)

4.5.1. Description

This association is defined by sequences of graded, matrix-supported conglomerate (lithofacies Cmg) with massive sandstone on top (Sm); the contacts between both lithofacies range from diffuse to planar. Association A4 is tens of meters thick and generally intertongued to the large-scale cross-stratified sandstone deposits of succession A3 in the upper member of the Algodão Synthem.

The conglomerates of the Cmg lithofacies constitute decimeter lenticular layers with slightly erosive to regular, parallel-sided base and symmetric internal grading (reverse to normal; Fig. 4A). The pebbles are mainly quartz and sandstone, although minor fragments of basement and intermediate volcanic rocks could be found in certain layers. Most clasts are rounded to subrounded with spherical forms. They

are supported by a sandy matrix that varies from medium- to very-coarse-grained compositions. The Sm lithofacies are composed of medium to coarse grains, massive subarkose in centimeter- to meter-thick layers.

4.5.2. Interpretation

This association marks a clearer action of cohesive debris flows, where the massive sandstone segregation would result from a more concentrated flow, which is represented by lithofacies Cmg.

4.6. Horizontal to low-angle and hummocky cross-stratification sandstone association (A5)

4.6.1. Description

Facies association A5 is characterized by a thick sandy succession that occurs along some intervals of the upper member of the Algodão Synthem; its minimum thickness is in the order of 200 m. This association is mainly composed of well laminated, horizontal to low-angle cross-stratification sandstone beds of lithofacies Slac. The A5 sedimentary succession is dominantly composed of texturally mature to supermature quartzarenites; however, subarkose compositions also occur. Although the individual beds show well sorted grain size, the layers vary from very coarse to coarse and medium to fine sand grains, some of which have fine granule fractions; erratic pebbles of well-rounded quartz are sometimes observed. In thin section, the lithofacies consist mainly of well-sorted, rounded to well-rounded quartz grains with secondary overgrowths and less feldspar grains (Fig. 6I).

The layers of low-angle cross lamination display a planar or slightly tangential base, which reassembled beds with decimeter thicknesses (20–40 cm) that generally have tabular to wavy parallel geometry; some of them show evidence of an erosive base. In addition, symmetrical small ripples are also found. Locally, it was possible to recognize thin to medium layers (5–10 cm) with hummocky cross-stratification in lithofacies Sh (Fig. 4G).

4.6.2. Interpretation

This association is largely rich in low-angle cross-stratification and interpreted as having originated from an oscillatory flow, which is mainly induced by normal waves. However, the presence of the hummocky cross-lamination type suggests the performance of current storms in certain periods of sedimentation.

4.7. Sandstone–mudstone bedded with minor conglomerate lens association (A6)

4.7.1. Description

This association makes up fine-grained successions on the order of a few tens of meter thickness, which is mainly composed of thin to medium bedded sandstone–mudstone (lithofacies SP) (Fig. 5C) with irregular lenses of matrix-supported conglomerate (lithofacies Cm). It was observed along the upper members of the Algodão and Sapiranga Synthems.

The medium- or fine- to very-fine-grained sandstone comprises nearly tabular, centimeter- to decimeter-thick layers. A massive aspect predominates, but it is sometimes possible to observe an incipient horizontal lamination inside the beds. The sandstone characteristically shows a light gray color and low maturity, which are most likely related to some amount of silt-clayey fractions in its framework. The sandy layers are generally interposed by interlaminae or centimeter thick beds of medium to dark gray or greenish-gray, pure to sandy mudstone. Sandstone and quartz pebbles are locally observed with erratic patterns or even forming isolated thin lenses (approximately 5 cm thick). The lenses are rarely medium to thick.

The conglomerate lithofacies materializes discontinuous, structureless, decimeters to meter thick layers. It contains random clast arrangements that are supported by a sandy matrix, which is texturally

analogous to the sandstone from lithofacies SP. Sometimes, there are so few pebbles (i.e., well dispersed) that are better classified as a muddy pebbly sandstone. We checked clasts of sandstone, quartzite, quartz and crystalline basement rocks with the maximum dimensions of up to 20 cm and subangular to subrounded shapes.

In certain outcrops of sedimentary association A6, the lithofacies Cm is found filling a meter-thick, channeled-shape layer. In this channel, there are distinct zones of lithofacies SP that shows ruptured bedding and convolution features, which laterally and complexly passes through portions of the conglomeratic lithofacies (Fig. 4H).

4.7.2. Interpretation

Association A6 exhibits little or no deposition characteristics in the unidirectional or oscillatory current processes. It is more plausible to interpret this result as produced by a sediment gravitational flow via relatively low-density currents into a subaqueous setting. In this environment, the lithofacies Cm was most likely deposited by cohesive debris flows, which were comparable to a mudflow type (Middleton and Hampton, 1973). In this process, the matrix is the main mechanism that supports the random clast occurrence in the layer (Fritz and Moore, 1988) (mostly in the channels).

4.8. Cross-stratification sandstone interbedded to a fine-grained lithofacies association (A7)

4.8.1. Description

This association is closely related to the sandstone–mudstone layers of the previous association. It comprises medium- to fine-grained, cross-stratification sandstone (lithofacies Ss), which is interbedded with thin massive mudstone (lithofacies M) and interlayered mudstone–sandstone (lithofacies SP). It was mainly detected along the top of the upper member of the Sapiranga Synthem.

The sandstone layers mainly occur as roughly tabular, decimeter- to meter-thick beds, solitary or in bedsets in a fine-grained lithofacies succession. The solitary beds typically show low-angle sigmoid to tangential (tabular with curved bases) cross-stratification. This stratification is defined by thin laminae (1–3 cm thick), composed of medium- to fine-grained sand and subordinate coarse to very coarse sand, including rare blades of granules and mudstone. The cross-lamination run great extent of the layer with general dips below 15° (Fig. 5D). The bedsets comprise at most three layers of decimeter thickness, which visibly shows a paleocurrent sense that is contrary to the paleocurrent shown by the large sets.

The lithofacies Ss is sometimes separated by massive, solitary and thin, gray to greenish mudstone layers without apparent internal features (lithofacies M). These layers are laterally discontinuous with various lateral thicknesses (up to 8 cm thick). They sometimes appear undulated and form mud drapes over lithofacies Ss. The more conspicuous lithofacies Ss is interlayered with fine-grained successions of less than 1 m thick that consist of the heterolithic lithofacies SP. This lithofacies has medium- to fine-grained sandstone, sometimes coarse-grained, thin and discontinuous millimeter-thick interlaminae of siltstone to muddy, very fine-grained sandstone; erratic and well-rounded clasts of quartz were observed in some places of the rock. Sometimes the sandstone fraction highlights a moderately to well developed horizontal or wavy stratification; ripples are common in small symmetrical forms ($\lambda < 5$ cm and $A < 2$ cm). Lenticular and flaser lamination types were also observed in some locations. In particular, it was locally observed that these levels are disrupted along its length and reveal a profile in the form of decimeter-scale dish structures with concave-up laminae, which may be related to wet-sediment deformation.

4.8.2. Interpretation

Lithofacies association A7 is not easy to interpret, but we suggest processes that are related to oscillatory flow induced by normal waves

and tidal currents. The type of cross-stratification exhibited by lithofacies Ss in association with the flaser-lenticular lamination and mud drapes of lithofacies SP and M, respectively, indicates that this process occurred (Collinson et al., 2006).

4.9. Volcanogenic lithofacies

4.9.1. Description

Pyroclastic rocks and minor lava flow were found in distinct stratigraphic positions of the upper member of the Algodão Synthem. Both were intercalated to an epiclastic deposit that is mainly composed of graded conglomerate and massive sandstone association. The lava flow is represented by a less than 2.5 m thick, aphanitic, dark-gray mafic volcanic rock. Larger volumes of the pyroclastic subfacies were found on top of the Algodão Synthem, directly in contact under the clast-supported conglomerate lithofacies that belongs to and occurs along the base of the Sapiranga Synthem (Fig. 7A and B). It was better investigated here and corresponds to an ignimbrite deposit with massive poorly sorted to symmetric (reverse to normal) graded beds; the textures vary from fine-grained tuff to fine- to coarse-grained tuff breccia. The tuff breccia comprises mainly tabular, subhedral to euhedral feldspar phenocrysts and minor fragments of rounded, mono and polycrystalline quartz (Fig. 7D). These fragments are immersed in a gray, very-fine-grained matrix (mineralogical distinction is extremely difficult on thin section), and they are interpreted as tuff here. Based on their fragmental components, they could be classified as a crystal tuff; some quartz grains are volcanic in origin (Fig. 7C) while others may be accidental country rock fragments. Sinusoidal ripple-drift laminations of short wavelength were observed in the tuff portions of a layer.

From the geochemical standpoint, this pyroclastic lithofacies is classified as tephriphonolite by Le Bas et al. (1986a, 1986b). It has 53.47% of silica, high concentrations of K₂O and Fe₂O₃ (10.89% and 9.67%, respectively) and low concentrations of Na₂O and MgO (0.13%

and 1.38%, respectively). This alkaline rock has a high K₂O/Na₂O ratio (83.77). (see Table 3 in the electronic supplement).

An extensive extrusive volcanic rock body occurs along the top of the Sapiranga Synthem at least 50 m thick and immediately underlies conglomerate deposits of the Pajeú Synthem; the boundary between both units was characterized by Danderfer and Dardenne (2002) as a regional unconformity with an important erosion break (more than 140 Ma considering the results of our paper). The lava flow rests on cross-stratification sandstones, which are interbedded with a fine-grained lithofacies association. It defines a gray volcanic rock, apparently of intermediate composition with porphyritic texture; larger feldspar crystals are observed immersed in a notably fine-grained or aphanitic matrix. It is sometimes found as a gray phyllite, particularly near the contacts with siliciclastic rocks because the protolith underwent stronger deformation; however, the original texture is better preserved in the body of volcanic rock. Volcaniclastic rocks also occur interdigitated with the extrusive body, hampering the differentiation of facies in the field.

Although well weathered, it was possible to identify on thin-section euhedral, tabular phenocrysts of alkali feldspars in a microcrystalline groundmass that is composed of alkali feldspars, quartz, and opaque minerals; the feldspar phenocrysts are altered to sericite. There are also euhedral, embayed quartz phenocrysts (Fig. 7E). This rock is classified as trachyte to trachydacite, following Le Bas et al.'s (1986a, 1986b) geochemical volcanic rock classification. The rock has 65.23% of silica, high concentrations of K₂O and Fe₂O₃ (9.29% and 6.23%, respectively) and low concentrations of Na₂O and MgO (1.27% and 0.44%, respectively). This alkaline rock has a lower K₂O/Na₂O ratio (7.31) than the volcanic rock from Algodão.

Following the classification of Irvine and Baragar (1971), the rocks from the Botuporã Supersynthem are alkaline. Both suites have K₂O/Na₂O ratios > 2 and K₂O > 3 wt.%, which fulfill the criteria of ultrapotassic rocks (Foley et al., 1987). However, their low concentrations of MgO wt.% (1.38% and 0.44%) suggest a felsic ultrapotassic

Fig. 7. (A) Contact between volcanic rocks of the Algodão Synthem (AS) and conglomerate Cc of the Sapiranga Synthem (SS); (B) detail view of the volcaniclastic rock. Representative photomicrographs of volcanic lithofacies: (C) volcanic quartz crystal with internal cracks in a fine matrix of volcaniclastic rock (plane polarized light); (D) broken phenocrysts of plagioclase in a fine-grained groundmass of volcaniclastic rock (cross-polarized light); (E) partially resorbed, quartz phenocryst in a recrystallized volcanic rock (cross-polarized light).

Fig. 8. (A) Primitive mantle-normalized REE (McDonough and Sun, 1995) patterns for the Algodão (●) and Sapiroanga (○) volcanic rocks; (B) primitive mantle-normalized (McDonough and Sun, 1995) spidergram for trace elements. (see Table 3 in the electronic supplement).

character. Both suites show low compatible-trace-element abundances (low concentrations of Cr and Ni).

The Algodão and Sapiroanga rocks show high incompatible-trace-element contents, including large ion lithophile elements (Fig. 8A). The rare earth element (REE) patterns (Fig. 8B) of both volcanic subfacies are comparable and show enrichment of light REEs and small europium anomalies. The Algodão pyroclastic rock has a moderate enrichment of heavy REEs, which is comparable with the Sapiroanga volcanic rock.

5. Interpretation of depositional systems

5.1. Depositional systems of the Algodão Synthem

Table 2 shows a synthesis of the depositional process and the environments that were interpreted for the basin-filling successions of the Algodão and Sapiroanga Synthems. The deposition of the entire lower member could be related to the evolution of alluvial fans and dominated by gravity flows, partially by avalanches (breccias deposits) and partially by non-cohesive debris flows (association A1). Toward the top, this system was covered by a braided river system, which is represented by low-sinuosity channels with sporadic non-channeled, associated gravitational flows (association A2), and coupled and laterally extensive aeolian reworking (association A3). The coarse-grained facies appears dominant in the north-central part of the occurrence area of the Algodão Synthem.

The upper member is difficult to interpret and shows facies associations that might be related to a lacustrine system (associations A5, A6 and A7) with features that alternate to a greater or minor water depth.

Short intervals of its sedimentation are characterized by tidal (association A7) and storm (association A5) currents. Moreover, there is evidence of a subaqueous gravity flow process, which was active during this deposition (association A6). Finally, the top appears to be dominated by the activity of alluvial fans associated with aeolian reworking (association A4). The extensive and thick aeolian deposits in the upper member (association A3) are here interpreted as a “dry” wind system, which is characterized by non-cohesive sand and deposited above a water table deep level. Explosive volcanism occurred during the remaining sedimentation along the top interval of the upper member, and it generated lava and pyroclastic flow facies.

5.2. Depositional systems of the Sapiroanga Synthem

The lower member of the Sapiroanga Synthem was also deposited by the gravitational flow-type alluvial fan system with predominated debris non-cohesive flow. Apparently, this system has evolved into sub-aerial conditions because of the absence of typical subaqueous features, as predicted by the models presented by Nemec and Steel (1984). Towards the north, this system becomes dominated by the development of a braided fluvial system with sporadic, interfingering conglomerate layers that were deposited by mass gravity flow.

An extensive and thick aeolian package characterizes the basal interval of the upper member. This package covers throughout the alluvial fan facies of the lower member and records the development of an extensive “dry” wind system in the original basin, which is characterized by the migration of non-cohesive sand without interdune facies (as prescribed by Kocurek, 1996).

Table 2

Depositional process and depositional systems interpreted for the facies associations described in the study area.

Facies association	Depositional process	Depositional system
A1 – Clast- to matrix-supported conglomerate with minor sandstone lenses	Non-cohesive debris flow, with flow transformation associated	Proximal alluvial fan dominated by debris flow
Sedimentary breccia (lithofacies Bs) deposits	Mass gravity flow (avalanche or rock fall)	Toe-of-slope (talus deposits)
A2 – Trough- to planar-cross bedded sandstone with minor conglomerate lenses	Stream flow involving bedload transport coeval to debris flow	Low sinuosity fluvial related to braided stream plain or to alluvial fan
A3 – Large-scale cross-stratified sandstone succession	Transport and accumulation dominated by eolian dunes (no interdunes)	Dry and extensive eolian dune field
A4 – Graded conglomerate and massive sandstone irregularly interbedded with large-scale cross-stratified sandstone	Cohesive debris flow interbedded to eolian dunes	Distal alluvial fan system dominated by eolian reworking
A5 – Horizontal to low-angle and hummocky cross-stratification sandstone	Normal waves and storm currents in shallow water	Shallow-lacustrine
A6 – Sandstone–mudstone bedded with minor conglomerate lens	Mass gravity processes and/or river underflows in deep water	Deep-lacustrine
A7 – Cross-stratification sandstone interbedded to a fine-grained lithofacies	Tidal currents	Lacustrine coastline
Volcanogenic lithofacies (lithofacies Vm, Vi and Vp)	Lava flow and pyroclastic flow	Volcanism and related volcanoclastic around volcanos intrabasin

On the top of the upper member, the lithofaciologic set is more complex and difficult to interpret because the apparently restricted occurrence constrains a more accurate interpretation of the depositional system. We believe that this stratigraphic level was deposited in a lacustrine environment context with various water depths. There is a facies association that may be related to shore-zone sedimentation, which is mainly dominated by tides and wave currents, as described in association A7. The lack of storm facies (e.g., hummocky structures) favors calm water conditions that prevailed during the sedimentation. In such circumstances, this system could be associated with the evolution of a tidal flat or deltaic environment or a distal fluvial system, although that system is not so common in Precambrian basins. Association A6 could be related to gravity flow sedimentation in deeper waters.

The volcanism finalizes the deposition along the top of the upper member succession. The volcanogenic lithofacies occurs stratigraphically on lacustrine facies; nevertheless, their direct relationships were not observed.

6. U–Pb geochronology

6.1. Samples

The lithofacies associated with the volcanism of the Algodão and Sapiranga Synthem are volcanic rocks of alkaline series (Kuno, 1966; Irvine and Baragar, 1971). We performed geochronological investigations on two samples (sample A2 from the Algodão Synthem and sample S2 from the Sapiranga Synthem). Furthermore, we conducted radiometric dating on detrital zircon grains that were collected from the basal clast-support conglomerates (lithofacies Cc) along the lower member of each synthem (sample A1 from the Algodão Synthem and sample S1 from the Sapiranga Synthem). The localities of these samples are plotted on the map in Fig. 2.

6.2. Analytical methods

The laser ablation-ICP-MS was performed using an Agilent 7700 Q-ICP-MS and a 213 nm New Wave laser at the Universidade Federal de Ouro Preto, Brazil. The operating conditions were optimized using zircon standards and NIST glasses to provide maximum sensitivity for the high masses (^{207}Pb and ^{238}U) while inhibiting the oxide formation ($\text{ThO} +/\text{Th} + < 1.0\%$). The standard and unknown zircon grains were ablated in a small-volume (tear-drop shape) sample cell with an insert that holds one 25-mm-diameter sample mount and a 7-mm-diameter standard mount (Lana et al., 2011, 2013). The acquisitions consisted of a 20 s of laser warm-up and a measurement of the gas blank, followed by 40 s measurements of the U, Th and Pb signals during ablation, and a 20 s washout (e.g., Buick et al., 2011; Lana et al., 2011). The samples, the standards and the sample holders were acid-washed before being analyzed to remove possible surface Pb contamination. Laser ablations were performed at 40 μm spot size, $\sim 6\text{--}8\text{ J/cm}^2$ fluence and 10 Hz repetition rate. Ablations occurred in an He carrier gas, and the resulting aerosol was mixed with Ar before introduced into the ICP-MS via a 4 mm Tygon tubing (pre-cleaned with 1% ultra-pure nitric acid). The integration times were 15 ms for ^{206}Pb , 40 ms for ^{207}Pb and 10 ms for ^{208}Pb , $^{204}\text{Pb} + \text{Hg}$, ^{232}Th , and ^{238}U . The relevant isotopic ratios ($^{207}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{232}\text{Th}$, $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$, where ^{235}U was calculated from the ^{238}U counts using the natural abundance ratio $^{235}\text{U}/^{238}\text{U} = 137.88$) have been calculated using the data reduction software Glitter (Van Achterbergh et al., 2001). The individual isotopic ratios were displayed in a time-resolved mode. For our laser system, the isotopic ratios that were generated during the first 5 s of each analysis were discarded. The instrumental drift was corrected against the zircon standard using linear interpolative fits. Calibrations were based on six or more analyses of the standard (6–8 analyses of unknowns bracketed between 2 and 3 analyses of standards). Two

secondary standards were used for monitoring the quality of the analyses. Seven analyses of the standard Plesovice (with an accepted age of $337 \pm 1\text{ Ma}$; Sláma et al., 2008) gave a concordia age of $336 \pm 5\text{ Ma}$ (2 sigma). Seven analyses of Std 91500 (accepted age of $1065 \pm 1\text{ Ma}$; Wiedenbeck et al., 1995) gave a concordia age of $1068 \pm 9\text{ Ma}$ (see Table 4 in the electronic supplement).

6.3. Results from volcanic rocks

Sample A2 is a volcanoclastic rock from the uppermost part of the Algodão Synthem and directly under the conglomerates from the Sapiranga Synthem. The zircon from this sample is prismatic and translucent, ranging from 200 to 350 μm . All grains show well-defined oscillatory zoning but not visible core–rim relationship (Fig. 9A). Thirty-three analyses on the center and the border of the grains provided similar concordant to discordant points that range in age from 2121 to 1680 Ma (Fig. 10A). Two analyses provided apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1900 and 2121 Ma, which are interpreted here as an inherited core age. The remaining points were concordant to reversely discordant but provided a similar $^{207}\text{Pb}/^{206}\text{Pb}$ age of approximately 1780 Ma. The concordant points provided a concordant age of $1775 \pm 7\text{ Ma}$ (Fig. 10A). We suggest that this age is the best approximation of the crystallization age of the Algodão volcanic rock sample.

Sample S2 represents a fine-grained fraction of the volcanic rock from the uppermost part of the Sapiranga Synthem and directly under the conglomerates from the Pajeú Synthem. This sample yielded a number of subhedral to anhedral translucent zircons with no visible zones of intense alteration and radiation damage. The zircon is well formed, mostly prismatic with visible cores and rims. The CL images show well-rounded (60–120 μm wide) cores surrounded by oscillatory rims that are 50–80 μm wide (Fig. 9B). Twenty-two LA-ICP-MS analyses on the core and the rims provided two distinct highly concordant ages on the concordia diagram. Fourteen analyses on the cores of the zircon grains provided slightly older ages: two of which were Paleoproterozoic discordant ages ($^{207}\text{Pb}/^{206}\text{Pb}$ ages = 2150 Ma and 2130 Ma), which are consistent with the age of the basement rocks of the Paramirim complex. The remaining core analyses were clearly sub-concordant to concordant and Paleoproterozoic, ranging from 1770 to 1800 Ma (Fig. 10C). They provided a concordia age of $1780 \pm 11\text{ Ma}$, which is inconsistent with the inherited age from sample A2 (Fig. 10A). We interpret this age as an inherited age. The analyses on the oscillatory rims provided slightly younger ages of $1740 \pm 10\text{ Ma}$ (Fig. 10C), which is here interpreted as the crystallization age of the Sapiranga volcanic rock sample.

6.4. Results from conglomerates

Sample A1 is a basal conglomerate of the Algodão Synthem, which occurred directly over basement rocks of the Paramirim valley. It contains dark brown zircon, which varies from prismatic to slightly stubby, all of which have round terminations. The grains are predominately CL-bright because of the low U content (Fig. 9C). Some bright complex cores are observed but the relationship with the overgrowth is difficult to constrain. Among 120 analyzed grains, only 37 were 100% concordant. They define a pattern with two main peak ages of 2138 Ma ($n = 9$) and 2698 Ma ($n = 3$) (Fig. 10B). Note that all $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages reflect crystallization ages of four main magmatic events in the Archean/Paleoproterozoic evolution of the southern São Francisco craton (e.g., Lana et al., 2013; Romano et al., 2013). The youngest dated detrital zircon grain of the analyzed conglomerate A1 sample records a $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1984 \pm 21\text{ Ma}$, setting the maximum deposition age of the precursor sediments.

Sample S1 is a basal conglomerate of the Sapiranga Synthem that occurred directly over the volcanic rocks of the Algodão Synthem. The zircon grains in the sample were large (200–350 μm in length), euhedral to only slightly rounded, and generally colorless, milky white

Fig. 9. Cathode-luminescence images of dated zircon grains in: (A) Algodão volcanic rock; (B) Sapiranga volcanic rock; (C) Algodão conglomerate; and (D) Sapiranga conglomerate.

and dark brown (Fig. 9D). A number of milky white to dark brown zircon grains that were of poor quality for U–Pb dating were also mounted. Approximately 150 zircon grains were analyzed (including the milky white and brown grains), but only 55 grains were 100% concordant (Fig. 9B). The 100% concordant ages provided three main age groups of ca. 3500 Ma, 2600–3000 Ma and 1700–1900 Ma. The primary age peaks are 1766 Ma ($n = 25$), 2143 Ma ($n = 5$) and 2658 Ma ($n = 5$). Significantly, fifteen grains record apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages that are inconsistent with the crystallization age of the Sapiranga volcanic rock sample (Fig. 10C) and a weighed mean age of 1741 ± 14 Ma, which is identical within error to the age of the Sapiranga. All other dated grains appear to record the magmatic ages of the basement rocks in the southern São Francisco craton (Lana et al., 2013). The youngest zircon grain of sample S1 records a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1704 ± 39 Ma.

7. Discussion and tectonic implications

7.1. Tectonics and sedimentation

The Algodão and Sapiranga Synthem represent two basin-fill successions related to the rifting process. Field-based stratigraphic evidence, such as the presence of alluvial and eolian deposits, vertical and lateral facilogic variations and volcanic rocks, strongly suggests that the successions that integrated both synthem were deposited in a continental context under intense tectonic activity for much of the sedimentation. The presence of intraformational breccias (as shown in Fig. 4F) in the Algodão sequence supports the assumption of tectonic instability of the basin during deposition. Subaqueous depositions are restricted to certain intervals of the upper members: two were detected

Fig. 10. Geochronological results for volcanic rocks and conglomerates of the Botuporã Supersynthem. (A) Concordia diagram for the Algodão Volcanic rock (sample A2); (B) relative probability diagram for one sample of the Algodão conglomerate (sample A1); (C) concordia diagram for the Sapiranga volcanic rock (sample S2); (D) relative probability diagram for one sample of the Sapiranga conglomerate (sample S1).

in Algodão, and one was detected in the Sapiranga Synthem (Fig. 3). These intervals were most likely associated with the creation of spaces by spasms of rapid mechanical subsidence in the basin. In such circumstances, the filling of the rift basin was most likely processed by a lacustrine depositional system interspersed with coarse-grained alluvial facies and partially by the formation of thick aeolian deposits. The coarse-grained facies associations of the lower members of Algodão and Sapiranga could relate to the more proximal parts of alluvial fans, which possibly mark the vicinity of a rift fault border.

The presence of feldspar and volcanic rock grains in much of the alluvial and eolian facies in the studied area could indicate that the climate was arid or the erosion was notably rapid because of the rift tectonics. In the Sapiranga Synthem, rounded to sub-rounded clasts of volcanic rocks (unstable fragments) are found in the conglomerates of lithofacies Cc, which preservation must have been most likely favored by arid climatic conditions. The developments of braided fluvial systems and “dry” aeolian deposits in part of the section are common to the filling under such climatic conditions (e.g., Aspler et al., 1994; Eriksson et al., 1998; Köykkä, 2011). The minor and thin lacustrine delta deposits (lithofacies associations A6 and A7) are also characteristic of sedimentation rift in an arid climate (e.g., Köykkä, 2011).

The paleotectonic reconstruction of the rift framework that stored the investigated sedimentary successions is notably difficult to perform. Several younger episodes of basin formation and the tectonic inversion of all Espinhaço aulacogens were responsible for destroying much of the original structural and stratigraphic record of the two discussed rifting phases (Danderfer, 2000). We can only discuss some clues to elucidate this question, but further studies are required to improve the model. Despite the scarcity of paleocurrent data, the direction provided by

through-cross lamination of lithofacies St from the Algodão Synthem indicates a contribution of sediments from a southeast basement block. Some paleocurrent measurements, which were obtained from the

Fig. 11. Schematic cartoon showing the evolution of the two superposed rifting phases (the Algodão and Sapiranga rifts) and related Statherian plutonic (Lagoa Real) and volcanic (São Simão) activity most southerly.

sandstones of fluvial facies from the Sapiranga Synthem, are also favorable to an eastern source area. In many rift basins, the braided river flows along the basin axis (e.g., Blair and McPherson, 1994; Mack and Leeder, 1999; Ebinger and Scholz, 2012). Thus, we could interpret a roughly east–west rift orientation with an axial fluvial flow from east to west. Supporting this idea, we have clasts of acid volcanic rocks in the conglomerates from the Sapiranga Synthem, which were not observed in its succession. Nevertheless, volcanic rocks similar to these clasts are common in Rio dos Remédios and São Simão formations (Danderfer and Dardenne, 2002), which are located east and south, respectively, of the occurrence area of the Sapiranga Synthem and suggest a probable source area.

7.2. Origin and age of rifting

The investigated area clearly reveals two rifting stages in the Statherian Period, which are named Algodão and Sapiranga rifts here (Fig. 11). The first one is associated with the Algodão Synthem with the minimum age of 1775 ± 5 Ma, which is obtained from a volcanic sample collected at the top of this sequence (Fig. 10A). Detrital zircon grains from the matrix of basal conglomerates are consistent with Paleoproterozoic sources, which range from 2.2 to 2.05 Ga, and two Archean sources (2696 ± 10 Ma and 3206 ± 5.6 Ma). Thus, the Algodão volcanism likely occurred later in the first rifting episode on Northern Espinhaço. The age of the beginning of the sedimentation remains undetermined, but we believe that it is not older than 1.8 Ga because rifts typically record relatively short periods of subsidence (e.g., Sengör, 1995). The Rhyacian source may originate from sin- to post-orogenic granites that are related to the orogenic activities along the belts, which sutured the several crustal blocks that constituted a large paleocontinent, including the Congo and São Francisco domains (for example, Rosa et al., 2000; Conceição et al., 2002, 2003, 2007; Paim et al., 2002; Rios et al., 2007). The Archean sources are found in the Gavião block (e.g., Nutman and Cordani, 1992; Mougeot, 1996; Pinto et al., 1998; Rosa et al., 2000; Teixeira et al., 2000; Barbosa and Sabaté, 2002, 2004; Lana et al., 2013), which constitutes the main basement of the studied region.

The second stage of the Statherian rifting is characterized by the Sapiranga Synthem with a minimum age of 1740 ± 10 Ma from volcanic rocks on top (sample S2, Fig. 10B). Therefore, we can calculate an approximate timing of ca. 35 Ma between the two rift stages. The 1780 ± 11 Ma age that was acquired for a significant population of zircon grains from the same lava flow sample is interpreted here as the reworked crystals generated from the early (Algodão) rifting stage. The zircon grains could have been assimilated from country rocks during the ascent of magma that resulted in volcanism on the Sapiranga sequence or as xenocrysts from the magmatic chamber, which was related to the first volcanism.

The detrital zircon studied in the basal conglomerates of the Sapiranga Synthem indicates an Archean source (major peaks: 2658 Ma and 3505 Ma) and a Rhyacian source (ranging from 2.2 to 1.9 Ga). We acquired populations of distinct Statherian ages with a major peak at 1766 Ma. The older ages are clearly correlated to the age of Algodão volcanism, whereas the younger one is related to the inherent volcanism of the Sapiranga rift. In this case, there must be a volcanic source at approximately this peak-age at the start of the rifting that was most likely cannibalized during the extensional tectonics. Then, we can estimate that the timing of the Sapiranga rifting evolution was less than 26 Ma.

The Algodão and Sapiranga Synthems represent two unconformity-bounded units of Statherian age, separated by an extensive and well-marked unconformity. The basal conglomerate of the lower member of the Sapiranga Synthem contains a high proportion of volcanic clasts (more than 50%) and EoStatherian detrital zircon grains, which suggests that the Algodão Synthem was the source area of the Sapiranga basin-fill in addition to the basement rock sources. For the Algodão Synthem, only Archean and Paleoproterozoic rocks that are older than 2.05 Ga

were available in the source area. In this case, the gap in the sedimentary geologic record between these two synthems is almost certainly less than 40 Ma, as determined by the age of the volcanic rocks on top (see Figs. 3 and 10). In addition to the short time span between the depositions of both units, they show comparable lithofaciologic successions formed in similar depositional systems. Thus, we group the Algodão and Sapiranga Synthems into the Botuporã Supersynthem (Fig. 3) to establish a useful hierarchy of higher order for Precambrian rocks in the context of the SFCP Statherian history.

Currently, we can only speculate about the process that originated the rift-related volcano-sedimentary sequences of the Algodão and Sapiranga Synthems in the continental setting. Considering Sengor and Natal'in (2001), there are two possibilities to explain intracontinental rifting: mantle plume (active rifting) and a far-field stress (passive rifting). Although this distinction is not easy for older rifts, based on the presented field/geochemical evidence, the Algodão and Sapiranga paleorifts present characteristics that are more typical of intracontinental passive rifting. The paleorifts appear solitary regionally; they are not part of star or chain rifts as the East African Rift (e.g., Chorowicz, 2005), which are more typical of active rifting.

The volcanism in both Algodão and Sapiranga rift-fill successions occurred after tectonic subsidence and sedimentation, which suggests that stretching and thinning occurred first and the volcanic extrusion occurred at the end of rift basin infill. This result suggests a mechanism of passive rifting (e.g., Turcotte and Emler, 1983). In general, volcanism related to active rifting, which is directly related to the doming above a hot spot, occurs first in the overall process (e.g., East Brazilian Margin; White and McKenzie, 1989; Morgan, 1983). The geochemistry signature of the volcanic rocks from the Botuporã Supersynthem cannot be straight related to a single plume-style source. The high-K characterizes an ultrapotassic volcanism that could have resulted from adiabatic decompression of the asthenosphere and/or lithosphere during intraplate extension. Both volcanic ultrapotassic rocks A2 and S2 have geochemical fingerprints that are compatible with intraplate volcanism most likely associated with a metasomatic enriched mantle due to the subduction of sediments as proposed, for example, for the Tibetan lithospheric mantle metasomatism (Miller et al., 1999). This process could be a consequence of the local asthenospheric mantle upwelling that heated the lower lithospheric mantle associated with the subduction of sediments.

7.3. Related Statherian rifting/magmatism throughout the São Francisco block

The map of Fig. 1 shows several studied places in the São Francisco block that are related to the Statherian rifting/magmatism process. In Fig. 12, we see the stratigraphic correlation of several Statherian and Calymmian units in this block. We briefly describe these records to integrate them in a tectonic model, considering the origin of the Botuporã Supersynthem rifts as part of the same evolutionary frame.

The first Statherian age for the U–Pb radiometric ages of rocks in the Espinhaço aulacogen was obtained from volcanic rocks from the Rio dos Remédios Formation (western Chapada Diamantina) at ca. 1.73 Ga (Cordani et al., 1992; Babinski et al., 1994, 1999; Pimentel et al., 1994; Schobbenhaus et al., 1994). On the east-southern border of Northern Espinhaço, the volcanic rocks of the São Simão Formation were U–Pb dated at 1733 ± 7 Ma by Danderfer et al. (2009). In the southern Paramirim valley outcrops, there are rocks that are older than ca. 2.05 Ga and were intruded by plutonic rocks of the Lagoa Real Complex of Statherian age. Their ages range from 1.75 to 1.71 Ga (U–Pb and Pb–Pb; Pimentel et al., 1994; Cordani et al., 1992; Turpin et al., 1988), and they are contemporaneous to the acid volcanism in the Chapada Diamantina and Northern Espinhaço domains.

Some volcanic rocks in southern Espinhaço (Conceição do Mato Dentro Meta-igneous Suite) also have similar ages between 1.71 and 1.77 Ga. The rocks were dated by Brito Neves et al. (1979) and Machado

Fig. 12. Stratigraphic correlation chart of the Statherian and Calymnian 1st-order sequences of the São Francisco block including the basement of the marginal orogenic Brasília and Araçuai belts (see text for explanation and references). Related rifting sequences: PR – Pajeú, MVR – Mato Verde, SR – Sapiranga, AIR – Algodão, SJCR – São João da Chapada, BR – Bandeirinha, ArR – Araí. Volcanic rocks: RRV – Rio dos Remédios, SSV – São Simão, DOV – Desembargador Otoni. Anorogenic granitoids: LRS – Lagoa Real Suite, CS – Catolé Suite, BS – Borrachudos Suite, PS – Paraná Subprovince, TS – Tocantins Subprovince.

et al. (1989) using the U–Pb method and Dussin and Dussin (1995) using the Pb–Pb and Pb evaporation methods. In addition, Dossin et al. (1993), Silva et al. (2002b), Noce et al. (2007) and Delgado et al. (2003) obtained an age of approximately 1.74 Ga for the coeval granitic plutonism that occurred in the eastern border of this segment (the several granitic bodies grouped under the Borrachudos Suite). Machado et al. (1989) also dated an acid metaigneous rock from Desembargador Otoni region (Central Espinhaço) at 1752 ± 2 Ma.

Based on the previous U–Pb age dating, previous studies interpreted the evolution of the entire Espinhaço basin-fill successions as part of one Paleo-Mesoproterozoic rifting episode in the São Francisco block (Schobbenhaus, 1996; Martins-Neto et al., 2001; and the references therein). The magmatism was considered anorogenic and related to an intracratonic extensional site. Nevertheless, studies conducted by Danderfer and Dardenne (2002) showed that the filling of the Espinhaço aulacogen is not continuous and related to a unique basin formation tectonic process. They interpreted a polycyclic and poly-historic evolution for this tectonic setting when several unconformity-bounded units materialized its interior. This hypothesis was better proved by Danderfer et al. (2009), who dated volcanic rocks from Pajeú Synthem between 1.59 and 1.55 Ga, and correlating them to the formation of an EoCalymnian rift. Because the Pajeú Synthem occurs directly under the Statherian volcano-sedimentary successions, a hiatus of more than 140 Ma marks the break between two distinct rifting episodes.

Recently, Chemale et al. (2012) provided U–Pb detrital zircon ages of 906 Ma to 1192 Ma for a great part of the Espinhaço basin fill-succession that is exposed along the Southern Espinhaço, which suggests that the two basins were formed in intraplate conditions: (i) the older basin was marked by a Statherian volcano-sedimentary sequence; and (ii) the overlying sequence characterizes a Stenian rift-sag basin. The

Calymnian rifting has not been detected in this domain, but recently, Costa et al. (2014) described volcanic rocks in Central Espinhaço that is related to a rift stage of this age (Mato Verde rift). Costa (2013) dated U–Pb granitic rocks of the Catolé Suite (revisited by Knauer et al., 2007) at 1.73 Ga as younger rocks of the Mato Verde rift basement.

On the northern basement of the Brasília belt, there is a volcano-sedimentary rift-fill succession (Araí Group) whose volcanic units (such as rhyolite from the Arraia Formation) were dated at 1771 ± 2 Ma (Pimentel et al., 1991; Pimentel and Botelho, 2001). In addition, in this domain, the alkali-rich plutonic rocks of the Paranã Suite (Soledade and Sucuri granites), which is genetically related to this rift, show similar ages (1767 ± 10 Ma and 1769 ± 2 Ma, respectively).

The Algodão rifting occurred simultaneously with the Araí rift and the related granitic rocks of the Paranã Suite in the west, although there is no connection between them. In Southern Espinhaço, the Sapiranga rift could be correlated in time to the Bandeirinha rift sequence. The Sapiranga rifting is chronologically correlated to the development of acid volcanic terrains immediately to the east, in the Chapada Diamantina domain (Rio dos Remédios Formation), in the south (São Simão Formation) and to the granitic terrains of the Lagoa Real Complex (Paramirim Valley). In Southern and Central Espinhaço, the Sapiranga rift is rather coeval to the São João da Chapada rift and the acid metaigneous rocks of the Conceição do Mato Dentro Meta-igneous Suite and Desembargador Otoni region as well as the Catolé Complex (Central Espinhaço) and the Borrachudos Suite (east of Southern Espinhaço).

7.4. Implications of the tectonic reconstruction

Understanding the geological Statherian evolution of the SFCP in the global tectonic context is challenged by the uncertainties of its position

in the pre-Rodinian supercontinent. Nevertheless, there is currently a broad consensus that a large supercontinent named Columbia appeared after several continental collisions and amalgamation between 2.1 and 1.8 Ga (Meert, 2002; Rogers and Santosh, 2002; Zhao et al., 2002, 2004; Hou et al., 2008a; Kusky and Santosh, 2009; Rogers and Santosh, 2009; Nance et al., 2014, among others). Presumably, its breakup occurred at ca. 1.35–1.20 Ga, which was related to the beginning of the Grenville cycle (e.g., Zhao et al., 2004; Hou et al., 2008b; Goldberg, 2010). Yet, numerous configurations of the Columbia supercontinent do not feature the SFCP as an independent crustal block in their paleogeographic reconstructions (e.g., Zhang et al., 2012). Because the SFCP was a part of this huge landmass according to most authors, it should record several tectonic events that occurred before its breakup in the late Mesoproterozoic. Therefore, as part of a research exercise, the meaning of the two superposed rifts that we investigated here could be considered in the context of a Mesoproterozoic supercontinent evolution. In addition to the geological evidence, paleomagnetic data are necessary to better constrain our hypothesis.

After the Rhyacian collage at ca. 2.05 Ga, the basement of the São Francisco crustal domain remained stable for slightly more than

200 Ma, while the continental collisions and the amalgamation of other parts of the Columbia supercontinent occurred. At this time, there was no intraplate deformation, rifting or magmatic record. Extensive rifting and anorogenic process throughout the São Francisco domain occurred only in the Statherian time (e.g., Schobbenhaus, 1993; Brito Neves, 1995, 2011). In general, intraplate extension and some silicic and mafic large igneous provinces (LIPs) arise after 1.8 Ga in other crustal blocks, and they have been interpreted as a breakup attempt of Columbia shortly after its final assembly (e.g., Teixeira et al., 2013; Youbi et al., 2013, and the references therein).

According to some authors (e.g., Rogers and Santosh, 2002; Hou et al., 2008a; Zhang et al., 2012), the Columbia supercontinent developed accretionary orogens over large extensions at its edge during a great part of its Paleo- to Mesoproterozoic evolution (Fig. 13A). The model proposed by Yakubchuk (2010) and Hou et al. (2008a) considers that the SFCP was adjacent to the present southeastern margin of the Amazon paleocontinent during Mesoproterozoic before the breakup. In this model, several Paleoproterozoic–Archean terranes of South America and West Africa compose a part of the Atlantica block as originally defined by Rogers and Santosh (2002). During the Statherian–

Fig. 13. The geotectonic hypothetical model to explain intracontinental rifting during the Statherian period in Atlantica block (Rogers and Santosh, 2002, 2004), for this time, part of the Columbia supercontinent as conceptualized by Hou et al. (2008a). The localization of the several cratonic nucleus older than 1.8 Ga inside the Atlantica block is not well constrained, but several authors believe that they made part of a single mega-continent soon after Rhyacian orogeny.

Calymnian time, the western margin of the Atlantica block was shaped by accretionary orogens, which are currently preserved as basement rocks of the Rio Negro-Juruena province of the Amazonian craton (Brito Neves, 2011; Fig. 13B). In fact, two superposed juvenile accretionary orogens have been characterized in this province: the Alto Jauru orogeny at ca. 1.79–1.73 Ga and the Cachoeirinha orogeny at ca. 1.60–1.53 Ga (Tassinari et al., 1996; Cordani et al., 2009; Hasui, 2013, and the references therein). At the intraplate region of the Amazonian protocraton (eastern Amazonian craton), we find a LIP related to the first orogeny, which is named the Teles Pires Igneous Province and consists of 1.80–1.75 Ga bimodal volcanic rocks and associated granitic rocks (Leite et al., 2001; Pinho, 2002; Batata et al., 2008; Fig. 13B). Based on the presented U–Pb and regional-based previous investigations, we favor this paleocontinental reconstruction.

The above framework allows us to correlate the extensive Statherian magmatism and rifting processes along the São Francisco block as a reflection of the Alto Jauru orogeny similar to the interpretation of the Teles Pires LIP. In this case, we interpret that several individual rifts dispersed in the São Francisco block were formed in intraplate environments in response to a far-field stress induced by convergence along the subduction zone (Fig. 13C). The overall picture includes all volcano-sedimentary successions (Algodão/Sapiranga, Araújo, São João da Chapada and Bandeirinha), anorogenic granitoids (Lagoa Real Suite, Borrachudos Suite, Paranã subprovince and Catolé Suite) and the related volcanic rocks (São Simão, Rio dos Remédios and Conceição do Mato Dentro, among others; Fig. 13). Furthermore, we could consider all magmatic records as part of a silicic LIP that was triggered by a convection-driven tectonic-plate motion – subduction-related upwelling (e.g., Faccenna et al., 2010). We define this first episode of intraplate extension/magmatism as the Tuxás event in order to avoid conflicts in the use of established stratigraphic names. The second episode of extension and silicic magmatism occurred during the EoCalymnian (1.6 to 1.53 Ga) and may be correlated to the Cachoeirinha orogeny as previously discussed. We call this episode Tupinaés Event (Fig. 13). Analogously to the Tuxás episode, the volcano-sedimentary records of the Pajeú and Mato Verde paleorifts and the anorogenic granitoids of the Tocantins subprovince could be a far-field response of the Tupinaés Event.

8. Conclusions

The Espinhaço aulacogen in the physiographic Northern Espinhaço domain records two superposed volcano-sedimentary sequences named Algodão (basal) and Sapiranga Synthem, which are here grouped into the Botuporã Supersynthem. The following conclusions can be drawn from the stratigraphic and geochronological data from these units:

- The Algodão and Sapiranga Synthems record similar lithofacies assemblages including mainly alluvial fan dominated by subaerial debris flows and associated braidplain and eolian facies association, lacustrine facies association and minor scree apron breccias. The petrographic composition and texture of the sandstones and conglomerates indicate a semi-arid/arid paleoclimate.
- Volcanic rocks occur near the top of both units with the contribution of volcanoclastic greater than effusive components. Preliminary data about their geochemical compositions indicates an ultrapotassic magmatism related to a complex magma source that could be associated with lithospheric extension where a decompression melting of hot asthenospheric mantle occurs as it rises passively beneath the intracontinental rifting zone.
- The U–Pb zircon ages of volcanic rocks from the Algodão and the Sapiranga Synthems indicate the development of two Statherian superposed rift precursors of the Espinhaço basin, at ca. 1775 ± 7 Ma and 1740 ± 10 Ma respectively.
- Several related-rift sequences and volcanic–plutonic associations of Statherian ages occur throughout the outcropping basement of the

western São Francisco–Congo paleocontinent, which could be related to the Late Paleoproterozoic extension events on the context of a Paleo-Mesoproterozoic supercontinent. Although the existence and configuration of pre-Rodinian continents and supercontinents are still much debated we invoke a far-field stress mechanism induced by the Statherian orogeny along the margin of the Atlantica block (part of Columbia) to explain this intracontinental rifting and associated magmatism. Additional studies will be necessary to better constrain the nature of this Statherian orogeny and related intracontinental riftings.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.gr.2014.06.012>. These data include Google map of the most important areas described in this article.

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