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ORIGINAL PAPER

# Provenance of Neogene deposits of Barreiras Formation in the southeastern Brazilian continental margin

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## Abstract
The Barreiras Formation records continental-to-shallow–water marine sequences deposited during the Paleogene–Neogene periods in the Brazilian continental margin. In northern Rio de Janeiro and southern Espírito Santo states, the Barreiras Formation preserve alluvial depositional system. The sediments were derived from a source located in the hinterland of the southeastern Brazilian continental margin, where rocks formed or reworked notably during the Gondwana supercontinent assembly are exposed. Detrital zircon U–Pb ages are mostly late Neoproterozoic, dominantly close to 608 Ma. Source rocks of this age occurred within the Ribeira and Araçuaí belts and were formed during their main magmatic activity. U–Pb zircon age distribution is similar to the southern and central Ribeira belt. Zircon fission-track ages occur in four main groups, between 429 and 358 Ma, 351 and 274 Ma, 270 and 171 Ma, and 167 and 127 Ma. Complex variation in the detrital zircon fission-track ages is related to the continental crust thermal evolution in the source areas. Older ages also occur between 534 and 433 Ma (Cambrian-to-Silurian periods) and are chrono-correlated to post-orogenic processes after the Gondwana supercontinent agglutination. Zircon fission-track ages between 429 and 274 Ma (Silurian to Permian periods) are related to the formation of the Pangea supercontinent, whereas the predominant zircon fission-track age group, between 270 and 171 Ma (Permian to Jurassic periods), is chrono-correlated to both orogeneses in the Gondwana supercontinent west margin and the Pangea supercontinent breakup. Zircon fission-track ages from 167 to 127 Ma are in the same period as the opening of the North and South Atlantic oceans. Data indicate that the thermal evolution of the source region either during the Gondwana supercontinent and South America Platform stages is complex.

**Keywords** Barreiras formation · Detrital zircon · Provenance · Thermal history

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## Introduction

The Barreiras Formation corresponds to the preserved sedimentary record of continental-to-shallow–water marine depositional systems developed from Paleogene-to-Neogene periods in the proximal portion of the sedimentary basins in the eastern and northern Brazilian continental margins (from Rio de Janeiro to Amapá states, e.g., Bigarella 1975; Arai 2006). In northern Rio de Janeiro and southern Espírito Santo states, the Barreiras Formation consists of alluvial depositional systems that transported sediments from a western located source region (e.g., Mello 2016). This region is included in the southeastern Brazilian continental margin (SEBCM), which is part of the South American Platform, the stable continental portion of the South American Plate (Fig. 1).


**Fig. 1** Satellite image of South America showing the location of the southeastern Brazilian continental margin (SEBCM) to the South American Platform and the Atlantic Ocean (Google maps; Milani and Thomaz Filho 2000)

The continental crust in the South American Platform agglutinated during the Gondwana supercontinent assembly when Amazonia, São Francisco, and Rio de la Plata cratons in South America, and Congo and Kalahari cratons in Africa collided to form the marginal orogenic belts (Araçuaí, Brasília, Dahomey, Damara, Dom Feliciano, East African–Antarctic, Gariep, Kaoko, and Ribeira belts; e.g., Trompette et al. 1992; Fig. 2). These processes occurred diachronically since the Cryogenian period and lasted until the final assembly in the Cambrian period (e.g., Schmitt et al. 2004). From Cambrian to Cretaceous periods, the Gondwana supercontinent was affected by several marginal continental arc accretions and intraplate magmatism, as well as the collision with Laurasia to originate the Pangea supercontinent in Permian period (e.g., Stampfli et al. 2013). The breakup of the Gondwana supercontinent in the Cretaceous period formed the South American Plate and the Brazilian continental margin (e.g., Martins and Coutinho 1981; Chang et al. 1992). These events influenced the thermal structure of the Gondwana supercontinent from its assembly to the breakup,

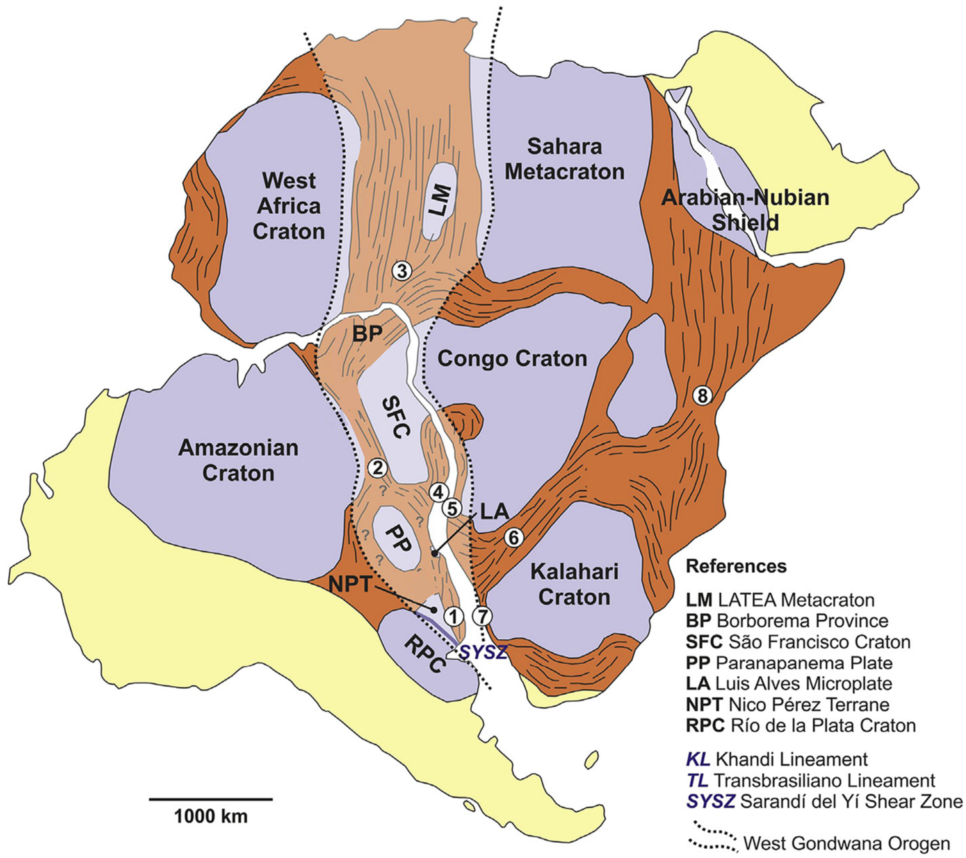



**Fig. 2** Cartoon of the southwest Gondwana supercontinent showing Neoproterozoic cratons in blue and orogenic belts in orange; yellow areas are Phanerozoic orogens: 1—Dom Feliciano, 2—Brasília, 3—Dahomey, 4—Ribeira, 5—Kaoko, 6—Damara, 7—Gariep, and 8—East African–Antarctic (modified from Oriolo et al. 2017)

and the SEBCM also underwent subsidence and exhumation processes from the breakup of the Gondwana supercontinent (Hackspacher et al. 2007; Maizatto et al. 2009; Cogné et al. 2011; Japsen et al. 2012; Jelinek et al. 2014; Oliveira et al. 2016; Krob et al. 2019; Vauchez et al. 2019).

The detrital zircon grains in the Barreiras Formation record the ages and thermal evolution of the source areas. To gain knowledge about the ages of the source region, we present a provenance study of Barreiras Formation based on U–Pb and fission-track (FT) ages of detrital zircon grains. The information points to a unimodal zircon U–Pb age pattern and a complex FT age distribution, attributed to the evolution of the Gondwana supercontinent and the South American platform.

## Regional geology

The Barreiras Formation is a result of a source-to-sink relation between the denudation of elevated source areas located to the west and the deposition of alluvial systems controlled by downstream factors (sensu Catuneanu et al. 2019; Arai 2006). In northeastern Brazil, deposition of the Lower Barreiras Formation occurred by a transgressive–normal regressive cycle during the Upper Oligocene-to-the Miocene (Serravalian; Arai 2006), whereas in the Tortonian, a forced regression occurred, with the development of a disconformity as a third-order sequence boundary. Another transgressive–normal regressive cycle controlled the preservation of the Upper Barreiras Formation during the Zanclean; this sequence is bounded at the top by another third-order sequence boundary developed during the Pleistocene sea-level fall and Holocene high (Arai 2006; Fig. 3). In the northern Rio de Janeiro and southern Espírito Santo states, the Barreiras Formation crops out in the coastal regions in several meter-high cliffs of low-lying coastal plateau. To the west, the Barreiras Formation onlaps the Neoproterozoic rocks (Fig. 4). To the south, it occurs in the lowest portions of the landscape, controlled by normal faults.

The SEBCM is classified as an elevated continental margin. Jelinek et al. (2014) calculated an average denudation of 3.5 km for the Mantiqueira Range from 110 Ma to the present. Jelinek et al. (2014) also present details about the sedimentary record, erosion time intervals, average denudation, and the range of denudation rates for each time interval and each geomorphic domain. Additionally, Maizatto et al. (2009) and references therein suggest that the abundance of *Callialasporites* sp. *cf. Perotrilites* sp. pollen grains in the Upper Cretaceous is possibly indicatives of elevated areas. The continental portion of the SEBCM actual geomorphology is formed by a series of elevated topographic

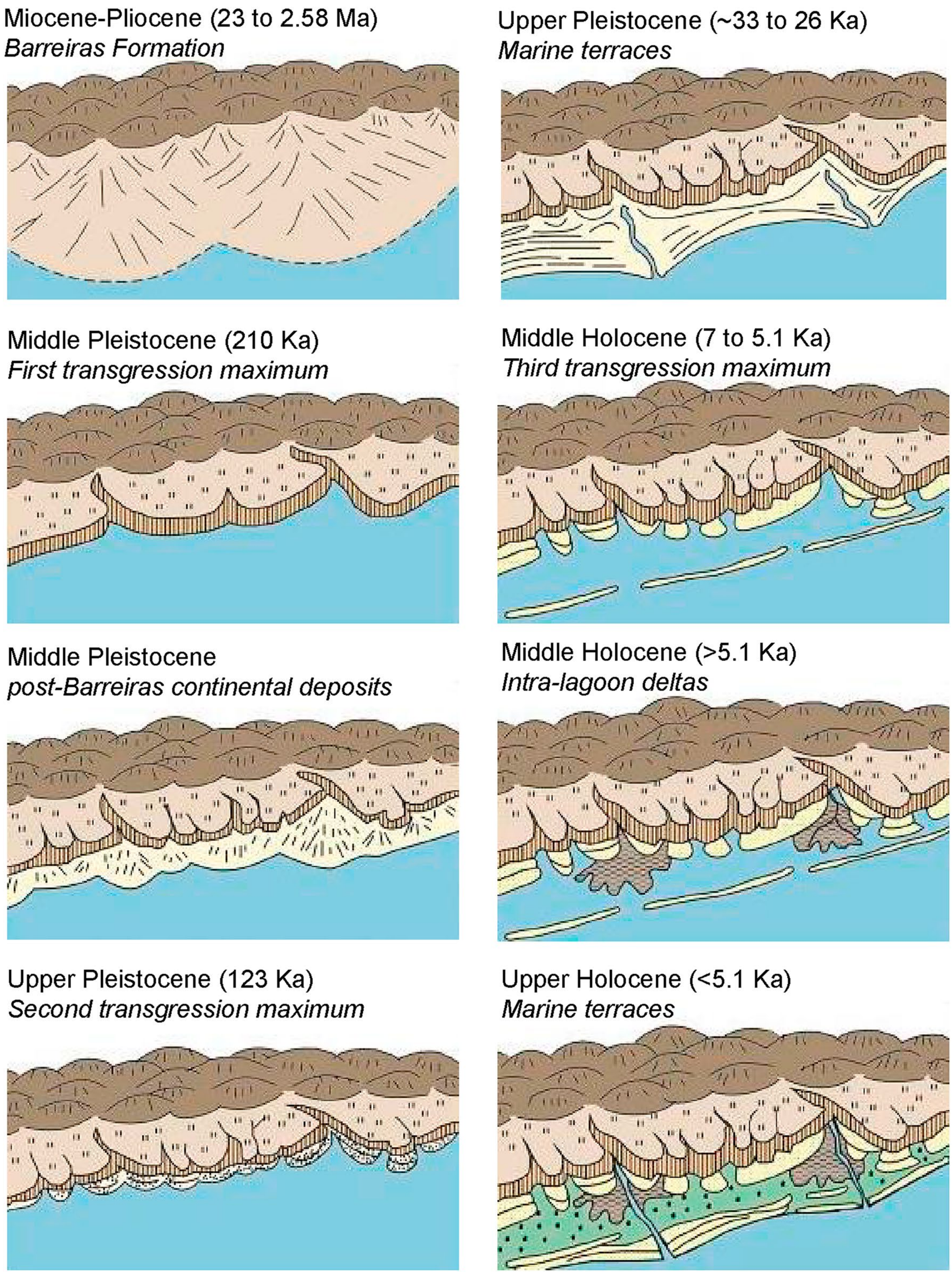



**Fig. 3** Model of the coastal sedimentation evolution from Miocene–Pliocene to Holocene, which fits the geological record from the southeastern Brazilian continental margin, according to Martin et al. (1993; . Last glacial maximum during Upper Pleistocene, according to Clark et al. (2009) (modified from Plantz, 2017)

features, which can have up to 2 km high as the Serra do Mar and Serra da Mantiqueira mountain ranges (Fig. 4b; e.g., Ab'Saber 1962; Cruz 1990; Almeida and Carneiro 1998; Hartwig and Riccomini 2010; Vieira and Gramani 2015).

The Neoproterozoic units within the Ribeira and Araçuaí belts are the most probable sources for the sediments preserved in the Barreiras Formation in northern Rio de Janeiro and southern Espírito Santo states (Fig. 4). Additionally, Archean and Paleoproterozoic units within these orogens and the distal São Francisco craton are also candidates for source rocks. The Ribeira and Araçuaí belts formed during the amalgamation of the western portion of the Gondwana supercontinent in the late Neoproterozoic (e.g., Almeida 1977; Pedrosa-Soares et al. 2001; Heilbron and Machado 2003; Vauchez et al. 2019). These belts are part of an orogenic continuity located in the southward termination of the rigid São Francisco craton, which caused an oblique collision and lateral escape to the Congo craton (e.g., Egydio-Silva et al. 2018). Both belts have similar magmatic record, P–T paths during peak metamorphism, and timing of orogenic events (e.g., Egydio-Silva et al. 2018, and references therein).

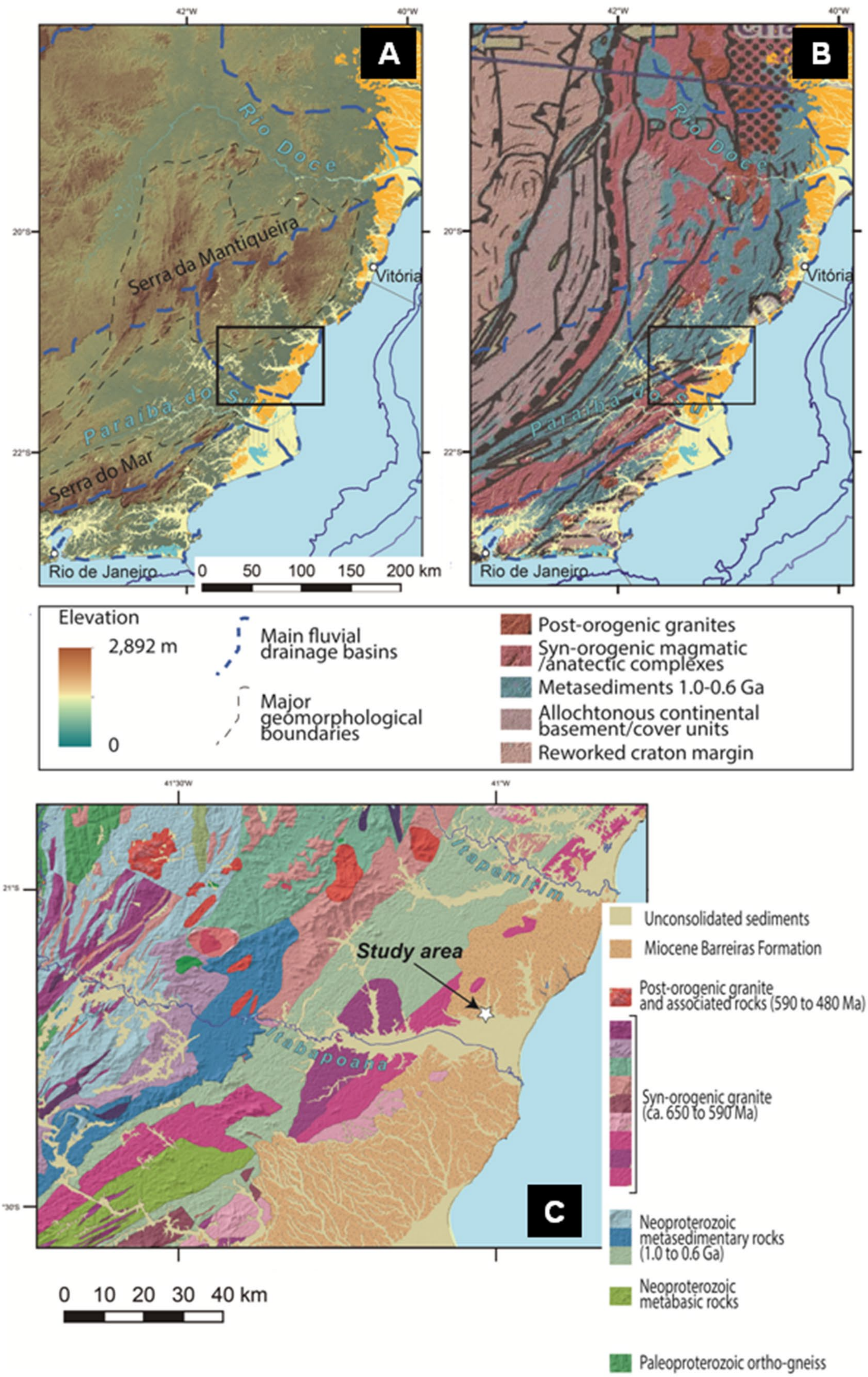
The older units in the Ribeira and Araçuaí belts comprise Archean blocks, such as the Guanhães and Porteirinha, reworked by Rhyacian–Orosirian orogenic systems, as the Juiz de Fora Complex (e.g., Noce et al. 2007; Van Ranst et al. 2019; Fig. 4b). There is not a consensus about the Neoproterozoic evolution of the Ribeira and Araçuaí belts. One hypothesis is that there are six Neoproterozoic granitoid suites within both belts, which are: (1) the Rio Doce magmatic arc (G1 suite) formed between 630 and 585 Ma; (2) the G2 suite formed between 585 and 564 Ma during the syn-collisional stage; (3) the G3 suite comprised mostly by leucogranites formed between 656 and 565 Ma; (4) the G4 and G5 suites which are related to post-collisional stages formed between 530 and 490 Ma; (5) and the last event attributed to the gravitation collapse of the orogen (e.g., Pedrosa-Soares et al. 2008; Van Ranst et al. 2019; Fig. 4b).

Another interpretation is that the main orogenic activity (deformation, magmatism, and metamorphism) occurred between 600 and 570 Ma in both Ribeira and Araçuaí belts, which are composed of a predominantly continental margin terrane; metasedimentary rocks, which can be migmatitic; and granitic intrusions and anatexites (e.g., Egydio-Silva et al. 2018 and references therein; Fig. 4b).

## Materials and methods

Sedimentary facies were described and classified in the field, including texture, structure, and composition descriptions, and paleocurrent vector measurements. Facies thickness was measured, and vertical facies logs were drawn. Facies were grouped into facies associations to unravel the architectural elements and depositional systems, according to Miall (2006).

Eleven samples were collected in an outcrop, which reveals the most representative facies succession of the Barreiras Formation in southern Espírito Santo state. The outcrop has a stratigraphic thickness of 17 m. Nearly 500 g of a sample from each stratigraphic level were taken and processed by panning, from which heavy mineral concentrates were extracted. After crushing and milling using a jaw crusher and ring mill apparatus as well as heavy mineral concentration by hand panning, zircons were separated using heavy liquids and a Frantz® magnetic separator. The handpicked grains were mounted in the PFA Teflon® with a hot plate. After assembly, the mounting was grinded in three stages: manually employing 1200-grit sandpaper (~ 10 µm), 2400-grit sandpaper (~ 5 µm) for 2 min, and 4000-grit sandpaper (~ 3 µm) for 5 min using a polishing machine with 60 rpm. The mount was then polished with 1/4 µm diamond compound for 10 min at 60 rpm. Finally, the zircon etching was made with a 1:1 eutectic mixture of KOH and NaOH at 225 ± 2 °C (Tagami et al. 1990) in periods varying from 2 to 4 h, since the time for the adequate etching can be different for each sample (Garver, 2003). The etching time applied in the samples following the criterion established and described in Yamada et al. (1995a; b). Furthermore, following the methodology from Garver and Kamp (2002), the zircons used in this work do not show a high degree of amorphization. Therefore, the zircons analyzed in this work do not need PAZ correction due to a high degree of amorphization. Results of samples analyzed via FT and U–Pb are presented in Table SM1. The FT densities ($\rho_S$) were obtained at the Physics, Chemistry, and Mathematical Department from Federal University of São Carlos, Sorocaba campus, Brazil, using a Leica DM2700 M microscope (dry, nominal microscope magnification 1500×). The U concentration measurement (to FT ages) and U–Pb dating were carried at the Isotope Geology Laboratory of the Federal University of Pará, Brazil, using a high-resolution Neptune Thermo Finnigan MC-ICP-MS equipped with an Nd:YAG 213 nm LSX-213 G2 CETAC laser microprobe. The U–Pb analyses were carried out using the standard-sample bracketing method (Albarède et al. 2004) using the GJ-1 standard zircon (Jackson et al. 2004) to control the ICP-MS fractionation. Details of the operating conditions and instrument settings of MC-ICP-MS and laser ablation system during analytical sessions are listed in Table 1. During the analytical session, zircon standard FCT was analyzed as an unknown sample, in agreement with the accepted age of 27.5 ± 5.2 Ma (2σ, $n = 37$) by Lanphere and Baadsgaard (1997) and Tagami et al. (2003). Common lead ($^{204}$Pb) interference and background correction are usually carried out by monitoring the $^{202}$Hg and $^{204}$(Hg + Pb) masses during analytical sessions and using a


A
B
C
42°W
40°W
20°S
22°S
Rio Doce
Serra da Mantiqueira
Vitória
Paraíba do Sul
Serra do Mar
Rio de Janeiro
0 50 100 150 200 km
Elevation
2,892 m
0
Main fluvial drainage basins
Major geomorphological boundaries
Post-orogenic granites
Syn-orogenic magmatic /anatectic complexes
Metasediments 1.0-0.6 Ga
Allochtonous continental basement/cover units
Reworked craton margin
41°30'W
41°W
21°S
Itapemirim
Itabapoana
Study area
0 10 20 30 40 km
Unconsolidated sediments
Miocene Barreiras Formation
Post-orogenic granite and associated rocks (590 to 480 Ma)
Syn-orogenic granite (ca. 650 to 590 Ma)
Neoproterozoic metasedimentary rocks (1.0 to 0.6 Ga)
Neoproterozoic metabasic rocks
Paleoproterozoic ortho-gneiss

◂**Fig. 4** Regional geomorphological, hydrological, and tectonic setting of the Barreiras Formation in the SEBCM. **a** Simplified geological map of part of the Ribeira and Araçuaí belts and the Barreiras Formation in the northern Rio de Janeiro and southern Espírito Santo states with the location of the study area. The inset shows the map location to South America (modified from Vieira et al. 2014; Heilbron et al. 2016)

model Pb composition (Stacey and Kramers, 1975). After the blank and common Pb corrections, the ratios and their absolute errors (one sigma level) of $^{206}Pb^*/^{238}U$, $^{232}Th/^{238}U$, and $^{207}Pb^*/^{206}Pb^*$ were calculated using an Excel spreadsheet (Chemale Jr. et al. 2012). The * indicates the radiogenic Pb.

The intercept method for laser-induced Pb/U fractionation was used to correct the $^{206}Pb^*/^{238}U$ ratio due to its usual linear fractionation (Kosler et al. 2002). The uncertainty of the fractionation-corrected ratio was calculated as one SD (standard deviation) of the intercept ($\sigma_{R(o)}$), which is the isotope ratio at the start of laser ablation. The internally derived errors were calculated conventionally by considering the uncertainties (1 SD) of the respective background signals. For the $^{232}Th/^{238}U$ and $^{207}Pb^*/^{206}Pb^*$ ratios, the mean values were used after discarding the outliers. The estimated age for each zircon grain was established as the $^{207}Pb/^{206}Pb$ age for zircons older than 1.0 Ga and the $^{238}U/^{206}Pb$ age for zircons younger than 1.0 Ga for zircon analysis that yielded 100 ± 10% of concordance. Probability density plot diagrams were constructed using the Isoplot/Ex software (Ludwig 2008). Analytical procedures were similar to those of Milhomem Neto and Lafon (2019).

The U–Pb and FT methods were applied to the same spot in each detrital zircon grain analyzed. The ages found by both methods (Table SM1) were obtained in the same grains and, more specifically, in the same areas of the grains. The grains were first dated by FT using absolute calibration (more details see Dias 2012; Soares et al. 2014; Dias et al. 2017b, 2018) and then by the U–Pb method by LA-MC-ICP-MS. The analysis can be concentrated at the same site of zircon grain, because the tracks revealed during the conventional etching to FT guided us to the dating by U–Pb. Images acquired by optical microscopy were used for the identification of the FT spot. It is known that zircon may exhibit different ages. Zircon with prolonged and complex histories can thus contain zones of dramatically different ages (usually, with the oldest and youngest zones forming the core and rim, respectively). The interest here is not to suppress the possible metamorphic events through which the sample passed, but to be able to compare both crystallization and thermal events experienced by the samples. The results present a degree of concordance (see Table SM1). The populations of U–Pb and FTT ages were determined using Isoplot 3.7 and Radial Plotter, respectively (Ludwig 2008; Vermeesch, 2009). Additionally, zircon grains that were analyzed by U–Pb and FT were grouped in different clusters using a k-means clustering algorithm—Fig. 10 (Lloyd 1982).

## Results

The results of the facies and detrital zircon U–Pb and FT analysis are described. In the study area, two facies sets are identified within the Barreiras Formation. The lower set is composed of massive quartz–feldspar wackes (Wqf; Fig. 5) that evolve to laminated mudstone or massive claystone (Mc). Above, trough cross-bedded sandstone, massive sandstone, and massive-to-graded conglomerate eventually cross-bedded occur (Ts; Fig. 6). Stratal geometry in the lower facies set is tabular to channelized. Facies association is related to proximal to an intermediate portion of an alluvial system. Sedimentary processes involve deposition of debris flow by a gravitational process, which generates massive muddy-sandstone, channelized conglomerate and sandstone, and flood events deposited mudstone and claystone. The upper facies set is comprised of cycles of massive muddy-sandstone composed mostly of quartz grains in a kaolinitic matrix (Quartz-wacke; Wq), interbedded by bioturbated mudstone (Btm), massive mudstone, and matrix-supported intraclastic breccia (Bcc). Quartz–wackes are unevenly cemented by goethite, forming lateritic concretions that preserve roots tubes in the lower part of the sedimentary cycles. Vertical and horizontal centimeter burrows occur in the bed top (Fig. 6). Debris flow events deposited the upper facies set in a proximal alluvial setting.

A total of 410 zircon grains were analyzed by the U–Pb method, from which 350 ages are concordant (85%). From the concordant zircon ages, 73% are in the time interval between 655 and 540 Ma. Remaining grains occur in the time interval between 535 and 467 Ma (5%), 716 and 658 Ma (7%), 854 and 735 Ma (4%), 1152 and 912 Ma (1%), 1745 and 1635 Ma (1%), 1977 and 1847 Ma (4%), and 2214 and 2005 Ma (5%). These age populations were determined using Isoplot 3.7 (Ludwig 2008). On the other hand, the FT ages were classified according to the main populations using the method published in Vermeesch (2009), and the ages occur in four main groups, between 429 and 358 Ma (14%), 351 and 274 Ma (19%), 270 and 171 Ma (32%), and 167 and 127 Ma (12%). Main FT age peaks are 463 ± 11 Ma, 345 ± 8.5 Ma, 243 ± 5 Ma, 163 ± 3.5 Ma, and 93.5 ± 2 Ma. Minor FT age groups occur between 534 and 502 Ma (5%), 494 and 433 Ma (8%), and 118 and 71 Ma (9%). The maximum and minimum FT ages are 534 ± 33 (MTZ-01-B01-C01-G02, grain 1) and 71 ± 5 (MTZ-01-B03-C03, grain 16; Table SM1), respectively. Figure 7 shows the U–Pb probability density plots (Fig. 7b) and central FT ages (Fig. 7c) for the 11

**Table 1** MC-ICP-MS and laser operating conditions

| MC-ICP-MS | Neptune (Thermo Finnigan) | Nd: YAG 213 *LSX-213 G2 CETAC* laser | |
|---|---|---|---|
| Cool gas (Ar) | 16.0 l/min | Helium gas flow | 450–500 mL/min |
| Auxiliar gas (Ar) | 0.7–0.8 l/min | Spot size | 25 µm |
| Carrier gas (Ar) | 1.2–1.3 l/min | Frequency | 10 Hz |
| Power | 1200 W | Power | 50–60% |
| Analysis mode | Static in low resolution | Energy | 4–5 J/cm$^2$ |
| Acquisition | 40 cycles of 1.049 s | Ablation time | ~40 s |
| Faradays | $^{206}$Pb, $^{208}$Pb, $^{232}$Th, $^{238}$U | – | – |
| MIC's | $^{202}$Hg, $^{204}$Hg + $^{204}$Pb, $^{207}$Pb | – | – |

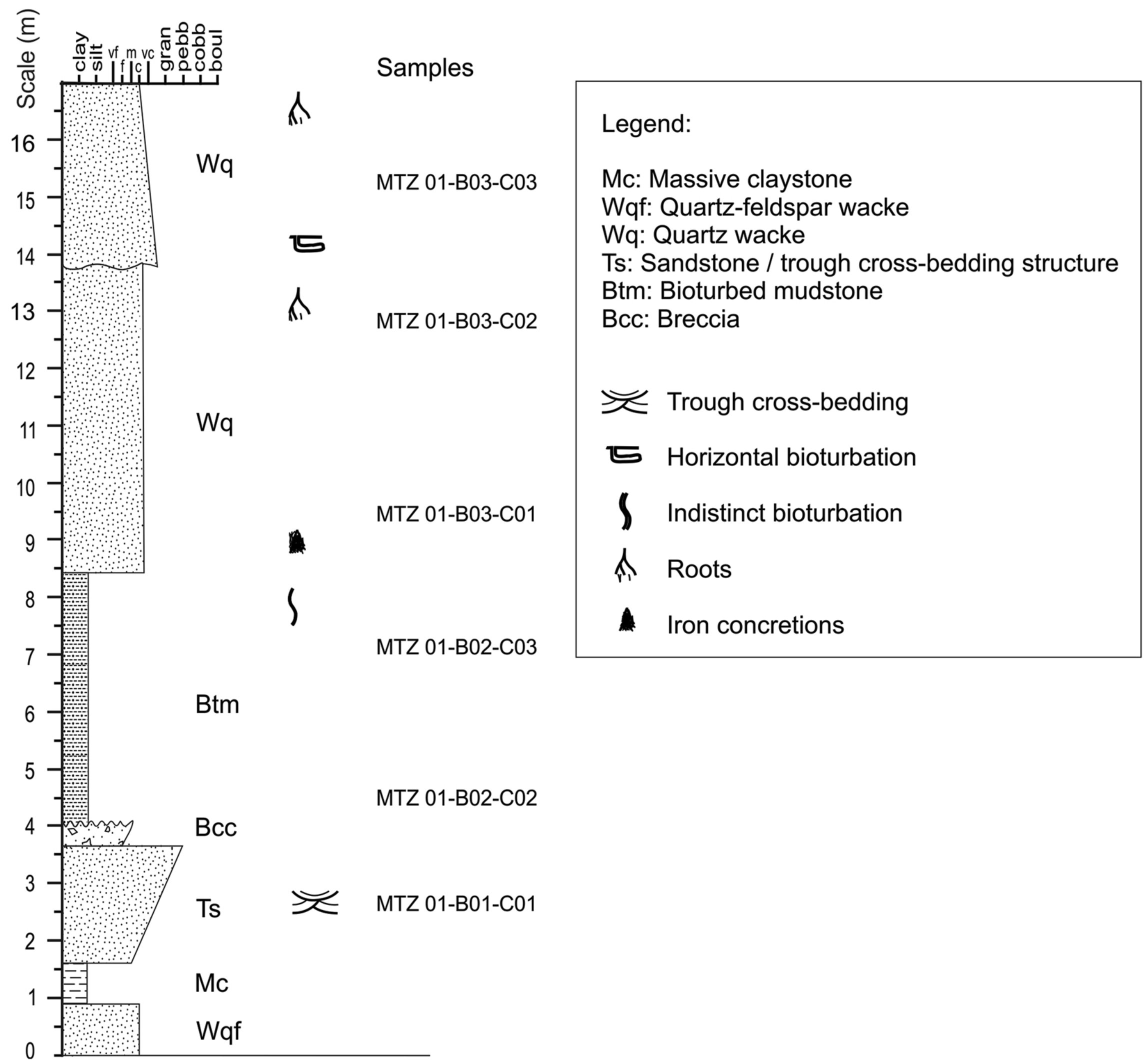



**Fig. 5** Facies succession of the Barreiras Formation in the southern Espírito Santo state. Facies code is according to the text

samples according to its stratigraphic positioning. Despite the small variations in the detrital zircon U–Pb ages, samples display rather the same age spectra, which allow us to construct an integrated probability density plot, including all samples, which is presented in Fig. 8.

## Discussion

The integration of the new data presented herein with published information allows the discussion of key aspects of

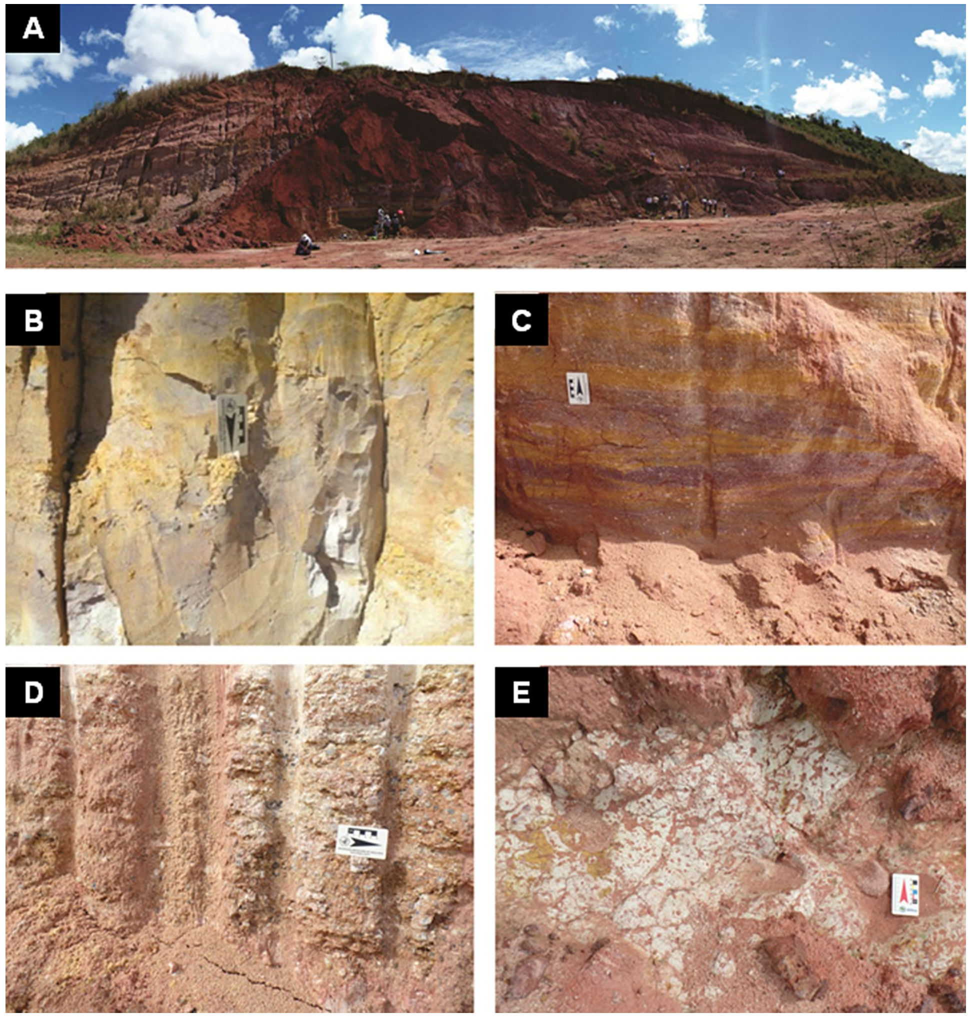


**Fig. 6** Field photos of the analyzed section. **a** General view; **b** Quartz–Feldspar wacke (Wqf) representing proximal facies of an alluvial system associated with debris flow; **c** Quartz feldspars sandstone (Ts) of the lower facies set. Feldspars are predominantly kaolinized and give the mottled appearance with white dots. The variation from reddish to orange colors are due to pedogenetic processes and is sometimes discordant with the stratigraphy; **d** Aspect of the conglomerate lowers facies set. These facies vary from massive to structured gravels with graded to trough cross-bedding structure filling channelized features. Conglomerates and sandstones represent proximal-to-median alluvial facies; **e** Aspect of quartz-wacke (Wq) of the upper facies set, with visible bioturbations

the SEBCM regional evolution, which are based on the depositional system preserved in the Barreiras Formation in the study area and the sediment source region.

## Depositional system

Facies analysis points to an alluvial depositional system by the identification of debris flow, bedload, and flood processes for the transport and deposition of the lower portion of the studied section, and proximal debris flow for the upper section, according to facies models (Miall 2010; Figs. 5, 6). Different authors have also concluded that the Barreiras Formation in northern Rio de Janeiro and southern Espírito Santo states was deposited in an alluvial depositional system (Martin et al. 1993; Morais et al. 2006; Mello, 2016; West and Mello 2020). Deposition occurred in the Miocene, and both Paleocurrent and facies gradient attest undoubtedly for a source area located in the hinterland of eastern Brazil (Fig. 4).

## Source area location

For the source area location, two main premises are considered. First, this region of the South American Continent has not changed significantly from Miocene to recent, neither its geomorphology nor hydrography. An elevated continental margin marks the geomorphology of the SEBCM (e.g., Japsen et al. 2012 and references therein) and by the most outstanding orographic features of the eastern portion of the South American continent, the Serra do Mar and Serra da Mantiqueira mountain ranges (e.g., Almeida and Carneiro 1998; Vieira and Gramani 2015; Fig. 4a). Second, the main hydrographic basins in the SEBCM are the Paraíba do Sul and Rio Doce basins, which total circa 130.000 km$^2$ of the drainage area (Fig. 4a). These drainage basins are active since at least the Cretaceous with the rifting of the Gondwana supercontinent and the Atlantic Ocean formation (e.g., Potter 1997; Ribeiro et al. 2018). Thus, it is evidenced that the exposed bedrocks in the hinterland of Rio de Janeiro and Espírito Santo states

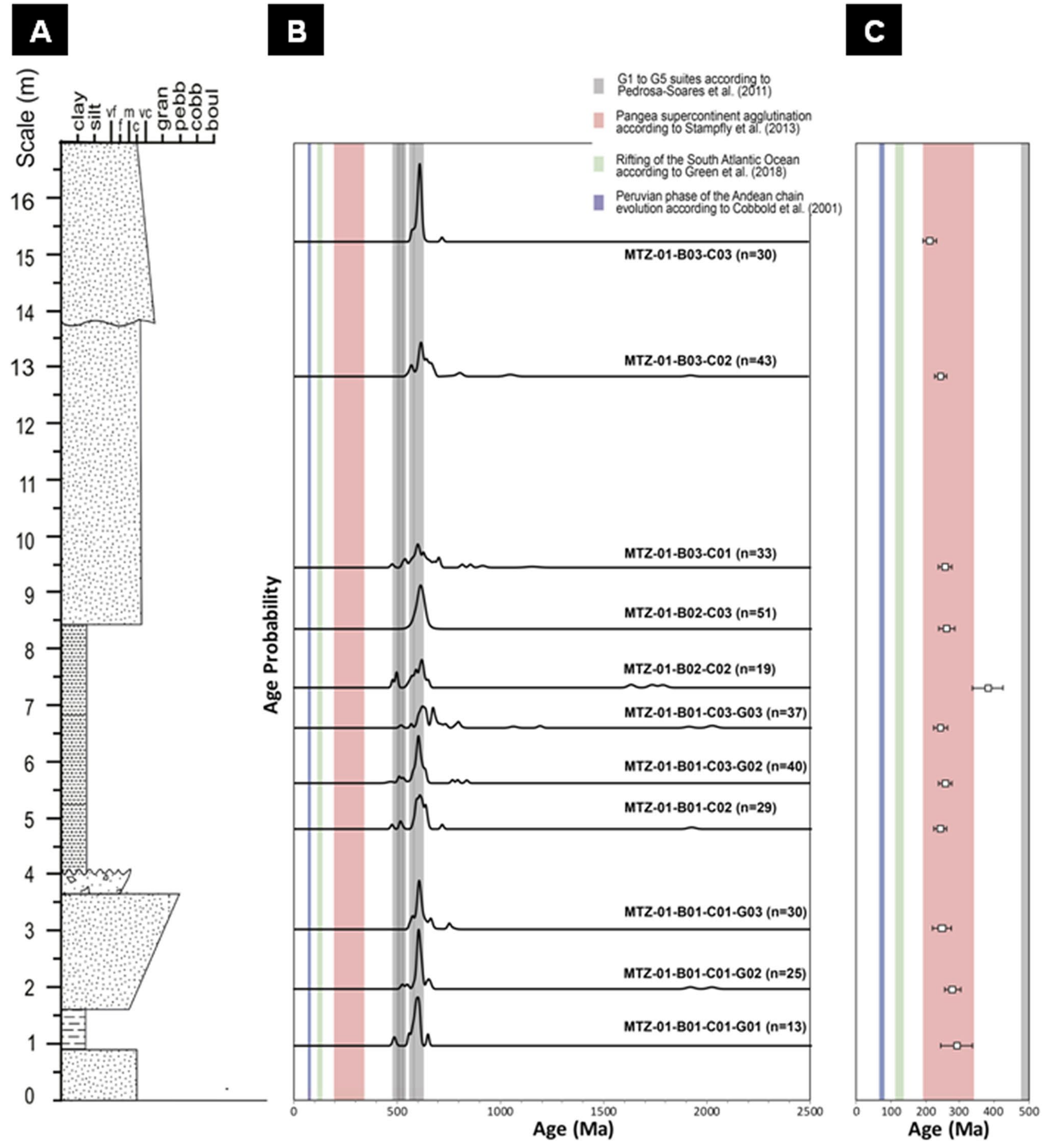



**Fig. 7** Detrital zircon U–Pb and FT ages along with stratigraphic positioning. **a** Facies succession; **b** normalized probability plot of the U–Pb ages; **c** FT central ages. Color intervals correspond to the main tectonic events discussed in the text

are the most probable Barreiras Formation sediments source area, and may also include the eastern portion of the Minas Gerais state. Bedrock in these areas is included in the Ribeira and Araçuaí belts and in the São Francisco Craton (Fig. 4b).

## Ribeira and Araçuaí belts as the probable sources for the zircon grains

Egydio-Silva et al. (2018) have comprehensively reviewed the connections between Ribeira and Araçuaí belts, and

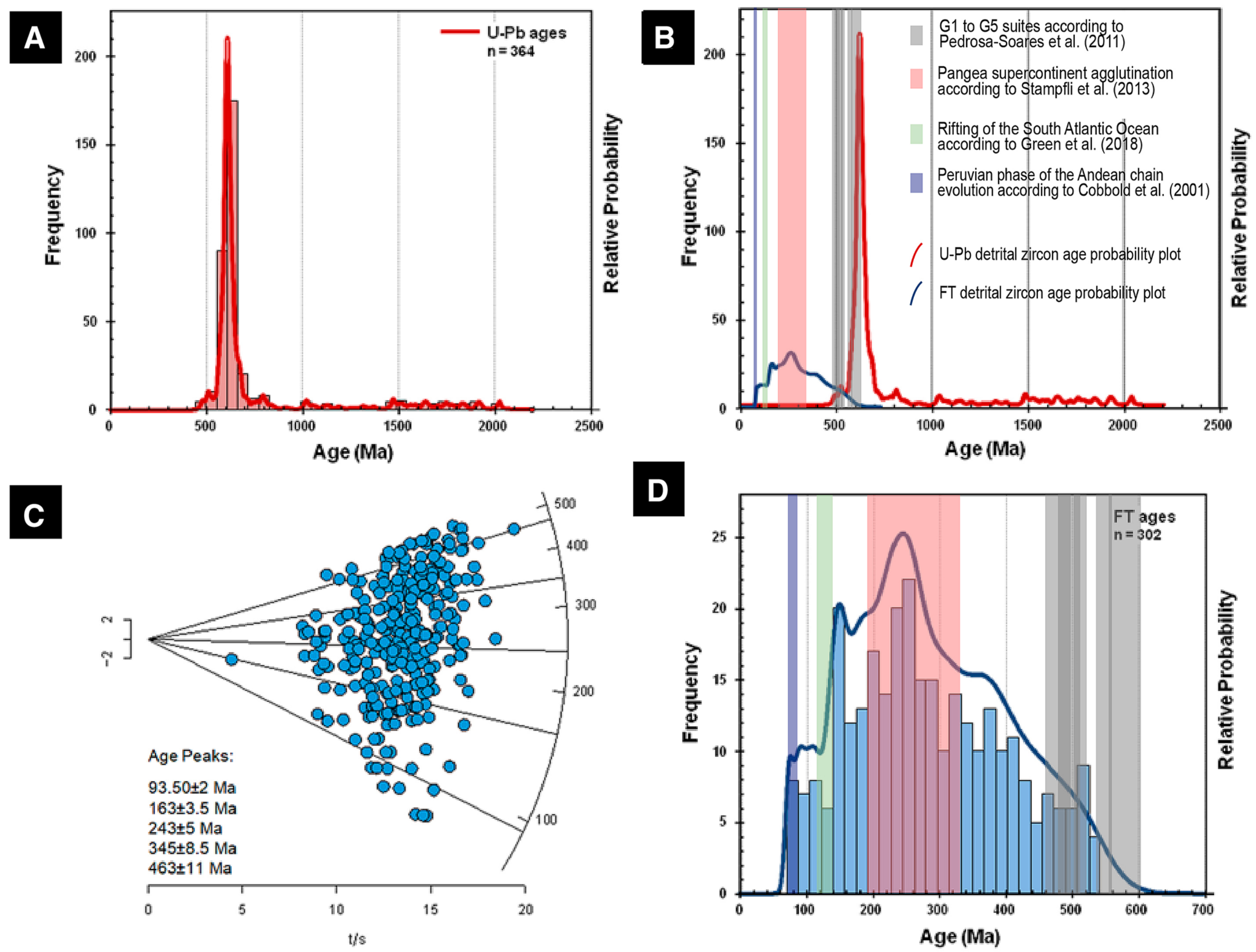



**Fig. 8** Results of the analytical data. **a** Histograms with normalized U–Pb age probability for all samples; **b** overlap of the FT apparent ages and U–Pb zircon ages with identification of geological events which are chrono-correlated; **c**, **d** radial plotter and histograms obtained by FFT

demonstrated that the age constraints in both belts are quite similar, both peak metamorphism and crystallization, but subtle differences are summarized. In central Ribeira belt, collision started at ca. 610–590 Ma, followed by granulite facies metamorphism and melting of the lower crust from 600 to 550 Ma, and post-orogenic magmatism at ca. 520–480 Ma (Bento dos Santos et al. 2015; Meira et al. 2015; Egydio-Silva et al. 2018). In northern Ribeira and Araçuaí belts, syn-kinematic metamorphism has been dated at ca. 590 and 580 Ma, respectively (Petitgirard et al. 2009; Machado et al. 1996). Compelling interpretation exists in the literature about the tectonic evolution of the Araçuaí belt; one hypothesis is that extensive magmatism in this belt was synchronous with high-temperature deformation and partial melting at least between 600 and 570 Ma (e.g., Egydio-Silva et al. 2019, and references therein). According to the same authors, most published ages are younger than 590 Ma and contemporaneous of the syn-kinematic high-grade metamorphism in the Araçuaí belt. After the orogenic peak, several magmatic events occurred until 520–500 Ma (Egydio-Silva et al. 2019, and references therein). Final orogenic processes occurred during Buzios orogeny, from 510 to 470 Ma (Schmitt et al. 2004).

Zircon grains in the Barreiras Formation in the study area have ages dominantly close to 608 Ma (Figs. 7, 8). Most zircon grains formed in the Neoproterozoic Era during the Gondwana supercontinent assembly. There is no record of Archean zircon grains in our data, which excludes the São Francisco Craton as a primary source area for the Barreiras Formation. However, the São Francisco Craton also includes Paleo, Meso, and Neoarchean terrains and Paleoproterozoic mobile belts, whereas Ribeira and Araçuaí belts are composed of reworked Paleoproterozoic units and Neoproterozoic sequences and magmatic arc associations (Fig. 4b). Figure 9 presents the cumulative and normalized probability plots for the U–Pb detrital zircon ages in the

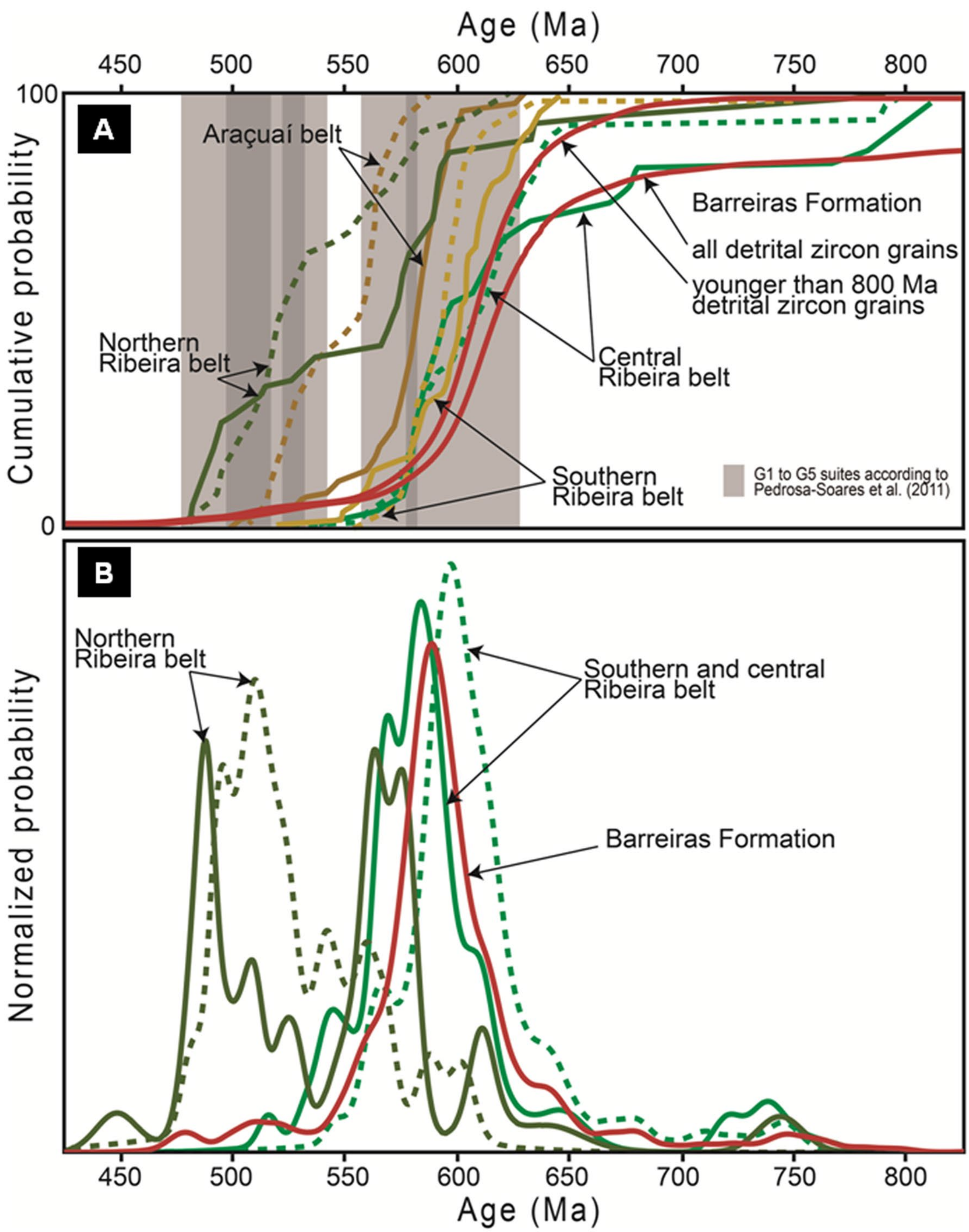



**Fig. 9** Age cumulative probability plot from Ribeira and Araçuaí belts (mostly U–Pb zircon ages; and the present study. The dotted line corresponds to peak metamorphism and continuous line to crystallization ages. Red lines are the cumulative probability plot for the Barreiras Formation U–Pb detrital zircon ages presented herein (modified from Egydio-Silva et al. 2019 and references therein)

Barreiras Formation and the U–Pb ages (mostly zircon) of the southern, central, and northern Ribeira and Araçuaí belt (data compiled by Meira et al. 2015 and Egydio-Silva et al. 2018). Two plots are shown for the Barreiras Formation in Fig. 9a, one including all dated grains and others including grains younger than 800 Ma. The U–Pb detrital zircon age distribution is similar to the U–Pb age distribution of the southern and central Ribeira belt (Fig. 9).

## Southern and central Ribeira belt as probable source terrain

The final orogenic stages in these belts led to the formation of the Gondwana Supercontinent. Igneous and high-grade metamorphic rocks formed during the compressional stages, associated with ductile deformation within the West Gondwana orogen (e.g., Alckmim et al. 2000). This region has been relatively stable during the Gondwana and later Pangea Supercontinents evolution from ca. 480 Ma until ca. 130 Ma, with rifting and formation of the South Atlantic Ocean. There is well-documented evidence for a complex thermal evolution of the SEBCM. Calculated cooling rates for the Ribeira and Araçuaí belts are approximately 1 °C/Ma (Bento dos Santos et al. 2015) and 3–5 °C/Ma (Petitgirard et al. 2009; Vauchez et al. 2019), respectively. Vauchez et al. (2019) calculated cooling rates for units within the Araçuaí belt, based on the integration of zircon U–Pb ages and amphibole, biotite, and muscovite $^{40}Ar/^{39}Ar$ ages. U–Pb zircon ages suggest that at circa 600 Ma to at least 570 Ma, the central portion of the Araçuaí belt was in the middle-to-lower crust conditions, heated at circa 800 °C and producing anatectic magmas (Vauchez et al. 2019). Same authors concluded that: (1) a differential tectono-thermal evolution occurred between the eastern portion and the central and western portions of the Araçuaí belt; (2) a protracted orogenic evolution occurred from circa 630 Ma, with the crustal thickening and heating initiation, to the ending of partial melting at least circa 570 Ma; (3) a slow cooling rate of 3–5 °C/Ma, reaching circa 500 °C at 510–500 Ma and circa 300 °C at 480 Ma; (4) anatexis of the eastern portion was diachronic. There is a spatial variance also in apatite FT ages in the SEBCM, which can be explained by differential reactivation of Araçuaí belt basement structures and impact from a drainage network (Jelinek et al. 2014; Van Ranst et al. 2020).

Krob et al. (2019) also addressed the complexity in the t-T-evolution for the SEBCM. According to these authors, zircon FT and zircon He ages to the south of the SEBCM have not been affected thermally since the basement formation in Late Neoproterozoic (Krob et al. 2019). In contrast, a complex t-T-evolution occurred for other areas, including the thermal influence of the Gondwana supercontinent breakup with large volumes of magma erupted during the Paraná-Etendeka flood basalt event (Krob et al. 2019). The same authors also concluded that the Late Neoproterozoic-to-Early Paleozoic t-T-evolution might not necessarily be closely related to the Upper Paleozoic-to-Cenozoic geological evolution, with distinct exhumation occurring in different blocks over time (Krob et al. 2019). Some authors tentatively relate the driving forces that produced exhumation of the SEBCM to regional-scale processes such as the compressive regime of the Andean orogeny and variable rates of spreading of the Mid-Atlantic Ridge (Van Ranst et al. 2020).

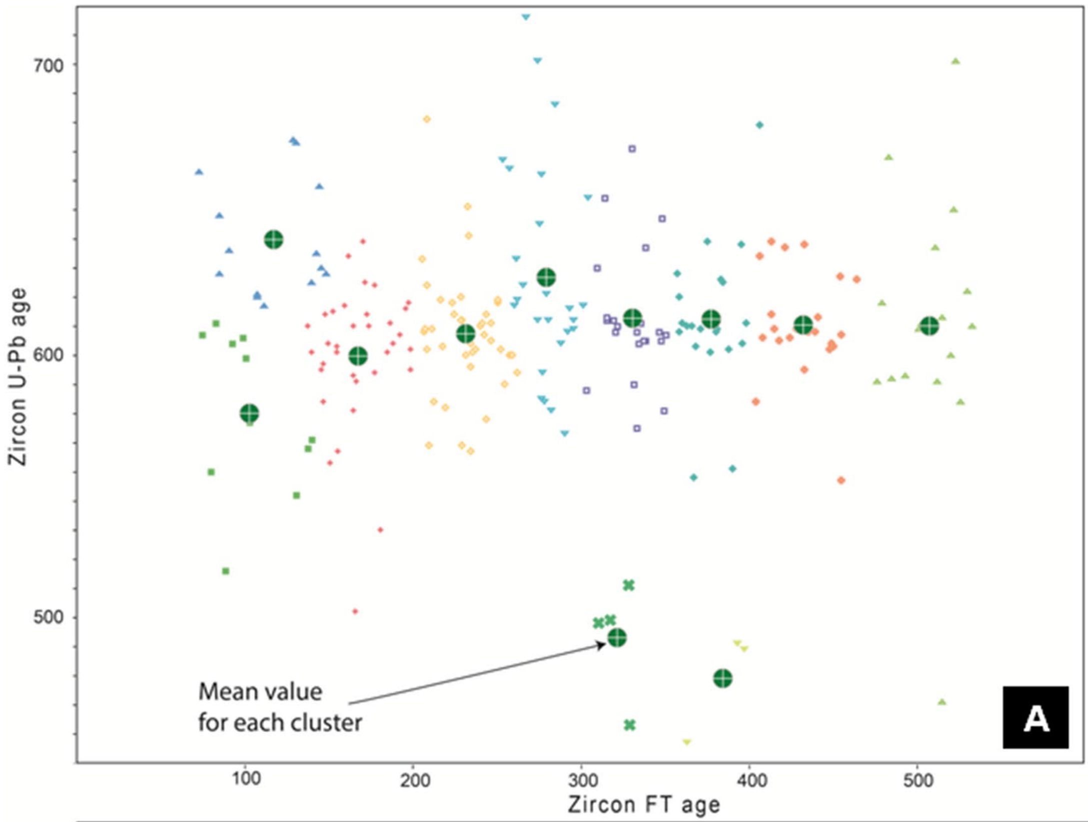
Additionally, in central Brazil, a relatively fast post-orogenic cooling occurred from Devonian to Permian with the exhumation of the Brasília belt (Fonseca et al. 2020). In contrast, from the Mesozoic to the present, the same region has been relatively stable (Fonseca et al. 2020). In southern Brazil, apatite FT and U–Th/He ages thermochronological studies also reveal a complex and multi-stage exhumation history in the low-elevation segment of the South American continental margin (Hueck et al. 2019).

To test the hypothesis that the southern and central Ribeira belt is the source terrain for the detrital zircon grains of the Barreiras Formation in the study area, we have compared the published cooling rates for the Ribeira and Araçuaí belts with the calculated cooling rates for the detrital zircons. Temperature variation between zircon crystallization at ca. 800 ± 20 °C and zircon partial annealing zone (PAZ) at ca. 250 ± 70 °C were related to the U–Pb and FT ages. The quotient between the difference of the crystallization and PAZ temperatures and the difference of the U–Pb and FT equal the cooling rate for each detrital zircon, expressed in °C/Ma (Table SM2). The mean cooling rate for the detrital zircons in this study is 2.1 ± 0.5 °C/Ma. Additionally, detrital zircon grains younger than 800 Ma were grouped by U–Pb and FT ages in 11 (eleven) clusters (Fig. 10a; Table SM3). The mean value and standard deviation for each cluster were calculated and plotted against temperature for U–Pb and FT. Cooling rates for the 11 clusters varied from 5.2 to 1.1 °C/Ma (Fig. 10b), and the mean value is 2.1 ± 1.2 °C/Ma (Table SM3). These values are according to the cooling rates calculated for the Ribeira belt (Bento dos Santos et al. 2015) but also fit the Araçuaí belt cooling path (Petitgirard et al. 2009; Vauchez et al. 2019).

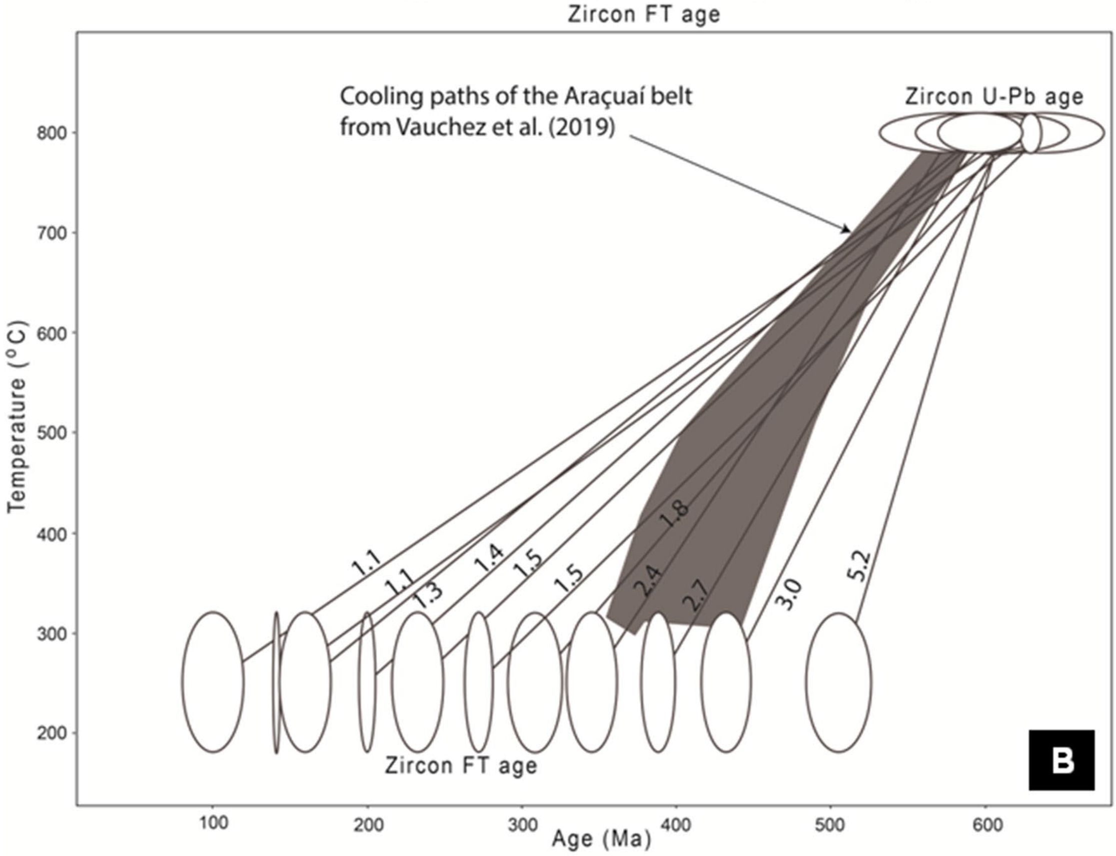
## Zircon FT ages and chrono-correlated events

In our work, the complex variation in the detrital zircon FT ages is attributed to a protracted continental crust thermal evolution in the source areas. Older ages, between 534 and 433 Ma (Cambrian-to-Silurian periods), are attributed to post-orogenic processes after Gondwana Supercontinent agglutination and are chrono-correlated to the formation of the intracontinental basins within Gondwana paleo plate (Paraná, Congo, Parnaíba, Amazonas, and Solimões basins).

Despite the older FT ages, the five main FT age groups, ca. 463 ± 11 Ma (Ordovician), 345 ± 8.5 Ma (Upper Devonian), 243 ± 5 Ma (Middle Triassic), 163 ± 3.5 Ma (Upper Jurassic), and 93.5 ± 2 Ma (Upper Cretaceous), are related to the Gondwana Supercontinent and its transition to the South American Platform. The Upper Devonian FT zircon ages are chrono-correlated to the Appalachian–Variscan orogens, which formed by the collision between Eurasia with Gondwana to form Pangea supercontinent. Also, the collision between the allochthonous Chilenia terrane with the



700
600
500
Zircon U-Pb age
100
200
300
400
500
Zircon FT age
Mean value
for each cluster
A

Cooling paths of the Araçuaí belt
from Vauchez et al. (2019)
Zircon U-Pb age
800
700
600
500
400
300
200
Temperature (°C)
1.1
1.1
1.3
1.4
1.5
1.5
1.8
2.4
2.7
3.0
5.2
Zircon FT age
100
200
300
400
500
600
Age (Ma)
B

**Fig. 10** U–Pb and FT age of the detrital zircon grains in this study. **a** Samples occur in 11 clusters. **b** The mean value for each cluster and the standard deviation were plotted against temperature variations of 800 ± 20 °C for U–Pb and 250 ± 70 °C for FT. The cooling path for the Araçuaí belt is shown in gray (Vauchez et al. 2019)

Proto-Andean margin of Gondwana produced the Achalian orogeny; the Panthalassa Ocean was subducted at the SW margin of Gondwana (e.g., Stampfli et al. 2013). The Middle Triassic FT zircon ages are chrono-correlated to an extensional phase within the Gondwana Supercontinent, generating several aborted rift basins. During this time interval, the Pangea was margined by the Panthalassa Ocean to the southwest and the Tethys Ocean to the northeast. The Upper Jurassic FT zircon ages are chrono-correlated to the rifting of Laurasia and formation of the North Atlantic Ocean and the early stages of rifting of Gondwana and configuration of the South Atlantic Ocean. The younger FT zircon ages are correlated to the Gondwana Supercontinent and the transition to the oceanic crust in the South Atlantic Ocean**.** This interval is coincident with the Peruvian phase of the Andean chain evolution (Cobbold et al. 2001).

## Conclusions

The Barreiras Formation deposited in the Paleogene-to-Neogene periods and is composed essentially of siliciclastic sedimentary rocks. The exposed bedrock in the hinterland of the SEBCM is the source of the detrital grains. The sedimentary facies and detrital zircon U–Pb and FT data presented herein indicate five main conclusions:

a. The deposition occurred in an alluvial depositional system, by a source-to-sink relation between elevated source areas located in the hinterland of the SEBCM and controlled by downstream factors.
b. The source area is mostly composed of ca. 600 Ma zircon fertile rocks and U–Pb age distribution is similar to the southern and central Ribeira belt.
c. Zircon grains have complex FT ages, chrono-correlated to the main events that affected the Gondwana supercontinent and the South American Platform from Lower Cambrian to Upper Cretaceous.
d. Five main groups of zircon FT ages occur: (1) Ordovician (463 ± 11 Ma), (2) Upper Devonian (345 ± 8.5 Ma), (3) Middle Triassic (243 ± 5 Ma), (4) Upper Jurassic (163 ± 3.5 Ma), and (5) Upper Cretaceous (93.5 ± 2 Ma).
e. The main zircon FT age groups are chrono-correlated to (a) the collision between Eurasia with Gondwana to form Pangea supercontinent; (b) extensional phase within the Gondwana Supercontinent; (c) rifting of Laurasia and formation of the North Atlantic Ocean and to the early stages of rifting of Gondwana and configuration of the South Atlantic Ocean; and (d) final rift stages of the Gondwana Supercontinent and the transition to the oceanic crust in the South Atlantic Ocean.

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