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Research Paper

A Laurentian affinity for the Embu Terrane, Ribeira Belt (SE Brazil), revealed by zircon provenance statistical analysis

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A B S T R A C T

New and compiled detrital zircon U–Pb ages from the southern Neoproterozoic–Cambrian Ribeira Belt, SE Brazil, demonstrate Laurentian affinity of the Embu Terrane which is statistically distinct from the adjoining Apiaí and São Roque terranes with cratonic affinity (e.g., São Francisco Craton). Zircon provenance results indicate that the type-area of the Embu Terrane is dominated by detrital zircon age modes at ca. 1200 Ma, 1400 Ma, and 1800 Ma, with maximum depositional age of ca. 1000 Ma. In contrast, the Apiaí and São Roque terranes are dominated by Paleoproterozoic detrital zircon ages (ca. 2200–2000 Ma age dominant component), with maximum depositional ages of ca. 1400 Ma and 1750 Ma, respectively. Multidimensional scaling (MDS) analysis of non-parametric similarity measurements on zircon age populations indicates for the first time that the Embu Terrane encompass two statistically distinct detrital zircon age spectra, which is also reflected in the metamorphic zircon age record. The statistical characterization of the Embu Terrane through populational metrics allow a quantitative comparison with surrounding tectonic domains and rock samples classified such as Embu-type. Our results clearly highlight the distinction between the statistically differentiated Embu Terrane from the Apiaí and São Roque terranes, supporting an allochthonous interpretation. In addition, we demonstrate that rocks samples previously classified as Embu-type are significantly dissimilar to the definition of Embu Terrane, failing to support alternative tectonic models (e.g., intracontinental evolution). Detrital zircon age spectra reveal that the Apiaí and São Roque terranes have similar zircon provenance to domains sourced from the São Francisco Craton, whereas detrital zircon populations from the Embu Terrane have greater affinity with SW Laurentia basins (and their inferred sediment sources), consistent with previous findings. Therefore, we interpret the Embu Terrane as a Rodinia descendant developed along the active margin of the SW Laurentia that collided with the Ribeira Belt during early Neoproterozoic (810–760 Ma).

1. Introduction

The geochronology of uranium bearing detrital accessory minerals (e.g. zircon, monazite, rutile and apatite) plays a key role in reconstructing ancient sedimentary systems (sources and routing), paleogeographic relationships, as well as tracking broader continental growth and geodynamics; for example, the characteristics of convergent, collisional and extensional tectonic settings (Cawood et al., 2007, 2012; Balis et al., 2020; O'Sullivan et al., 2020, 2021, Pereira et al., 2020, 2021; Ribeiro et al., 2020a; Ricardo et al., 2020; Barham et al., 2022). The use of multi-mineral-isotopic systematics integrated with statistical analysis

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has become the mainstay of sedimentary provenance studies, enabling the differentiation of complex source histories involving different degrees of first versus multicycle components (Chew et al., 2020; Barham et al., 2021; Zoleikhaei et al., 2021, 2022; Anders et al., 2022). Detrital mineral U–Pb ages have been traditionally visually compared to assess relationships with other basins or crystalline sources (using kernel or probability density plots). Recently, a range of statistical tests have been deployed to highlight the differences (dissimilarity) between different detrital populations, reducing intrinsic biases and permitting effective evaluation of large datasets (Kirkland et al., 2008; Saylor et al., 2012, 2019; Satkoski et al., 2013; Vermeesch, 2013, 2018a, 2018b; Andersen et al., 2016; Saylor and Sundell, 2016; Spencer and Kirkland, 2016; Barham et al., 2019; Campanha et al., 2019; Martin et al., 2020; Ribeiro et al., 2021; Seraine et al., 2021).

The detrital zircon U–Pb record of the Neoproterozoic–Cambrian Ribeira Belt (SE Brazil) have been explored in several studies (Basei et al., 2008; Faleiros et al., 2011; Campanha et al., 2015, 2019; Henrique-Pinto et al., 2015; Meira et al., 2015; Heilbron et al., 2020; Ricardo et al., 2020; Cabrita et al., 2021). In addition to complementary structural and petrochronological datasets, the detrital zircon record provides a potential foundation on which to test tectonic models proposed for the Ribeira Belt. Tectonic models for this region vary from involving multiple collisions with exotic terranes (Basei et al., 1992; Faleiros et al., 2011, 2016; Passarelli et al., 2019; Campos Neto, 2000) to intracontinental evolution (Meira et al., 2015, 2019; Konopásek et al., 2020). Since some of these contrasting tectonic models rely on sediment provenance and lithological associations (among other factors), a re-evaluation of detrital zircon U–Pb signatures through modern statistical treatments is a useful means to clarify the impacts of detrital mineral provenance interpretation on models for the geodynamics and paleogeography of the Ribeira Belt in West Gondwana.

This paper focuses on the detrital zircon characteristics and provenance of the Embu Terrane (Ribeira Belt) (Fig. 1), which has been pivotal to constrain the tectonic setting of the Embu Terrane (Meira et al., 2015, 2019; Vinagre da Costa et al., 2017; Campanha et al., 2019). In this contribution, we attempt to resolve the auto- versus allochthonous character of the Embu Terrane with respect to the adjoining Apiaí and São Roque terranes by assessing their respective detrital zircon records. The new detrital zircon U–Pb data from the Apiaí and São Roque terranes presented here are integrated with a compiled detrital zircon U–Pb dataset, which is further used to assess the dissimilarity between different tectonic domains via multidimensional scaling (MDS) (Vermeesch, 2013, 2018a, 2018b; Vermeesch et al., 2016; Nordsvan et al., 2020). Out results shed light on an apparent São Francisco Craton affinity of the Apiaí and São Roque terranes and in contrast a Laurentian affinity for the Embu Terrane, highlighting its allochthonous characteristics and supporting a model involving collision of exotic terranes. We envisage a paleogeographic and tectonic model for the Embu Terrane from 1100 Ma to the final collisional stages.

2. Geological overview

The Neoproterozoic–Cambrian Ribeira Belt is mostly interpreted as a NE-trending orogen that formed at the interface between the São Francisco, Paranapanema, Congo, Luís Alves and Rio de la Plata paleocontinents during West Gondwana assembly (Fig. 1A) (De Almeida et al., 1973; Campanha and Sadowski, 1999; Campos Neto, 2000; Heilbron et al., 2004, 2020; Faleiros et al., 2011; Cabrita et al., 2021). It comprises a series of tectonostratigraphic terranes (e.g., São Roque, Apiaí, Embu, Costeiro and Curitiba), generally dissected by crustal-scale NE-trending dextral shear zones developed under a transpressional system active between 900 Ma and 530 Ma (Egydio-Silva et al., 2002, 2005, 2018; Ribeiro et al., 2019, 2020b, 2020c; Conte et al., 2020; Cabrita et al., 2022; Faleiros et al., 2022).

2.1. São Roque Terrane

This terrane is bounded by the Taxaquara shear zone to the south and the Jundiuvira shear zone to the north (Fig. 1C). It comprises two main groups (São Roque and Serra do Itaberaba) generally composed of volcanosedimentary sequences including MORB-like volcanic to subvolcanic rocks and tuff interlayered with pelites and chemical sedimentary rocks metamorphosed under greenschist to amphibolite facies conditions imprinting a general NE-trending structural fabric. Zircon U–Pb ages from the volcanosedimentary rocks indicate a depositional age of 1395 ± 10 Ma for the Serra de Itaberaba Group (Juliani et al., 2000) and 1760 ± 17 Ma for the lower formations of the São Roque Group (Henrique-Pinto et al., 2018). Detrital zircon U–Pb data indicate Paleoproterozoic to Archean sources for the metasedimentary rocks of the São Roque Group (Henrique-Pinto et al., 2012, 2015; Campanha et al., 2019), and are generally interpreted as derived from the surrounding cratons (e.g., Paranapanema and São Francisco). The São Roque terrane is commonly interpreted as the reworked border ("passive margin") of the São Francisco paleoplate displaced southwestward in response to Neoproterozoic dextral orogen-parallel tectonics (Henrique-Pinto et al., 2015).

2.2. Apiaí Terrane

The Apiaí Terrane is a composite terrane formed by a collage of units with distinct ages and tectonic settings, including remnants interpreted to represent continental passive margins associated with carbonate platforms and flysch-type deposits (Campanha and Sadowski, 1999; Faleiros et al., 2011; Campanha et al., 2015; de Brito Neves et al., 2021). From NW to SE, the Apiaí Terrane includes the Itaiacoca, Lajeado and Votuverava, groups, as well the Água Clara Formation, along with a spatially restricted Paleoproterozoic orthogneiss nucleus, extensive Cryogenian to Ediacaran granites and some late-orogenic Ediacaran to Cambrian basins.

The majority of the major tectonostratigraphic units have Mesoproterozoic depositional ages (Calymmian to Ectasian) and underwent low- to medium-grade Barrovian-type metamorphism. The Votuverava Group accumulated between ca. 1500 Ma and 1300 Ma based on igneous zircon U–Pb and igneous hornblende Ar-Ar crystallization ages from mafic rocks interlayered with the metasedimentary successions (Siga Júnior et al., 2009, 2011; Campanha et al., 2015; Campanha et al., 2019). The age of the basal unit from the Itaiacoca Group is constrained by mafic intrusions at ca. 1000 Ma and detrital zircons as young as ca. 1750 Ma, while the top unit has metavolcanic rocks with igneous zircon U–Pb ages of 645–628 Ma (Basei et al., 2008; Siga Júnior et al., 2009). The age of the Lajeado Group lies between a maximum depositional age from detrital zircons of ca. 1200 Ma and the emplacement of the Apiaí gabbro at 877 ± 8 Ma (igneous zircon U–Pb, Campanha et al., 2016).

2.3. Embu Terrane

The Embu Terrane can be traced for 500 km and is bounded by the Apiaí, Curitiba and Costeiro terranes (Fig. 1C). It comprises the Paleoproterozoic Rio Capiravi Complex, the Embu Complex and several Neoproterozoic granitic plutons (Alves et al., 2013, 2016; Maurer, 2016; Campanha et al., 2019).

The Embu Complex is composed of terrigenous metasedimentary rocks, including pelitic schist, paragneiss, and minor

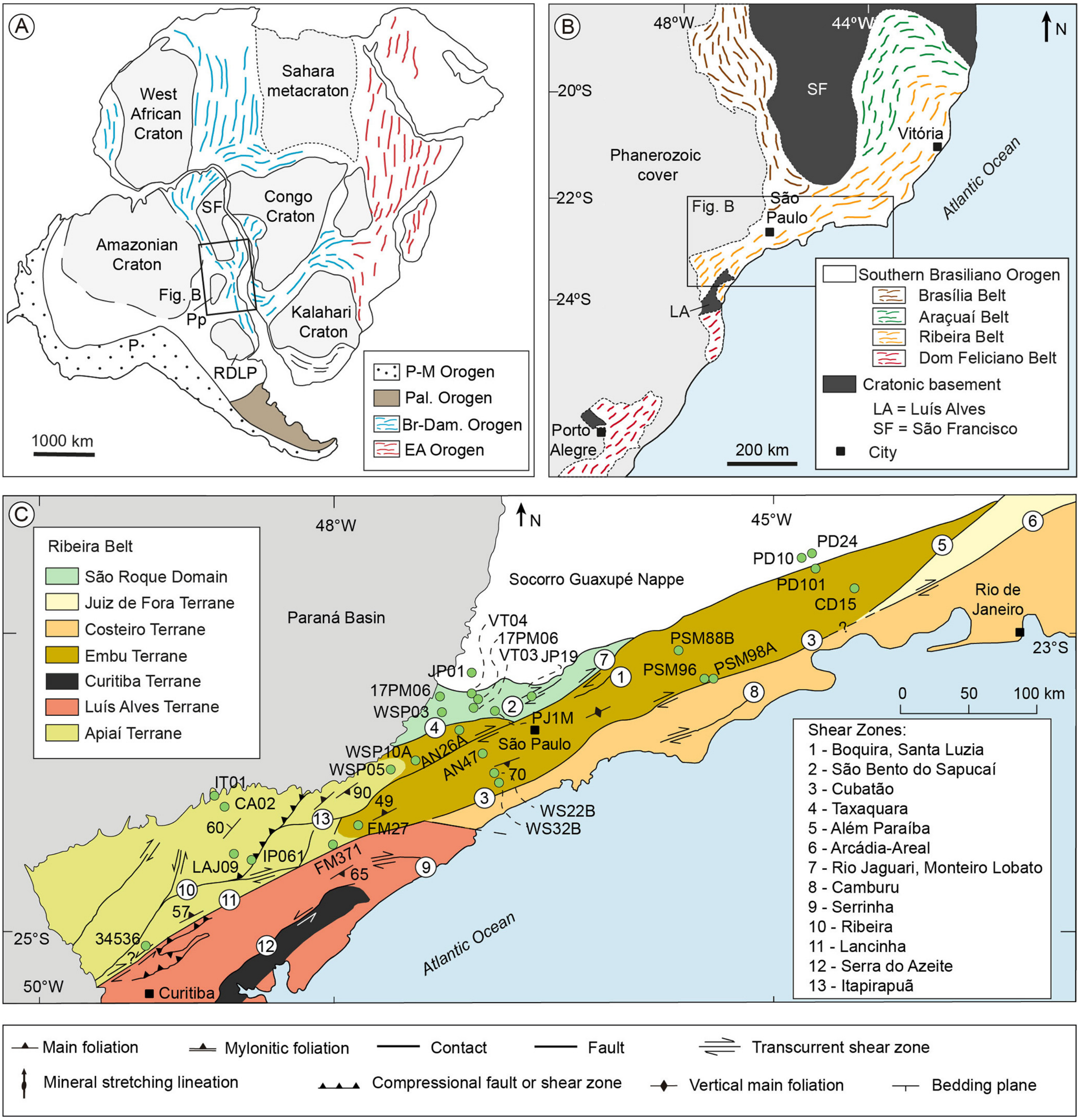

Fig. 1. Geotectonic context and geological map of the Ribeira Belt (adapted from Cabrita et al., 2022). (A) Geotectonic context of the Ribeira Belt in West Gondwana configuration. Abbreviation includes SF – São Francisco Craton, Pp – Paranapanema Craton, RDLP – Rio de la Plata Craton, Pal. – Paleozoic Andean Orogen, P-M – Phanerozoic–Mesozoic Andean orogeny, Br-Dam. – Brasiliano orogen. (B) Geotectonic sketch map of the Southern Brasiliano Orogen, showing the subdivision in belts; (C) Geological map of the Ribeira Belt highlighting different terranes, shear zones and samples (green circles) used in this study.

calc-silicate rocks, quartzite and amphibolite. Metamorphic studies indicate a variable degree of metamorphism from low- to high-grade developing regional migmatitic units (Cabrita et al., 2021 and references therein). Recent studies indicate two Neoproterozoic metamorphic events recorded in the Embu Complex spanning 810–760 Ma and 675–565 Ma (Cabrita et al., 2021). Detrital zircon U–Pb data from the Embu Complex has a multimodal pattern with principal age modes at ca. 1200 Ma and 2000 Ma, along with a minor Archean contribution (Meira et al., 2015; Vinagre da Costa et al., 2017; Campanha et al., 2019; Cabrita et al., 2021).

3. Methods

3.1. Detrital zircon U–Pb geochronology

We selected seven metasedimentary rock samples for detrital zircon U–Pb analysis, including one sample of the São Roque

Group, four of the Votuverava Group, one of the Itaiacoca Group, and one from the Água Clara Formation (Table 1). The lack of fresh outcrops imposes difficulties to establish a systematic sampling throughout the southern Ribeira Belt, however we tentatively collected representative samples from each domain where weathering was not too pervasive. The new samples investigated in this study are primarily sand-dominated (i.e., sandstone to quartzite) up to amphibolite upper-greenschist facies conditions.

Zircon grains were extracted using standard gravimetric and magnetic techniques (e.g., Ribeiro et al., 2020a). The grains were hand-picked using a binocular microscope attempting to capture all zircon grains within an aliquot to avoid selection bias as best possible using this approach (for instance, see Dröllner et al., 2021 for limitations). Grains were mounted in 25 mm diameter epoxy resin discs and polished to half grain thickness to reveal grain interiors. Cathodoluminescence (CL) and scanning electron microscope (SEM) images were used to characterise grain growth histories and identify points for U–Pb analysis, avoiding mixed growth domains, fractures, inclusions or metamict areas.

Zircon U–Pb isotopic analyses were performed in three different institutions: (i) Isotopia Laboratory, School of Earth, Atmosphere and Environment, Monash University, Australia; (ii) University of Sao Paulo, Brazil; and (iii) University of Brasilia, Brazil. The methods employed by each laboratory is presented in Appendix A1 (Supplementary Data). U–Pb ages were calculated using IsoplotR (Vermeesch, 2018a, 2018b) with no common-Pb correction performed due to the generally low ^{204}Pb counts, and a limit of ±10% age discordance, defined as the percentage ratio between ^{207}Pb/^{206}Pb and ^{238}U/^{206}Pb ages, used as concordance filtering criteria. All ages and uncertainties are presented at the 2σ confidence level. The complete detrital zircon U–Pb dataset is available in Supplementary Data (Table S1).

3.2. Multidimensional scaling (MDS)

MDS analysis was carried out with the 'Provenance' package, built in R environment, using the Kolmogorov-Smirnov (KS) metric (Vermeesch et al., 2016). This routine provides a 'dissimilarity map' visualising the difference in zircon age fingerprints between the various samples' detrital zircon populations. The quality of the MDS fit can be assessed using the stress value (Vermeesch, 2013), where lower stress values indicate a better fit between the distances on the MDS diagram and the measured dissimilarities between samples (Cox and Cox, 2000; Nordsvan et al., 2020). For transparency purpose, we calculated additional MDS diagrams using the Kuiper metric which is more sensitive to different analytical methods (e.g., laser ablation vs SHRIMP) and to the distribution tails (Vermeesch, 2018a, 2018b; Nordsvan et al., 2020). Both KS and Kuiper metrics produce the same clusters, reinforcing the quality of our statistical analysis.

The MDS analysis considers new detrital zircon (this study) and compiled data from the Embu (Meira et al., 2015; Duffles et al., 2016; Vinagre da Costa et al., 2017; Campanha et al., 2019; Cabrita et al., 2021), Apiaí (Basei et al., 2008; Campanha et al., 2016; Campanha et al., 2019) and São Roque terranes (Henrique-Pinto et al., 2015; Campanha et al., 2019) with a maximum ±10% age discordance. A minimum age cut-off of 1000 Ma was applied to the Embu, Apiaí and São Roque terranes associated with zircon Th/U characteristics and CL textures to avoid metamorphic grains/domains (cf., Campanha et al., 2019; Cabrita et al., 2021). The full detrital zircon age compilation is available in Supplementary Data (Table S2). The results from the KS statistical test are available in Supplementary Data (Table S3).

Table 1
Geographic coordinates and rock type of the samples analysed in this study.

Sample	Geological unit	Geographic coordinates (latitude, longitude)	Rock type
17PM06	São Roque Group	23.3835°S, 47.2584°W	Conglomerate sandstone
TY056B	Votuverava Group	24.9075°S, 49.0161°W	Muscovite-bearing quartzite
RIB02	Votuverava Group	24.6233°S, 48.5807°W	Conglomerate
FM102A	Votuverava Group	24.0968°S, 48.1221°W	Sandstone
FM87A	Votuverava Group	24.1019°S, 48.2162°W	Sandstone
IT01	Itaiacoca Group	24.0137°S, 48.9160°W	Rhythmite
CA02	Agua Clara Formation	24.1520°S, 48.8293°W	Sandstone

4. Detrital zircon U–Pb data

The detrital zircon grains extracted from metasedimentary rock samples of the São Roque and Apiaí terranes are mostly euhedral to subhedral with oscillatory and sector zoning visible in the CL images, indicative of igneous crystallization processes in their ultimate magmatic source.

4.1. São Roque Terrane

A total of 131 U–Pb measurements were performed on zircon grains from sample 17PM06 (conglomerate sandstone), which resulted in 111 concordant data points. The majority of the crystallization ages range from 2500 Ma to 1800 Ma, with few grains yielding Archean ages (>2500 Ma) (Fig. 2A). The age population is multimodal in the KDE diagram, with a clearly dominant age mode of ca. 2250 Ma with shoulders at 2400 Ma, 2100 Ma and 1800 Ma (Fig. 2B).

4.2. Apiaí Terrane

New detrital zircon U–Pb data were collected from four samples of the Votuverava Group (TY056B, RIB02, FM102 and FM87A), one sample from the Itaiacoca Group (IT01) and one sample from the Agua Clara Formation (CA02).

4.2.1. Votuverava Group

We collected 100 detrital zircon U–Pb measurements from sample TY056B (muscovite-bearing quartzite), from which 93 U–Pb data were considered concordant. The majority of the data range from 2900 Ma to 2000 Ma, with two zircon grains yielding Meso- and Paleoarchean ages (Fig. 3A). This sample has a multimodal detrital zircon age distribution with prominent age modes at ca. 2500 Ma, 2300 Ma and 2100 Ma and a minor Archean contribution (Fig. 3B).

A total of 50 zircon U–Pb measurements were collected from sample RIB02 (conglomerate), from which 35 were concordant. The majority of the data range from 2400 Ma to 1800 Ma, with two zircon grains yielding Neoarchean ages (Fig. 3C). This detrital zircon population is multimodal with a strongly dominant age mode at ca. 2200 Ma and subordinate contributions at ca. 2500 Ma and 2100 Ma (Fig. 3D).

All 39 zircon U–Pb measurements from sample FM102A (sandstone) were concordant. The majority of the data range from ca. 2400 Ma to 2100 Ma, with few zircon grains yielding Archean ages up to ca. 3200 Ma (Fig. 3E). This detrital zircon population is

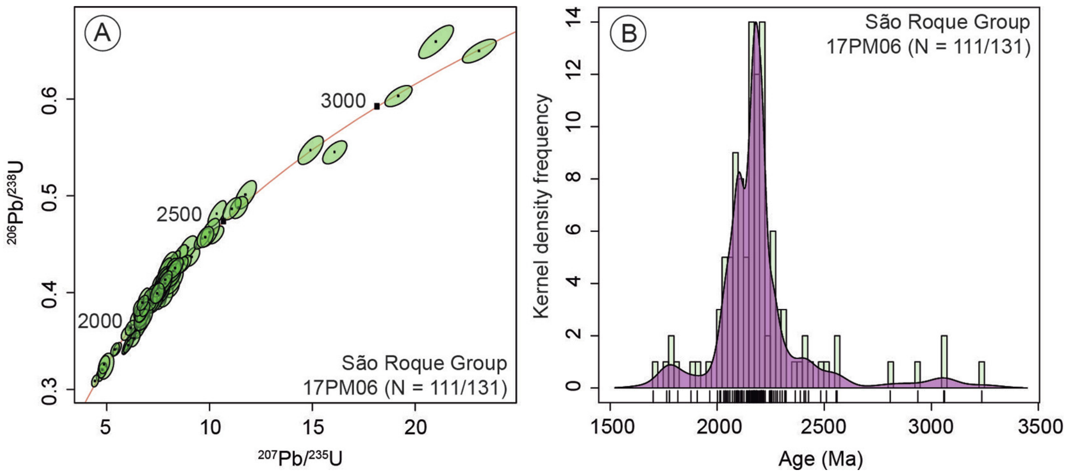

Fig. 2. Wetherill (A) and Kernel density estimate and histogram (B) diagrams of detrital zircons (with a 10% concordance filter) from the São Roque Group, São Roque terrane. Ellipse uncertainties and age errors are 2σ with no common-Pb correction applied. Kernel density frequency diagram was calculated using the IsoplotR (Vermeesch, 2018b) with a 25 Ma band width and bin width. N = x/y indicates the number of concordant ages (y) from the complete dataset (y).

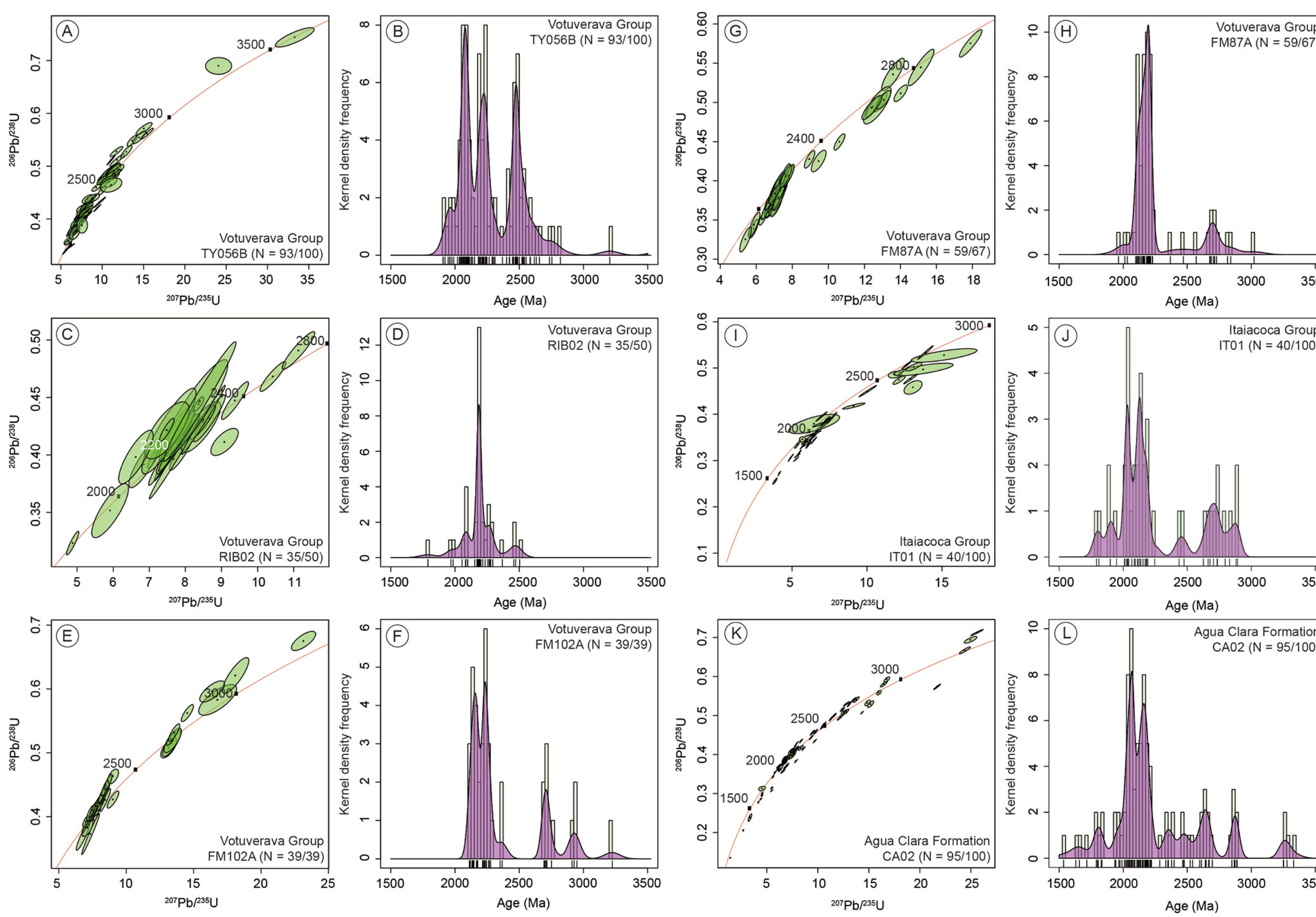

Fig. 3. Wetherill and Kernel density estimate diagrams of detrital zircons from sedimentary rock sequences of the Apiaí Terrane, including the Votuverava Group (A–H), Itaiacoca Group (I, J) and Agua Clara Formation (K, L). Ellipse uncertainties and age errors are 2σ with no common-Pb correction applied. Kernel density estimates diagrams were calculated using IsoplotR (Vermeesch, 2018b) with a 25 Ma band width and bin width. N = x/y indicates the number of concordant ages (y) from the complete dataset (y).

multimodal with a dominant bimodal age grouping at ca. 2200 Ma, minor Archean mode at ca. 2750 Ma and a few Mesoarchean zircon grains (Fig. 3F).

A total of 67 zircon grain U–Pb measurements from sample FM87A (sandstone) yielded 59 concordant results. The majority of the data range from 2000 Ma to 1800 Ma, with a small subset of Archean aged grains (Fig. 3G). This detrital zircon population has a bimodal characteristic with a main age mode at ca. 2200 Ma and a minor mode at ca. 2700 Ma in the KDE diagram (Fig. 3H).

The majority of the new detrital zircon U–Pb data from the Votuverava Group are multimodal despite the small dataset for some samples, with main Paleoproterozoic age modes (mainly ca. 2200 Ma) and a minor Archean contribution.

4.2.2. Itaiacoca Group

Of 100 detrital zircon grain U–Pb measurements from one sample of the Itaiacoca Group (IT01, rhythmite), only 40 yielded concordant data. This population presents a wide age spread from ca. 3000 Ma to 1500 Ma (Fig. 3I) with multimodal distribution with modes at 2200 Ma and 2000 Ma and significant Archean contribution (Fig. 3J).

4.2.3. Agua Clara Formation

Of 100 zircon U–Pb measurements from sample CA02 (sandstone), 95 are considered concordant. The multimodal (principal modes at ca. 2200 Ma and 2100 Ma, and several subordinate Paleoproterozoic and Archean modes) population contains a wide age spread from ca. 2900 Ma to 1500 Ma with only minor Meso- to Paleoarchean contribution (Fig. 3K, L). This is the first detrital zircon data from the Agua Clara Formation, and show similarities with the age patterns from the Votuverava Group (Campanha et al., 2019; this study).

5. Discussion

5.1. Detrital characteristics of the Apiaí and São Roque terranes

MDS analysis based on the KS and Kuiper metrics highlights the dissimilarity between the Embu Terrane and the adjoining São Roque and Apiaí terranes (Fig. 4A, B), while demonstrating greater relative similarity between the São Roque and Apiaí terranes despite the slight differences in maximum depositional ages (Campanha et al., 2019). This result reinforces the distinct character of the Embu Terrane in relation to the main adjoining terranes. In general, the metasedimentary rock successions of the São Roque and Apiaí terranes have multimodal distributions with consistent strong representation of grains that crystallized around ca. 2200 Ma and ca. 2100–2050 Ma (Fig. 4C, D), and fewer Archean (>2500 Ma) and Mesoproterozoic grains (1600–1200 Ma). The similarity in the detrital zircon age populations highlighted by the MDS and KDE diagrams (Fig. 4A–D) support a common sedimentary provenance for both terranes, generally interpreted to be sourced from surrounding cratonic areas (e.g., São Francisco and Paranapanema cratons) (Henrique-Pinto et al., 2015; Campanha et al., 2019; Balis et al., 2020). The detrital zircon similarity between the Apiaí and São Roque terranes also implies that the structural limit between them represented by the Taxaquara shear zone (Fig. 1C) does not represent a "suture zone", but a late-orogenic structure reactivated at ca. 560–535 Ma possibly in an intracontinental setting (Ribeiro et al., 2019, 2020c; Faleiros et al., 2022). Thus, we envisage that the Apiaí and São Roque terranes may represent the same tectonic domain crosscut by late shearing. Our findings are consistent with the interpretation that the São Roque and Apiaí terranes might represent the reworked border of the São Francisco Craton displaced southwestward in response to Neoproterozoic dextral orogen-parallel tectonics (Henrique-Pinto et al., 2015). This lateral displacement is supported by the long-lived shear deformation in the Ribeira Belt spanning 900 Ma to 530 Ma (Faleiros et al., 2022), partially coeval with at least two major episodes of terrane accretion (850–760 Ma and 610–585 Ma) (Forero-Ortega et al., 2020; Ricardo et al., 2020; Cabrita et al., 2021; Faleiros et al., 2022).

5.2. Detrital characteristics of the Embu Terrane

The MDS diagrams aid in visualizing the dissimilarity between the Embu Terrane and the São Roque and Apiaí terranes. Additionally, the samples from the Embu type-area are statistically divisible into two groups for the first time (Fig. 4A, B; plus additional KS results in Supplementary Data, Table S3), which has been overlooked by conventional zircon age analysis (Meira et al., 2015; Vinagre da Costa et al., 2017; Campanha et al., 2019; Cabrita et al., 2021). Given the lack of additional isotopic fingerprints such as zircon Lu–Hf data to characterize the Embu Terrane signature, a statistical description of the detrital zircon age spectra of the Embu Terrane type-area facilitate the comparison with other rocks age spectrum and associated tectonic domains.

Our analysis shows that group 1 is characterized by a bimodal positive asymmetric distribution with a principal Mesoproterozoic age mode (ca. 1200 Ma) and a secondary Paleoproterozoic mode (ca. 1850 Ma) (Fig. 4E). Conversely, group 2 has a multimodal negative asymmetric distribution with a main Paleoproterozoic age mode (ca. 1800 Ma) and secondary Mesoproterozoic modes (ca. 1500 Ma and 1200 Ma). Although slightly different, the KS statistical test demonstrates that the internal differences between groups 1 and 2 of the Embu Terrane are notably smaller than the differences when compared to the detrital zircon distribution of the Apiaí and São Roque terranes (see KS results in Supplementary Data, Table S3), which may indicate internal variations of the Embu Terrane rather than an association with another terrane. Additionally, both groups also indicate distinct metamorphic zircon records (group 1 is bimodal at ca. 730 Ma and 610 Ma, and group 2 has a more unimodal negative asymmetric distribution with an age mode of ca. 810 Ma; Fig. 4F). These results confirm the suggestion that the Embu Terrane has a distinct provenance and metamorphic evolution from the São Roque and Apiaí terranes as previously suggested (Campanha et al., 2019; Cabrita et al., 2021).

Since the detrital zircon characteristics of the Embu Terrane are key in determining its auto- or allochthonous character in tectonic models for the Neoproterozoic evolution of the Ribeira Belt (Meira et al., 2015; Vinagre da Costa et al., 2017; Campanha et al., 2019; Cabrita et al., 2021), it is critical to review the samples classified as Embu-type in comparison to those from the Embu type-area to avoid erroneous correlations due to misclassification. Some rock samples collected in the northern Ribeira Belt and classified as Embu-type (PSM88, PD10 and PD24; Meira et al., 2015; Duffles et al., 2016) display detrital zircon spectra with multimodal distributions and principal modes at ca. 2200 Ma and ca. 2100–2050 Ma (Fig. 4C), resembling the detrital zircon patterns from the São Roque and Apiaí terranes. Some authors used this age similarity to suggest a potential switch of the source area, indicating proximity to cratonic domains (e.g., São Francisco Craton; Meira et al., 2015).

The statistical analysis indicates considerable detrital zircon dissimilarity between samples PSM88B, PD10, PD24 and PD101 in one association, and those from the Embu type-area on the other (Fig. 4A, B). Instead, samples PSM88B, PD10, PD24 and PD101 show greater similarity with the Apiaí and São Roque terranes group, suggesting that these samples may be misclassified and may not represent the Embu Terrane (after Campanha et al., 2019). Therefore, the provenance correlation between the Embu-São Roque-Apiaí terranes might be incorrect due to the misclassification of a few rock samples as Embu-like. These results shed light into potential biases or problems in mapping the distribution of the Embu Complex in the northern Ribeira Belt.

We recognize that detrital zircon U-Pb age spectra can be bias due to zircon separation and handpicking, hydraulic sorting and metamorphism (Hay and Dempster, 2009; Lawrence et al., 2011; Chew et al., 2020; Nordsvan et al., 2020; Dröllner et al., 2021).

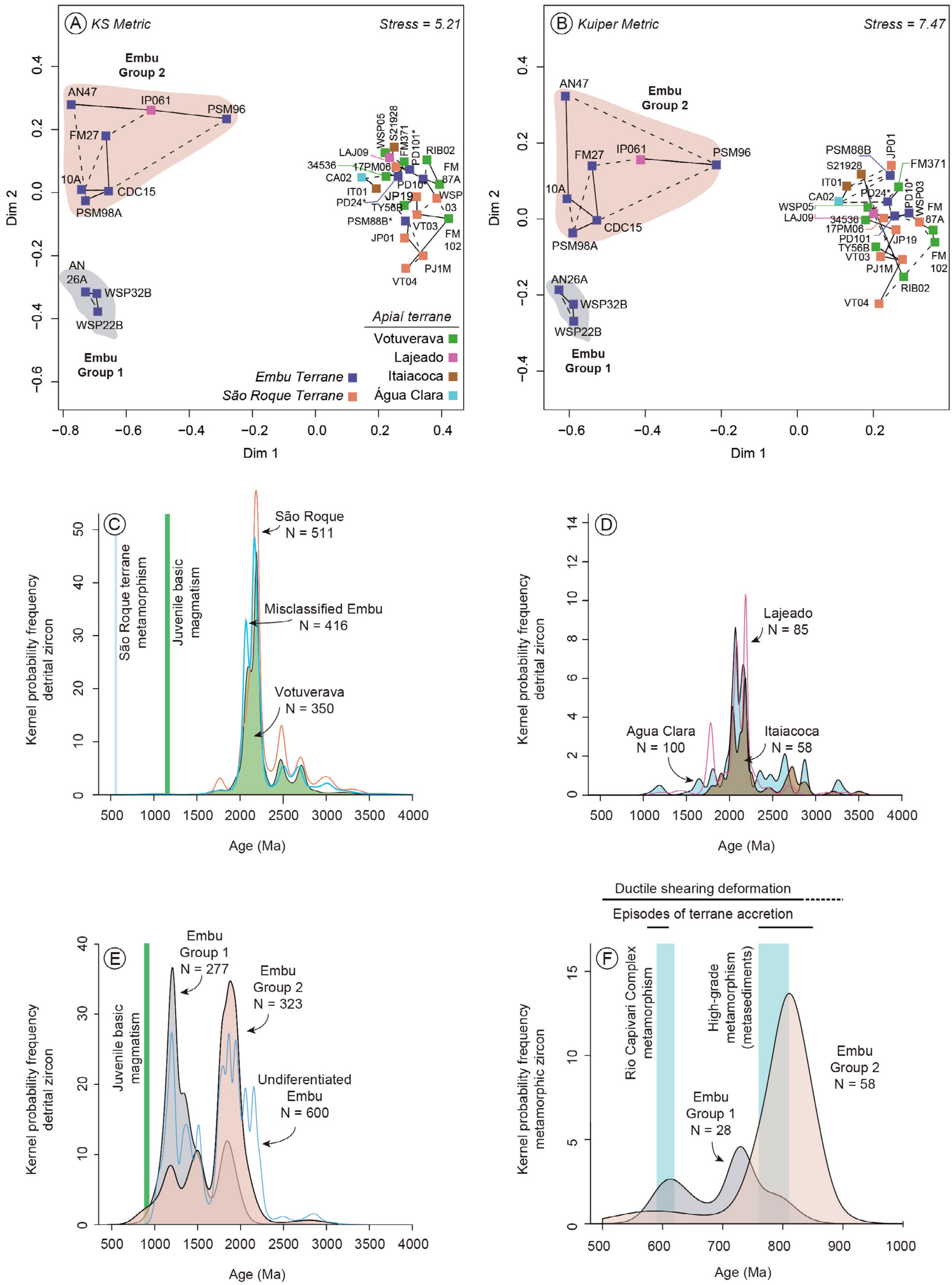

Fig. 4. (A, B) Multidimensional scaling diagram comparing the Embu, São Roque and Apiaí terranes; (C, D) Kernel density estimate diagrams of the detrital zircon record from the São Roque and Apiaí terranes, respectively; (E, F) Kernel density estimate diagrams of the detrital (E) and metamorphic zircon (F) record from the Embu Terrane. Kernel density estimate diagrams were produced using IsoplotR (Vermeesch, 2018b) with a 25 Ma band width and histogram bin width. More details regarding the metamorphic ages, ductile shearing deformation and episodes of terrane accretion are presented in the literature (Henrique-Pinto et al., 2015; Campanha et al., 2019; Balis et al., 2020; Ribeiro et al., 2020c; Cabrita et al., 2021, 2022; Faleiros et al., 2022). Samples labels highlighted with (*) represent misclassified samples from the Embu Terrane.

Zircon separation from all samples (new and from the literature) were carried out using similar techniques including gravimetric (Wilfley table and tetrabromoethane heavy-liquid) and magnetic techniques (Frantz isodynamic magnetic separator), and zircon grains were handpicked and mounted into rounded epoxy mounts. Thus, a potential age bias in virtue of zircon separation and picking is unlikely. Hydraulic sorting and metamorphism are unlike to produce the differences observed in the dataset from the Embu Terrane, given that the majority of the samples are sand-dominated (from sandstones to quartzite) and metamorphosed under greenschist to amphibolite facies conditions (Meira et al., 2015; Duffles et al., 2016; Vinagre da Costa et al., 2017; Campanha et al., 2019; Cabrita et al., 2021). Thus, the differences in the detrital zircon age spectra observed in samples interpreted as from the Embu Terrane is likely due to problems in mapping the distribution of the Embu Complex in the northern Ribeira Belt. For instance, samples PD10 and PD24 from Duffles et al. (2016) were collected along the boundary between the Embu Terrane and the Socorro-Guaxupé nappe and are more likely to represent the latter given their São Francisco Craton provenance (Westin and Campos Neto, 2013; Rocha et al., 2018; Tedeschi et al., 2018; Fontainha et al., 2021). We suggest that mapping the Embu Complex should be carefully compared with other geological proxies to confirm lithological associations; such techniques could include statistical analysis of the detrital zircon age spectra (as demonstrated in this study) and perhaps most fruitfully detrital zircon fingerprints with reference to the characteristics of the Embu-type area (Campanha et al., 2019; this study).

5.3. Provenance and preservation bias

The sedimentary provenance of the Embu Terrane has been tentatively addressed in many studies (Meira et al., 2015; Duffles et al., 2016; Vinagre da Costa et al., 2017; Campanha et al., 2019). These studies relied on visual detrital zircon age signature analysis, via probability density diagrams, which have the potential to impart subjective bias (Vermeesch, 2013, 2018a, 2018b; Nordsvan et al., 2020). One study used the KS statistical test to compare the detrital zircon signatures of the Embu Terrane with potential source areas in Brazil and worldwide (Campanha et al., 2019), which demonstrated the lack of correlation between the Embu Terrane and surrounding potential source areas in Brazil. Campanha et al. (2019) demonstrated a meaningful statistical correlation between the Embu Terrane and the Moine Supergroup (Scotland), of known Laurentian affinity (Friend et al., 2003; Cawood et al., 2004, 2007; Banks et al., 2007; Kirkland et al., 2008).

In this study, we revisited the Embu-Moine comparison using MDS analysis while also considering a variety of potential zircon sources with São Francisco Craton and Laurentian affinities (Fig. 5). The Paranapanema block is also considered to be a potential source for some terranes of the Ribeira and Brasilia belts (e.g., Frugis et al., 2018), but it is not possible to evaluate this aspect here due to the lack of geochronological data.

The MDS and the KDE diagrams highlight the similarity between the Embu Terrane and the *syn*-orogenic sedimentary basins developed along Laurentia margin including the Cordilleran Belt, Grenville orogen and associated Mesoproterozoic sequences (Fig. 5). This correlation supports the allochthonous characteristics of the Embu Terrane representing a Rodinia descendant of Laurentia affinity entrapped in the Neoproterozoic Ribeira Belt (SE Brazil) during Gondwana assembly (cf., Fuck et al., 2008). We note that the detrital zircon age spectra of the Embu Terrane and the *syn*-orogenic sedimentary basins developed along SW Laurentia margin are largely multimodal, which is not the typical spectra expected for basins developed in convergent settings (Cawood et al., 2012; Barham et al., 2022).

The multimodal detrital zircon age spectra of tectonic domains with a Laurentia affinity could be due to preservation bias (Hawkesworth et al., 2009; Spencer et al., 2015; Mulder et al., 2017; Mulder and Cawood, 2022). We observe a large dominance of detrital zircon older than 1100 Ma in the Embu Terrane (Table 2; Fig. 5), similar to what has been observed in the Laurentian domains and interpreted to represent pre-orogenic sedimentary successions (Spencer et al., 2015; Mulder et al., 2017). Similar to the Alpine and Himalayan foreland basins, these pre-orogenic sequences could have been initially sourced from local basement and low-grade sedimentary successions imbricated by thrust tectonics in the respective orogen (Mulder et al., 2017). This pattern is expected because during continent–continent collision the magma volume decreases significantly, with only isolated magmatism within the interior of the colliding continents (Hawkesworth et al., 2009; Spencer et al., 2015; Mulder and Cawood, 2022). Although this magmatism has great preservation potential by being protected within the enveloping supercontinent (Hawkesworth et al., 2009; Cawood et al., 2013), it might not represent the main source for pre-orogenic foreland basins. Instead, the reworked pre-existing crust exhumed during thrust tectonics might represent the main source for *syn*-orogenic basins (DeCelles et al., 2004; Spencer et al., 2015; Mulder et al., 2017; Barham et al., 2022). These considerations imply that statistical approaches to characterize the tectonic setting of convergent sedimentary basins must be used with caution, given that the detrital zircon record might represent different stages of the convergence process with the different temporal intervals of the tectonic process recording distinct age spectra, due to changing preservation bias (c.f., Spencer et al., 2015; Mulder et al., 2017).

5.4. Tectonics inferences

The widespread metamorphic overprint in the rocks of the Embu Terrane impose difficulties to obtain paleomagnetic poles in order to reconstruct its paleogeography and associated tectonic evolution. The statistical analysis of detrital zircon U–Pb ages linked to metamorphic and magmatic records support an allochthonous nature of the Embu Terrane, likely with a Laurentian affinity. Whole-rock Sm–Nd and zircon U–Pb–Hf isotopic data from metamafic rocks from the Embu Terrane indicate an episode of juvenile arc-related tholeiitic magmatism at 890 ± 2 Ma (Cabrita et al., 2022, *submitted*). Metasedimentary rocks from the Embu Terrane record a Barrovian-type metamorphic sequence with four main regional zones (garnet, staurolite, sillimanite, sillimanite-K-feldspar) achieving conditions of 750–780 °C and 7.5–9.2 kbar for the sillimanite and sillimanite-K-feldspar zones in the southern portion of the Embu Terrane (Cabrita et al., 2021). Zircon U–Pb and monazite Th–U–Pb_T chemical data yielded ages between 820 Ma and 770 Ma for the regional metamorphism of the Embu Terrane (Vlach, 2008; Campanha et al., 2019; Cabrita et al., 2021). Available zircon U–Pb isotopic data from granitic, granodioritic and tonalitic orthogneisses indicate that the Embu Complex experienced a period of igneous activity between 810 Ma and 770 Ma (Cordani et al., 2002; Meira et al., 2015; Passarelli et al., 2019), concomitant with the main regional Tonian medium- to high-pressure metamorphic event.

The Tonian magmatic and metamorphic record of the Embu Terrane is consistent with an accretionary to collisional tectonic setting between 820 Ma and 770 Ma along the passive margin of the Paranapanema block and São Francisco Craton represented by the Apiaí and São Roque terranes. Although Tonian magmatic and metamorphic records are virtually absent in the Apiaí and São Roque terranes, Tonian metamorphic ages have been locally reported along the tectonic contact with the Embu Terrane (zircon U–Pb age of 794 ± 13 Ma; Campanha et al., 2019). Additional

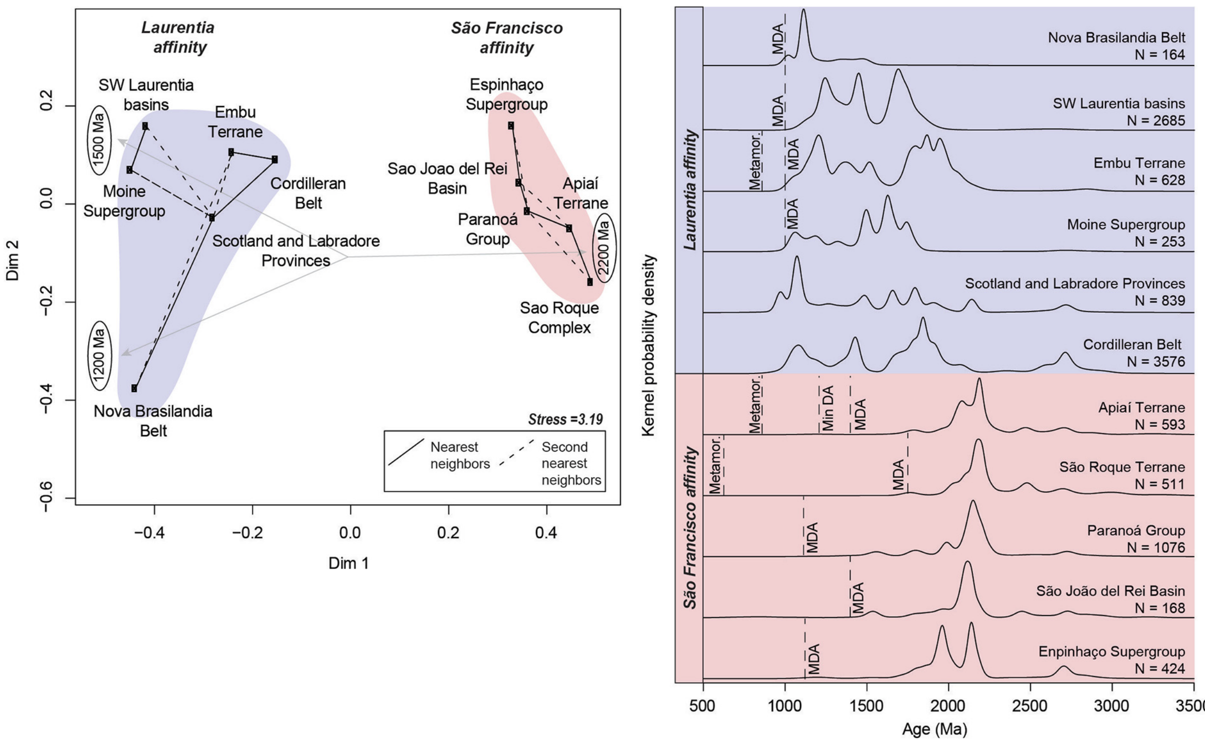

Fig. 5. Detrital zircon comparison between the Embu (groups 1 and 2), Apiaí and São Roque terranes from the Ribeira Belt with metasedimentary sequences with Gondwana affinity surrounding the São Francisco Craton (Santos et al., 2000; Valladares et al., 2004; Chemale et al., 2012; Matteini et al., 2012; Ribeiro et al., 2013; Oliveira, 2017; Martins-Ferreira et al., 2018; Seraine et al., 2020; Quadros et al., 2021) and Laurentia affinity (Cawood et al., 2004; Kirkland et al., 2008; Anfinson et al., 2012; Gehrels and Pecha, 2014; Tochilin et al., 2014; Bickford et al., 2015; Spencer et al., 2015; Mulder et al., 2017, 2018; Thomas et al., 2017).

Table 2
Proportion of detrital zircon ages with respect to the timing of continent–continent collision related to Rodinia assembly (ca. 1100 Ma) based on the data compilation presented in this paper.

	Moine Supergroup	Scotland and Labrador Provinces	SW Laurentia basins	Embu Terrane
Ages > 1100 Ma	90%	71%	99%	95%
Ages < 1100 Ma	10%	29%	1%	5%

Tonian metamorphic ages were reported from two major terrane bounding structures such as the Lancinha shear zone (zircon U–Pb age of 827 ± 14 Ma) and the Itapirapuã shear zone (*syn*-kinematic titanite U–Pb age of 896 ± 39 Ma and monazite U–Pb age of and 827 ± 14 Ma) (Cabrita et al., 2022; Faleiros et al., 2022). These data suggest that the juxtaposition between the Embu and Apiaí terranes likely occurred during Tonian (820–770 Ma), representing a major period of terrane accretion in the Ribeira Belt (Siga et al., 2009; Campanha et al., 2019; Cabrita et al., 2021; Caxito et al., 2022). If the Laurentian affinity of the Embu Terrane is correct (yet to be confirmed from detailed zircon Lu–Hf isotopic signatures), the Embu Terrane would have been rifted and drifted away from the Laurentia margin between 1000 Ma and 820 Ma likely during Rodinia breakup (Fig. 6) (Cawood et al., 2007; Chew et al., 2011; Cawood and Pisarevsky, 2017).

Meira et al. (2019) described two episodes of regional metamorphism recorded in the central portion of the Embu Terrane and in the Costeiro Terrane characterized by an intermediate-pressure regime at 620–600 Ma and a low-pressure regime at 600–575 Ma, respectively. Despite clearly different in terms of detrital zircon U–Pb ages and magmatic setting before Ediacaran, Meira et al. (2019) proposed a common tectonic evolution since at least ~650 Ma for both Embu–Costeiro domains. Thus, the Ediacaran metamorphism recorded in the central portion of the Embu Terrane may be related with the juxtaposition of the hot Costeiro Terrane, representing an Ediacaran episode of terrane accretion along the Ribeira Belt (Fig. 6). Rocks from the Embu Terrane in proximity to the Costeiro Terrane record isothermal decompression paths and re-equilibration at low-pressure conditions (Meira et al., 2019), likely representing the result of the Embu–Costeiro collage. The widespread felsic granitic magmatism from 660 Ma to 590 Ma with dominant peraluminous character and important crustal reworking/contamination component on whole-rock Nd–Sr isotopes (Alves et al., 2013, 2016; Janasi et al., 2003) might be result of the Embu–Costeiro collage (Fig. 6).

6. Conclusion

In this work, statistical tests are deployed to quantitatively characterize the dissimilarity among detrital zircon spectra from different terranes of the Ribeira Belt. These results demonstrate significant similarity between the São Roque and Apiaí terranes with detrital zircon spectra dominated by Paleoproterozoic ages (ca. 2200–2000 Ma) supporting a São Francisco Craton affinity. In addition, the detrital zircon record of the Embu Terrane is clearly dissimilar from those of the Apiaí and São Roque terranes, support-

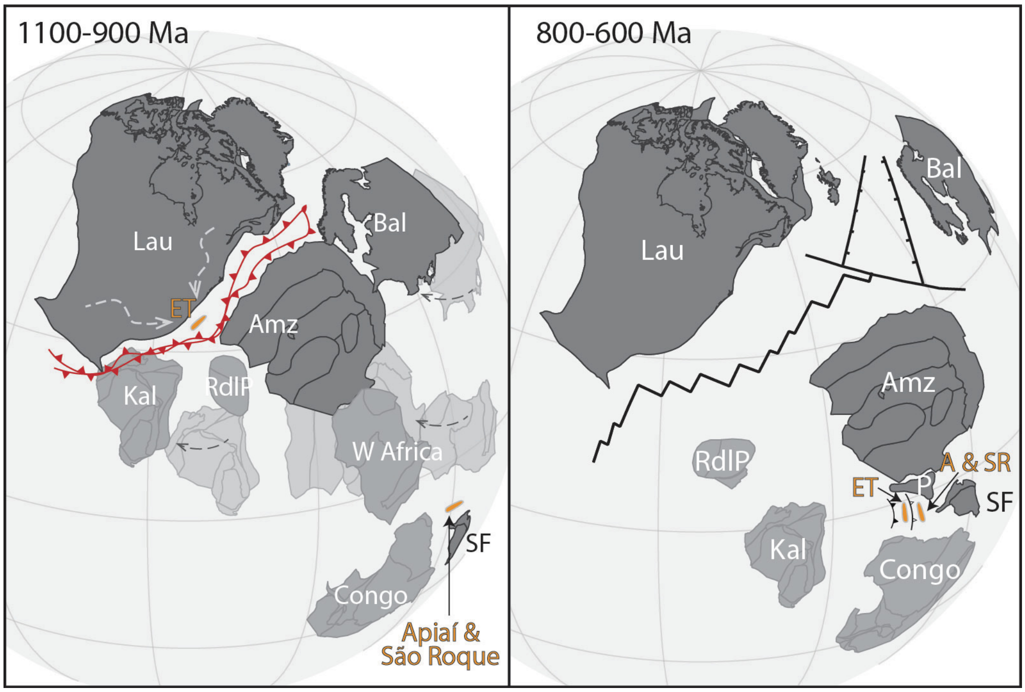

Fig. 6. Inferred paleogeographic reconstructions of the Embu, Apiaí and São Roque terranes during Rodinia assembly and breakup. Accretionary orogens drive rotation Amazonia, Baltica and Kalahari counter-clockwise to collide with Laurentia in Rodinia between 1100 Ma and 900 Ma. The Embu Terrane lies on the Laurentian side of the Rodinian suture, receiving detritus from the hinterland. Outboard, the Apiaí and São Roque terranes lie outboard of the São Francisco craton, which remains connected to Congo Craton. The scenario requires early Tonian rifting at the south western margin of Laurentia and commences breakup for Rodinia soon after assembly. Here, we adopt a modified version of Robert et al. (2020) reconstructions. The Embu Terrane rifts from the Laurentian margin of Rodinia drifting towards São Francisco Craton, with arc magmatism commencing between 900 Ma and 800 Ma. Accretion of the Embu terrane to the Ribeira Belt and juxtaposition with the Apiaí and São Roque terranes during the Tonian. A & SR: Apiaí and São Roque terranes; Amz: Amazonia; Bal: Baltica; ET: Embu Terrane; Lau: Laurentia; Kal: Kalahari; RdlP: Rio de la Plata; SF: São Francisco; W Africa: West Africa; P: Paranapanema Block. Reconstructions created in GPlates using shapefiles of Merdith et al. (2021) and rotation files modified from Merdith et al. (2021) and Robert et al. (2020).

ing its autochthonous characteristic. We demonstrated a potential affinity between the Embu Terrane and pre-orogenic SW Laurentia basins which are dominated by Meso- to Paleoproterozoic detrital zircon ages, likely representing the local basement and low-grade sedimentary successions imbricated by thrusting tectonics. We envisage a possible paleogeographic reconstruction for the Embu Terrane rifting from Laurentia between 900 Ma and 800 Ma with arc magmatism, accreting to the Apiaí and São Roque terranes during the Tonian. Campaign-style detrital zircon U–Pb–Hf study could go a long way to evaluate this hypothesis to strength the statistical correlation between the Embu Terrane and Laurentia affinity provenance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2022.101477.

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