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The Tonian Embu Complex in the Ribeira Belt (Brazil): revision, depositional age and setting in Rodinia and West Gondwana

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ABSTRACT:

The Embu Complex in the Neoproterozoic Ribeira Belt of Brazil provides a record of sedimentation associated with the Rodinia supercontinent and its subsequent deformation and metamorphism during assembly of West Gondwana. It is composed of a succession of variably migmatized pelitic schists and paragneisses, as well as minor calcsilicate rocks with quartzite intercalations, and orthogneiss. Detrital zircon U-Pb (LA-ICP-MS and SHRIMP) determinations for key samples of the Embu Complex in its type-area (West and Southwest of São Paulo City), and samples from neighboring units (Votuverava and São Roque groups) indicate distinct provenance histories and in combination with other data, discrete times of sediment accumulation. Detrital zircons from the Embu Complex are characterized by ages in the range 1500-1000 Ma and 2000-1700 Ma, with a very minor number of older ages. The youngest detrital grain is dated at 974 ± 12 Ma. Metamorphic zircon overgrowths range from 850 to 570 Ma with age peaks at ca. 820-790 and 650-570 Ma. Thus, the depositional age of the Embu Complex is constrained to 970-850 Ma. The detrital zircons of the Votuverava and São Roque groups are dominated by ages in the range 2200-2000 Ma, along with minor Paleoproterozoic and Archean ages. The youngest detrital grains are ~1400 Ma (Votuverava Group) and ~1750 Ma (São Roque Group). Metamafic rocks from the Votuverava Group have crystallization ages of ca. 1300 Ma, with a higher metamorphic grade amphibolite showing a range of discordant ages with upper and lower intercepts of 1300 Ma and ~800 Ma, respectively. These results demonstrate that the Embu Complex was probably accreted to the Apiaí Terrane during a Tonian (820-790 Ma) orogenic event, prior to final development of the Ediacaran Ribeira belt arc-related magmatism and a transcurrent shear zone system. The main source area for detrital zircons of the Embu Complex is likely to be the Grenville-Sveconorwegian-Sunsás orogen or time-equivalent regions rather than the central portions of the neighboring cratons. The Embu Complex geological context is consistent with accumulation on the margin of the Rodinia supercontinent.

KEY WORDS: Neoproterozoic, Mesoproterozoic, Votuverava Group, São Roque Group, Apiaí Terrane, detrital zircon, U-Pb geochronology.

1. Introduction

The Ribeira Belt in Southeast Brazil records the Neoproterozoic amalgamation of the São Francisco, Congo and Paranapanema cratons within West Gondwana (Almeida et al., 1973; Hasui et al., 1975; Porada, 1979). The belt is composed of a series of tectonostratigraphic terranes (blocks) bounded by late Neoproterozoic transcurrent shear zones. Ages of terranes range from Paleoproterozoic to early Cambrian, with widespread late Neoproterozoic (Ediacaran) granitoids, mainly arc-related, emplaced across the belt (Campanha and Sadowski, 1999; Campos Neto, 2000; Heilbron et al., 2008; Faleiros et al., 2011, 2016; Campanha et al., 2008, 2015, 2016; Henrique-Pinto et al., 2015). The depositional ages and tectonic settings of most supracrustal rock units are contentious (Soares, 1987; Fiori, 1992; Reis Neto, 1994; Campanha and Sadowski, 1999; Campanha et al., 2008, 2015, 2016; Siga Júnior et al., 2009, 2011a, 2011b; Faleiros et al., 2011, 2016; Henrique-Pinto et al., 2015; Meira et al., 2015; Costa et al., 2016) resulting in contrasting tectonic models for the evolution and environs of the Ribeira Belt. These models include those based on Wilson cycles of oceans opening and closing (e.g., Soares, 1987; Fiori, 1992; Reis Neto, 1994; Campanha and Sadowski, 1999), multiple collisions (Basei et al., 1992; Campos Neto and Figueiredo, 1995), sometimes dominated by exotic and suspect terrane accretion (Faleiros et al., 2011, 2016), lateral escape tectonics following oblique collision (Vauchez et al., 1994; Passarelli et al., 2011) and intracontinental settings (Meira et al., 2015). These models have important implications to reconstructions of the supercontinents Gondwana and Rodinia.

The southern and central Ribeira Belt is limited to the northwest by the Paranapanema Craton (covered by the Paleozoic Paraná sedimentary basin) to the southwest by the Luís Alves cratonic terrane and to the northeast by the system of nappes bordering the southern portion of the São Francisco Craton (Fig. 1). It comprises several tectonostratigraphic terranes such as the Apiaí, São Roque, Curitiba, Embu and Costeiro. A major tectonic boundary has been assigned to the the Lancinha - Cubatão strike-slip shear zone, which is considered by some authors as a late Neoproterozoic plate boundary (Faleiros et al., 2011, Basei et al., 2008).

The Apiaí Terrane comprises extensive carbonate platforms, such as the Itaiacoca and Lajeado groups (Campanha et al. 2016), and the Calymmian metavolcano-sedimentary Votuverava Group (Campanha et al., 2015). They were considered to have formed on the passive margin of the Paranapanema Craton (Campanha and Sadowski, 1999, Campos Neto, 2000). Known Ediacaran metavolcano-sedimentary units in the Apiaí Terrane are restricted and Neoproterozoic ages have mainly been determined from the extensive Andean-type arc-related plutonism that intrude these sequences and for the tectono-metamorphism that affected its metasedimentary rock formations (Campanha and Sadowski, 1999). The São Roque Terrane includes the São Roque and Serra de Itaberaba groups (Hasui, 1975; Juliani, 1992, Henrique-Pinto et al., 2015).

South of the Lancinha - Cubatão shear zone and bordering the Luís Alves Craton, the Curitiba Terrane is composed largely of a Paleoproterozoic TTG-type migmatitic orthogneiss suite (Atuba Complex) and Cryogenian to Ediacaran shallow continental-shelf metasedimentary assemblages (Turvo- Cajati and Capiru formations, Faleiros et al., 2011). Following the coast to the northeast lies the high-grade Ediacaran Costeiro Terrane, which is equivalent to the Serra do Mar Terrane (Campos Neto, 2000) and the Oriental and Cabo Frio terranes in Rio de Janeiro (Heilbron et al., 2008, Schmidtt et al., 2004).

The Embu Complex, also known as the Embu Terrane (Hasui, 1975, Hasui and Sadowski, 1976, Vieira, 1989, 1990, 1996, Vieira et al., 1988, Fernandes et al, 1990, Fernandes, 1991, Campos Neto, 2000), extends for some 500 km within the central portion of the Ribeira Belt from Eldorado Paulista to Resende towns, and is bounded by the Apiaí, São Roque, Curitiba and Costeiro terranes (Fig. 1). It consists of a variably metamorphosed interbanded siliciclastic sedimentary succession with rare mafic to ultramafic rocks. The Embu Complex has been only partially mapped regionally. Robust geochronological data have been acquired recently (Meira et al., 2015; Duffles et al., 2016; Costa et al., 2017) but were focused on the eastern portion of the Embu Complex, in areas distant from its original definition, and the overall areal extent of the complex remains uncertain.

In this paper, we present results from a study of the Embu Complex from its type area SW of São Paulo City, based on field mapping and U–Pb zircon dating as well as for the adjoining Votuverava (at Pilar do Sul) and São Roque (at Brigadeiro Tobias) groups. The results are used to: (a) assess the detrital zircon U-Pb signature of the Embu Complex in its type-area; (b) test the regional correlation with distant areas mapped as Embu Complex; (c) evaluate the proposed boundaries of the Embu Complex by analyzing samples from adjoining units (Votuverava and São Roque groups); and (d) determine possible source areas from detrital zircon signatures and their implications to large-scale tectonic correlations and the assembly of Proterozoic supercontinents (Gondwana and Rodinia).

2. Geologic Setting

The crystalline basement west of São Paulo town is cut by a series of transcurrent shear zones (Figures 1 and 2). The Taxaquara shear zone was originally defined as separating the São Roque and Serra de Itaberaba groups to the North from the Açungui Group to the South (Hasui, 1975; Juliani, 1992). The Embu Complex was defined as the higher metamorphic grade component of the Açungui Group, and possibly partially representing a basement to the group (Hasui, 1975, Hasui and Sadowski, 1976). More recently, this metamorphic-based division has been abandoned and the Embu is considered as a "terrane" with the lower metamorphic grade rocks attributed to the Votuverava Group (Campanha and Sadowski, 1999, Campos Neto, 2000). Orthogneiss bodies within the metasedimentary rocks of the Embu Complex are referred to as the Embu Gneiss (Cordani et al., 2002, Janasi and Lima, 2003, Duffles et al., 2016). A Paleoproterozoic basement unit, locally referred to as the Rio Capivari Complex, occurs within the complex in the region east of the São Paulo city (Fernandes, 1991, Motidomi, 1993, Babinski et al., 2001, Meira, 2014, Maurer, 2016; Costa et al., 2017), and has yielded a U-Pb SHRIMP zircon age of 2153 ± 15 Ma (Meira et al., 2015).

The Embu Complex in the region SW of São Paulo city (Figure 2) consists of a relatively monotonous, variably migmatized, succession of pelitic schists, paragneiss, banded metasedimentary rocks, and minor to rare calc-silicate rocks, quartzites, amphibolites and metaultramafic rocks. The paragneiss and pelitic schist are biotite- and muscovite-bearing along with variable amounts of feldspar and quartz, plus or minus garnet, sillimanite, tourmaline and opaque oxide minerals. Vieira (1990) also mentions kyanite and staurolite-bearing assemblages. Quartz schist and quartzite are distinguished on the basis of quartz content. Calc-silicate rocks are composed of quartz, diopside, amphibole (tremolite-actinolite), epidote, garnet, plagioclase, titanite, calcite, zircon and apatite (Vieira, 1990). Neosomes have granitic and pegmatitic composition with widths ranging from millimeters to meters, but small mappable bodies also occur. Amphibolite facies metamorphism affects the sedimentary rocks of the Embu Complex. The garnet-biotite geothermometer and anorthite-grossular-Al_2SiO_5-quartz geobarometer yield temperatures between 605^o C and 772^o C and pressures between 5 and 6 kbar (Vieira, 1996). Fibrolite (sillimanite) - muscovite aggregates are superimposed on the main metamorphic assemblage.

Detrital zircon grains from the sedimentary rocks in the Embu Complex to the east of São Paulo city have yielded ages from 3740 ± 7 Ma to 1002 ± 12 Ma (Meira et al., 2015).

Duffles et al. (2016) reported detrital ages as young as ca. 1000 Ma from the inferred northeastern extent of the complex with metamorphic overgrowths on the zircon yielding a variety of ages including 670–640 Ma, 621 - 599 Ma, and 576–574 Ma. In another geochronological study from the northeastern region of the complex, Costa et al. (2017) considered that accumulation of the sedimentary protoliths began after 852 ± 40 Ma, the youngest detrital grain, and was completed by the time of metamorphism at ~786 Ma. Metamorphosed aplites and granites within the complex yielded concordant crystallization ages of 783 ± 6 Ma and 768 ± 8 Ma, respectively (Meira et al., 2015). Monazite microprobe dating of muscovite-bearing garnet-sillimanite-biotite gneiss from the Embu Complex suggest a main metamorphic episode at ca. 790 Ma with evidence for partial resetting of the monazite at ca. 730 and 590 Ma (Vlach, 2001, 2008).

The Embu Complex displays isoclinal and transposed folds with a strong S_2 schistosity in which the more competent layers are boudinaged. At least two phases of open folding, sometimes associated with crenulation cleavages, post-date the main D_2 deformation. The regional structural pattern in the study area is defined by the upright transcurrent Taxaquara, Caucaia and Cubatão shear zones (the latter lying just south of the study area shown in Fig. 2). Close to these main shear zones, the foliation has an upright ENE trend, being more variable and tending to NS further away, and outlining a regional scale S/C structure in the block between the Caucaia and Cubatão shear zones (Fig. 2).

A large orthogneiss body (Fig. 2) outcrops along the Rodoanel and Regis Bittencourt highways. It is composed of grayish homogeneous porphyritic biotite gneiss cut by lighter granite and pegmatite veins. Cordani et al. (2002) obtained U-Pb SHRIMP zircon age of 811 ± 13 Ma, which they interpreted as its timing of emplacement. Feldspars within the body yielded a 560 Ma Rb-Sr isochron age, which they attributed to the sample falling below the 300-350 °C closure temperature of feldspar during the Brasiliano orogenic cycle.

U-Pb ages on zircons and monazites from granites intruding the Embu Complex give ages around 590 Ma with the zircon having inherited cores with Archean (∼3.1 Ga), Paleoproterozoic (2.4–2.1 Ga), and late Mesoproterozoic to early Neoproterozoic (1.1–0.9 Ga) ages (Alves et al., 2013).

The Votuverava Group in the Pilar do Sul region is composed of a metamorphosed fine-grained and well-banded succession of slate, phyllite and schist, interpreted as distal turbidites. A large number of metabasites with minor metavolcanic rock intercalations also occur, together with local and subordinate occurrences of quartzite, calc-silicate rocks, and small layers of gondites and tourmalinites, the last interpreted as the result of exhalative, hydrothermal processes (Campanha and Sadowski, 1999, Campanha et al., 2015, Stein et al., 1986). The group is deformed about a regional D_3 fold with ENE axial-plane, folding previous S_0, S_1 and S_2 foliations (Stein et al., 1986). In the hinge region of this fold, there is a progressive change from greenschist facies slates and epidote-actinolite bearing metabasites in the west to sillimanite zone mica schists, which in turn pass into migmatized schists and hornblende - plagioclase amphibolites in the east.

Lithological associations define the main differences between the Embu Complex and the Votuverava Group, with the latter characterized by abundant metabasites and metavolcanic intercalations, which are largely absent in the Embu Complex.

The São Roque Group in the study area is represented by low grade slates and phyllites, mainly rhythmites, with sandstones and marbles. Higher metamorphic grade rocks north of the Taxaquara shear zone have been generally assigned to the Serra de Itaberaba Group.

3. Analytical Methods

We selected eight samples from the Embu Complex and adjoining units (Votuverava and São Roque groups) for zircon U–Pb geochronology (Table 1). Mineral separation and zircon U-Pb geochronology was undertaken at the University of São Paulo. Zircons were extracted from 100-200 mesh fractions using standard isodynamic, gravimetric and magnetic techniques. The grains were hand-picked using a binocular microscope. Cathodoluminescence (CL) and scanning electron microscope (SEM) images were used to identify points for U/Pb analysis, avoiding fractures, inclusions or metamict areas that may have experienced Pb loss.

SHRIMP U/Pb data were obtained using a ~25 µm diameter spot. Details of the analytical procedure, as well as the calculations of the analytical errors are presented in Stern (1998), Williams (1998) and Sato et al. (2014). The decay constants and the ^{238}U/^{235}U ratio of Steiger & Jager (1977) has been used to calculate ages. U concentrations were calculated using the SL13 standard (U = 238 ppm) and ^{206}Pb/^{238}U ratios were calibrated using the TEMORA 2 standard (concordant, 416.8 ± 1.3 Ma; Black et al., 2004). U–Pb analyses by LA-MC-ICP-MS were carried out on a Finnigan Neptune MC-ICP-MS coupled to an excimer ArF laser (193 nm) ablation system. The mounts containing zircons were cleaned in a HNO_3 solution (3%) and in ultraclean water bath. The ablation was done with spot size of 29 µm, at a frequency of 6 Hz and an intensity of 6 mJ. The ablated material was carried by Ar (~0.7 L/min) and He (~0.6 L/min) and analysis was undertaken in 60 cycles of 1 s. Unknowns were bracketed by measurements of the international standard GJ-1, following the sequence 2 blanks, 3 standards, 12 unknowns, 2 blanks, and 2 GJ1 standards. Mud Tank zircon was used as a secondary standard. Raw data were reduced off-line with corrections for background, instrumental mass bias drift and common Pb.

The ages for zircons older and younger than 1300 Ma are derived from $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ ratios respectively, following correction for common Pb based on measured ^{204}Pb and the Cumming and Richards (1975) model Pb composition for the likely age of the zircons. The dates were calculated using the program Isoplot (Ludwig, 2003). Results are summarised as $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$ concordia diagrams. Comparisons of detrital zircon ages were established through histograms, probability density plots (PDP), cumulative density plots (CDP) and Kolmogorov-Smirnov (KS) test, carried out through excel spreadsheets (Stephens,1992; Gehrels et al., 2011). The Kolmogorov-Smirnov (KS) test compared if two analyzed distributions are the same or came from the same parent population, considering a 95% confidence level, and the null hypothesis is not rejected if P-value exceed 0.05.

4. Results

Six samples were analyzed by U-Pb LA ICPMS for detrital zircons and two samples of metamafic rocks were analyzed by U-Pb SHRIMP for igneous zircons (Fig. 2 and Table 1). The detrital zircon grains were collected from samples of metasandstone and quartz-rich calc-silicate beds. Three of these samples are from a region belonging to the Embu Complex (AN-47, WSP-22B, WSP-32B, in the block between the Caucaia and Cubatão shear zones), one from the Votuverava Group in Pilar do Sul region (WSP-05), one from the São Roque Group (WSP-03, Brigadeiro Tobias region), and one from a region attributed to both the Embu Complex (Hasui, 1975, Hasui and Sadowski, 1976) and the Votuverava Group (Janasi and Lima, 2003; Campos Neto, 2000) (AN-26A, Ibiúna region, between Taxaquara and Caucaia shear zones).

4.1. Votuverava Group samples (Pilar do Sul region)

The metamafic rocks are from the Votuverava Group and record contrasting metamorphic conditions. Sample WSP-04 is a greenschist facies titanite-epidote-actinolite metabasite with decussate texture. The main concentration of analyzed zircon grains have a xenomorphic habit with compositionally poorly zoned or sector zoned internal textures, typical of mafic rocks (Plate I - supplementary data). This zircon population yields a Concordia age of 1299 ± 6.2 Ma (MSWD = 0.48, n = 14) with Th/U varying from 0.57 to 1.64. A second group of analyses gave an age of 655 ± 18 Ma (MSWD = 0.86, n = 3), with Th/U between 0.25 and 0.40 (Fig. 3a, Table 2 - supplementary data).

Sample WSP-13 is a schistose amphibolite primarily composed of tschermakite and andesine. It yielded fractured and metamict zircon grains, which in CL display poorly zoned U-rich dark cores and U-poor light overgrowths (Plate I - supplementary data). U-Pb isotopic results are dispersed along a discordia line with an upper intercept of 1314 ± 29 Ma and a lower intercept of 750 ± 39 Ma (MSWD = 1.2, Figure 3b, Table 3 - supplementary data). The discordia line is anchored by two groups of concordant data with dates of 1279 ± 11 Ma (MSWD = 0.82, n = 2, Fig. 3b) and 794 ± 13 Ma (MSWD = 0.71, n = 2) that are interpreted as igneous emplacement and metamorphic overprint ages, respectively.

Sample WSP05 is from a thin bedded, meta-turbidite succession from the Votuverava Group in Pilar do Sul region that hosts the metamafic rock sample WSP04. Sample WSP05 is composed of quartz and muscovite with minor biotite, Fe-oxides and chlorite, indicating middle greenschist facies conditions. Analyzed grains range in age from 3.1-1.4 Ga with the main concentration of ages between 2.2 Ga to 1.8 Ga (Figs 4-5, Table 4 - supplementary data). The youngest grain gave an age of 1371 ± 14 Ma.

4.2. São Roque Group sample (Brigadeiro Tobias region)

Analyzed grains from sample WSP03, a metasandstone bed interlayered with phyllites from São Roque Group, range from 3.25 Ga to 2.0 Ga with the main concentration of ages between 2.25-2.0 Ga (Figs. 4-5, Table 5). Igneous rocks associated with the group include the Polvilho Volcanics, dated at 1760 ± 8.7 Ma (Van Schums et al., 1986, Henrique-Pinto et al. 2018), and metamafic rocks from the Cajamar region with an age of 1750 ± 40 Ma (Oliveira et al., 2008). These results suggest a depositional age for the group, in at least this region, of 1.76 Ga.

4.3. Embu Complex samples (SW of São Paulo City region)

Samples from the Embu Complex are mainly from thin beds of metasandstones interbedded with pelitic metasedimentary rocks of lower greenschist to upper amphibolite facies conditions. Sample WSP22B is a ferruginous metasandstone primarily composed of rounded quartz grains preserving a clastic sedimentary structure. It is interbedded with greenschist facies phyllite primarily composed of quartz, muscovite and Fe-oxides with minor tourmaline and biotite. Samples AN26A and AN47 are schistose quartzites with an interlobate granoblastic texture hosted by banded migmatitic paragneiss with residual neosome composed of biotite, quartz, sillimanite, plagioclase and K-feldspar and granitic leucosome. Sample WSP32B is a calc-silicate metasandstone with 70% quartz along with diopside, plagioclase, garnet, epidote, hornblende, opaque oxide minerals and titanite; it comes from a 20 cm-thick layer hosted by migmatized schist composed of quartz, biotite, garnet, plagioclase, K-feldspar, tourmaline and minor muscovite, with millimeter-thick lenses of granitic and trondhjemitic leucosome.

Zircon grains from samples AN47, AN26A and WSP22B are rounded and exhibit partially resorbed cores dominated by oscillatory compositional zoning and lower U contents (lighter colors in CL images; plates II, III, IV, supplementary data), and homogeneous to poorly zoned overgrowths with higher U contents (darker colors in CL images and low Th/U ratios, usually less than 0.1). The cores are interpreted as detrital grains derived mainly from igneous source rocks, whereas the rims represent textural and compositional characteristics of metamorphic overgrowths (e.g., Corfu et al., 2003). Zircon grains from sample WSP32B show no metamorphic overgrowths despite the upper amphibolite facies assemblage of the sample. Its zircon grains are dominantly subhedral, sometimes poorly rounded, with oscillatory zoning typical of igneous source rocks (Plate V - supplementary data). Some grains exhibit partially resorbed cores, sometimes with convolute textures, overgrown by oscillatory zoned rims.

Detrital grains within the analyzed Embu Complex samples display age peaks at 2.0-1.7 Ga and 1.5-1.0 Ga (Fig. 5). The youngest detrital grains in these samples yield ages between 1.02 - 0.97 Ga (Fig. 6, Tables 6-9 - supplementary data) with the youngest age of 974 ± 12 Ma obtained from sample WSP32B (spot 39.1). Metamorphic overgrowths on detrital igneous grains give ages between 0.85 and 0.57 Ga with peaks at ~ 0.8 (0.85 – 0.75) and ~0.6 (0.65 - 0.57) Ga (Fig. 7). These data constrain the depositional age of the Embu Complex to between 0.97 Ga and 0.85 Ga.

Discussion

Detrital zircons from the Embu Complex are mainly in the range 1.5 – 1.0 Ga with a subordinate group at 2.0 – 1.7 Ga, and few older ages. Samples WSP-32B, WSP-22B and AN-26A show strong similarity in the histograms (Fig. 5), cumulative density plots (CDP) (Fig. 08) and probability density plots (PDP) (Fig. 09). The KS test (table 10 - supplementary data) rejected the null hypothesis meaning these samples are the same or came from a similar parent population. Sample AN-47, also from the Embu Complex type-area, shows no correlation with the other samples and its CDP is right-shifted from those samples and left-shifted from those from the Votuverava and São Roque groups. Whereas samples WSP-32B, WSP-22B and AN-26A show mean peaks around *ca.* 1200 Ma, sample AN-47 has a principal peak around *ca*. 2000 Ma. Nevertheless, besides different mean peaks, they show a similar age range that spans *ca.* 2000 – 1000 Ma suggesting these samples were from similar sources but with different proportions of individual age components, along with the predominance of a Statherian source in the AN-47 sample (Fig. 5).

Detrital age signatures, including constraints on depositional age, indicate distinctive patterns for the Embu Complex, Votuverava and São Roque groups (Fig. 4-5). The depositional age of the Embu Complex is constrained in the range 0.97 – 0.85 Ga, whereas the Votuverava Group, in the Pilar do Sul region, accumulated between 1.4-1.3 Ga and the depositional age of at least part of the São Roque Group can be asserted at 1.76 Ga (Henrique-Pinto et al., 2015, 2018; this paper).

The analyzed Votuverava and São Roque groups have a main age peak at 2.2-1.8 Ga, with other ages in the remainder of the Paleoproterozoic and a few Archean ages. The pattern of detrital zircon ages for the Votuverava Group sample is consistent with data for this unit from further south (Faleiros et al., 2013; Basei et al., 2008). The age of the mafic magmatism is also compatible but not identical: the mafic magmatism at Pilar do Sul is 1.3 Ga whereas published data give ages of 1.5 – 1.47 Ga (Siga Jr. et al., 2011a, b; Campanha et al., 2015). Rims on zircons grains for sample WSP13 indicate the Votuverava Group experienced an amphibolite facies metamorphic event at ca. 810 - 780 Ma.

The pattern of detrital zircon ages for São Roque Group sample WSP03 is consistent with that obtained by Henrique-Pinto et al. (2015), who recorded ages restricted to the Paleoproterozoic and Archean (~3440-1730 Ma) and a main peak at ~2200 Ma.

A major metamorphic event, including anatexis, affected the rocks of the Embu Complex at about 0.85 – 0.75 Ga, as constrained by metamorphic rim ages as well as some oscillatory zoned prismatic grains, the latter attributed to crystallization in neosomes of migmatized schists. It is also the age obtained for biotite-bearing orthogneisses of the Embu Complex by Cordani et al. (2002) and Meira et al. (2015), as well the timing of metamorphism determined by Vlach (2008) using chemical dating in metamorphic monazite. Younger ages for metamorphic rims at about 0.6 Ga were also obtained (Figure 7). These events at 0.8 Ga and 0.6 Ga also affect the Votuverava Group in Pilar do Sul region, including the biotite-bearing Serra dos Lopes orthogneiss that is interbedded with Votuverava schists (Stein et al., 1986) and dated at 0.78 Ga (Leite, 2003).

Sample AN26A from an area previously mapped as either Embu Complex or Votuverava Group, has a detrital zircon pattern similar to Embu zircon grains, and hence should be included within the former. An implication of this result is that the Caucaia shear zone does not separate the two units. In Pilar do Sul, the Votuverava Group shows a metamorphic transition from slates, phyllites and epidote-actinolite metamafic rocks of the chlorite zone to medium to high grade migmatitic schists and amphibolites, thus metamorphic grade and structural style cannot be used to differentiate between the Votuverava Group and

Embu Complex. The contact between the two units must occur around the Piedade region but the nature of the contact is yet to be determined. Thus, assembly and juxtaposition of the Apiaí and Embu terranes occurred prior to final Ediacaran development of the transcurrent shear zone system and was likely contemporaneous to the 0.85 - 075 Ga metamorphic and migmatitic event (Fig. 10).

Embu Complex redefinition

The Embu Complex together with the Pilar Complex were defined as occurring in the block to the south of the Taxaquara shear zone, the former including units of medium to high metamorphic grade and the latter constituting the lower metamorphic grade rocks of the Açungui Group (Hasui, 1975, Hasui and Sadowski, 1976). As originally defined, the Embu Complex would also include older basement rocks together with the high metamorphic “Brasiliano” rocks of the Açungui Group in a complex structural arrangement.

Based on data presented here, along with previous geologic and geochronologic information (Stein et al., 1986, Campanha and Sadowski, 1999, Campos Neto, 2000, Campanha et al, 2015), we propose that the name Embu Complex be maintained in its original area but dissociated from the concept of the "Pilar Complex", which in its type-area (Pilar do Sul) should be replaced by the "Votuverava Group". The Embu Complex would comprise a metasedimentary unit, mostly terrigenous and metapelitic, with variable amounts of sandstones, metamorphosed at low to high grade, and an orthogneiss unit, with both forming in the early Neoproterozoic (Tonian). Older basement units like the Paleoproterozoic Capivari Complex in the region east of the São Paulo city should be considered separately .

Provenance record

The pattern of detrital zircon ages from the Embu Complex, characterized by a major age peak in the range between 1.5 – 1.0 Ga and a subordinate group at 2.0 – 1.7 Ga, along with a few older ages, is distinct from other units of the Southern Ribeira Belt and neighboring cratons (Faleiros et al., 2013, 2016; Basei et al., 2008, Henrique-Pinto et al., 2015, 2018, Campanha et al., 2016).

The pattern of detrital zircons ages within the Embu Complex is not only different from the units of the Apiaí Terrane but from units associated with the São Francisco, Paranapanema and Luís Alves cratons, which have a major age peak at about 2.2-1.8 Ga as well as some Archean ages (Campanha et al., 2008, 2015, 2016; Siga Jr. et al., 2011a, b;

Henrique-Pinto et al., 2015), the latter almost absent from the Embu Complex (Fig. 11). The Paranapanema Craton (Mantovani and Brito Neves, 2005, Campos Neto, 2000) is completely covered by Paleozoic sedimentary rocks and was recognized by data from deep boreholes and geophysical studies. The Luis Alves cratonic fragment has a Paleoproterozoic basement (Siga Jr. et al, 1993, Basei et al., 1998, Hartmann et al. 2015).

The main Mesoproterozoic to early Tonian units in the South American shield that can be sources and /or chrono-correlatives for the Embu detrital zircons include (Fig. 12) the Espinhaço Supergroup in the São Francisco Craton and the Araçuai belt (Chemale Jr. et al, 2012), the Cariris Velhos orogen in the Borborema province (1.05 to 0.95 Ga, Brito Neves et al, 1995, Santos et al., 2010), the Sunsás–Aguapeí province (1.20–0.95 Ga, Litherland et al., 1986, 1989, Sadowski and Bettencourt, 1996, Teixeira el al., 2010), as well units of the Apiaí Terrane in the Ribeira belt (Siga Jr. et al., 2011a, b; Campanha et al., 2015, 2016), all more or less affected by the Neoproterozoic Brasiliano / Panafrican cycle. Mesoproterozoic units in Africa include the Namaqua, Irumide and Kibaran belts around the Kalahari and Congo cratons (Hanson, 2003, Cordani et al., 2010).

The mafic magmatism of the Votuverava Group could be a source area for the 1.5 - 1.3 Ga detrital zircons (Campanha et al., 2015) but not for the younger detrital grains that range from 1.3 - 1.0 Ga. The Capivari Complex, which underlies the Embu Complex in the region east of São Paulo town, seems not to be a consistent source as Paleoproterozoic detrital zircons are rare in the Embu Complex.

The Espinhaço Supergroup has initial felsic volcanism at ~1.75 Ga and a mafic dike swarm at 1.1 - 0.9 Ga (Chemale Jr. et al., 2012) thus it does not have a complete range of igneous ages to be a reliable source for the detritus of the Embu Complex.

Although possible sources could include mafic rocks of appropriate age, such as the Votuverava Group and the mafic dike swarm of the Espinhaço Supergroup, they generally do not crystallize large numbers of zircons and hence are unlikely to have been a significant source of detritus. Additionally, zircon grains from these mafic rocks invariably show unzoned to poorly zoned internal textures (Siga Jr. et al., 2011a, b; Campanha et al., 2015), being very different from the oscillatory zoned detrital zircon grains from the Embu Complex metasedimentary rocks, which present internal textures typical of zircons derived from felsic rocks (Corfu et al., 2003).

Metasedimentary units around the western and southern borders of the São Francisco Craton (Brasília Belt) include syn-orogenic basins, passive margins and foreland basins (Fig. 11). The São João Del Rei, Canastra and Paranoá groups have been interpreted as passive margins of the craton displaying provenance patterns dominated by Paleoproterozoic and Archean zircons. On the other hand, the Andrelândia, Araxá and Ibiá groups display distinct provenance patterns with a large proportion of Neoproterozoic zircon grains, as young as 640 Ma. But all show a variable presence of Mesoproterozoic detrital ages, with unknown sources inside the São Francisco Craton (Pimentel et al., 2011, 2016, Matteini et al., 2012, Rodrigues et al., 2010, 2012, Frugis et al., 2018).

In the core of the Brasília Belt three large mafic-ultramafic complexes (Barro Alto, Niquelândia and Canabrava complexes) are representative of two rift systems, one at ca. 1.25 Ga, and the younger at. ca. 0.79 Ga. According to Pimentel et al. (2016) these ages are not common in the South America platform, and therefore, these complexes and associated volcano-sedimentary sequences (Juscelândia, Indaianópolis and Palmeirópolis, respectively) are interpreted as allochthonous units in the Brasília Belt evolution.

Basei et al. (2008) differentiated “African” and “South American” signatures with different detrital zircon ages across West Gondwana. Whereas the Ribeira (understanding “Ribeira” mainly as the Apiaí Terrane) sources are only Archean and Paleoproterozoic, the sources for the Southern Dom Feliciano Belt and the African Damara and Gariep–Rocha belts include Mesoproterozoic and Neoproterozoic zircons; it was proposed that the sources for the “Ribeira basin” was essentially derived from the Paranapanema and Rio de la Plata cratons, whereas for the Damara and Gariep–Rocha belts source areas were from the Namaqua Belt. The detrital zircon age signatures for the Damara-Gariep-Rocha belts are similar to the Embu Complex, with a main age group between 1.4 – 1.0 Ga and a minor around 2.0 – 1.8 Ga, but also include an Ediacaran to Cambrian younger group (Fig. 11).

Other Mesoproterozoic to Early Tonian units more distant that could be sources for the Embu Complex in the final configuration of the Gondwana continent (Fig. 12) are the Kiberan and Lufilian belts on the African side around the Congo Craton, the Namaqua Belt around the Kalahari Craton, and the Sunsás-Aguapeí Belt in the Southwest border of the Amazonian Craton. The Namaqua Belt has a prolonged interval from 1376 to 1135 Ma involving arc magmatism and initial stages of collision followed by high-grade metamorphism and voluminous plutonism at c. 1068-1020 Ma; the Kibaran and Irumide belts represent parts of a long-lived Mesoproterozoic c.1400 to 1000 Ma orogenic province formed during the Rodinia assembly (Hanson, 2003 and citations therein). The Sunsás–Aguapeí province formed at 1.20–0.95 Ga and includes passive margin (< 1.2 Ga), collisional (1.11–1.0 Ga), and post-tectonic and anorogenic magmatic events (1.0 – 0.95 Ga) (Litherland et al., 1986, 1989, Sadowski and Bettencourt, 1996, Teixeira et al., 2010).

Most potential Mesoproterozoic to Early Tonian source units (e.g., Namaqua, Sunsás–Aguapeí, Kiberan and Lufilian belts) lie in the core of the Grenville orogen (sensu lato) in several Rodinia reconstructions (e.g., Li et al., 2008, Merdith et al., 2017) (Fig. 13) and thus this orogenic system is the most probable source for the detrital zircons of the Embu Complex. The large distance from source (Grenville) to sink (Embu) is comparable to that invoked for basins in northwestern Laurentia. For example, Rainbird et al. (2012) proposed that weathering and erosion of the ca. 12,000 km long Grenvillian mountain range produced huge volumes of sedimentary detritus that were dispersed by an enormous system of braided rivers.

Regional significance

Our new age data indicate that the Embu Complex displays a distinct provenance and age history relative to the adjoining Votuverava Group of the Apiaí Terrane. The former accumulating between 970-850 Ma, whereas the turbiditic Votuverava Group is associated with immature island arc magmatism at ~ 1490-1300 Ma (Siga Jr. et al., 2009, 2011, Campanha et al., 2015, this paper). Juxtaposition of these two assemblages occurred at 820-790 Ma based on the timing of metamorphism and deformation (this paper). In addition to the Votuverava Group, the Apiaí Terrane incorporates a Stenian-Tonian carbonate platform and passive margin (Lajeado Group, 1200 to 877 Ma; Campanha et al., 2016). The Tonian age for deposition and tectonothermal history of the Embu Complex along with its age of assembly with the Apiaí Terrane indicate that they developed on the periphery of the supercontinent of Rodinia and could not have occupied an internal, intracratonic position.

Cryogenian and Ediacaran marine units immediately to the south of the study region are the Turvo-Cajati and Capiru formations in the Curitiba Terrane (Fig. 1 and 11), as well the Dom Feliciano Belt in southern Brazil (Basei et al., 2008; Faleiros et al., 2013, 2016, Siga Jr., et al. 2012), suggesting that this peripheral position on the Rodinia supercontinent remained until the final Gondwana closure.

A temporal correlative of the Embu Complex is the Mara Rosa magmatic arc complex in the Brasilia Belt**.** This unit formed between 900 to 600 Ma with peaks of U-Pb ages for orthogneisses and granitoids at 860, 800 and 640 Ma (Pimentel et al. 2011, 2016). Further south, the São Gabriel juvenile magmatic arc adjacent to the Rio de La Plata Craton shows a similar time evolution from 965 to 600 Ma (Gubert et al., 2016 and citations therein). The recently defined Tonian Serra da Prata juvenile magmatic arc in the Eastern portion Ribeira Belt shows similar age pattern (Peixoto et al, 2017). These units represent active margins of the Rodinia supercontinent. Although these units are temporal correlatives of the Embu Complex, there are no (meta)sedimentary units in the Brasília and Dom Feliciano belts with a similar provenance record to the Embu Complex.

The provenance record and setting of the Embu Complex is similar to some units that are inferred to have accumulated on the margin of Rodinia, such as the Moine Supergroup and related units of the Valhalla Orogen, which out crops in Scotland, Greenland and Scandinavia (Cawood et al., 2010, 2015, Krabbendam et al., 2017a, Slagstad et al., 2017). The Embu Complex (this paper; Vieira, 1990, 1996, Fernandes, 1991, Motidomi, 1993) and the Moine Supergroup (Stratchan et al., 2002, Krabbendam et al., 2017b, Cawood et al., 2015, Mazza et al, 2018, and references therein) have similar lithological, metamorphic, igneous and structural associations. Both are mainly siliciclastic metasedimentary successions, including psammites, pelites, calc-silicates and rare mafic igneous rocks, with strong and polyphase deformation. They have major age peaks for detrital zircons in the late Paleoproterozoic and Mesoproterozoic, with few Archean and other Paleoproterozoic ages. Deposition of the two units is younger than 1.0 Ga (Fig. 9). The Moine Supergroup has an igneous episode at 0.87 Ga whereas in the Embu Complex this occurs at about 0.81 Ga. Both have high-grade metamorphic and pegmatite episodes between 0.83 and 0.79 Ga, and less clear events in the Neoproterozoic until ~0.6 Ga. Both also have granite intrusions at 0.6 – 0.58 Ga. The Moine was subsequently affected by the Caledonian metamorphic and deformational orogeny, which is absent in southeast Brazil. Despite the similar metamorphic and structural styles at the outcrop scale, the overall tectonic arrangement of the Moine Supergroup is a series of nappes with transport to NW over the Lewisian Complex, while the final tectonic disposal of the Embu Complex is largely dominated by the late Neoproterozoic upright dextral transcurrent shear zones.

Our samples, WSP-32B, WSP-22B and AN-26A from the Embu Complex show high P-values and strong correlation in cumulative distribution plots (CDP) with the sample SH02-13 (Cawood et al., 2004) from the Loch Eil Group (Fig. 09, Table 11 - supplementary data). Non zero P-values were found with sample SH02-1 from the Glen Urquart site of the Moines (Cawood et al., 2004) and with the ARDN-3 sample from the Glenfinnan Group (Kirkland et al., 2008). Zero P-values were found with the ARDN-1 sample from the Morar Group (Kirkland et al., 2008). The samples from the foreland Torridon and Sleat groups (Krabbendan et al., 2017) also show zero P-values with the samples from the Embu Complex. These data suggest similar source for the detrital zircons of the Embu Complex and the upper units of the Moine Supergroup (Glen Urquart, Loch Eil and Glenfinnan groups).

Similarities between the Embu and Moine do not reflect a spatial association but rather a similar tectonic environment on the margin of Rodinia; the Embu Complex accumulated and was then deformed and metamorphosed in an analogous setting to the Moine Supergroup. They accumulated on the margin of Rodinia and were derived from a hinterland source region within the core of the supercontinent and associated with its assembly (Fig. 13). For the Moines this included the Sveconorwegian orogen and older basement units exhumed during this tectonothermal event. Thus, they are dominated by detritus derived from units associated with the Grenville-Sveconorwegian-Sunsás Belt. For the Embu, African sources such as the Namaqua, Kiberan and Lufilian belts can also considered but they usually incorporated in the Grenville-Sveconorwegian-Sunsás Belt in most Rodinia reconstructions. The paucity of Archean grains reflects the fact that this collisional orogen did not involve significant area of Archean rocks. Thus, the Archean was low ground that was not being eroded. In contrast, 2.0 to 1.0 rocks were a major part of the collisional Grenville-Sveconorwegian-Sunsás Belt. Major river systems drained these highlands and deposited detritus in basins on the edge of Rodinia.

Conclusions

The Embu Complex, originally defined SW of São Paulo City, in the Ribeira Belt, has a distinctive lithological, metamorphic, structural and igneous pattern, including the ages of detrital zircons that enable it to be distinguished from the adjacent units of the Apiaí and São Roque terranes.

The depositional age of the Embu Complex is constrained by the youngest detrital zircon at 0.97 Ga and a metamorphic overprint commencing at 0.85 Ga. In contrast, the currently structurally adjoining Votuverava Group in the Pilar do Sul region accumulated between 1.4-1.3 Ga, whereas the depositional age of at least part of the São Roque Group is 1.76 Ga. Detrital zircons from the Votuverava and São Roque groups fall mainly in the range of 2.2-1.8 Ga (Orosirian – Ryacian), with some additional minor early Paleoproterozoic and a few Archean ages. The Embu Complex is dominated by grains in the range 1.5-1.0 Ga with a secondary range at 2.0-1.7 Ga and a very few older grains. Metamorphic events at ca. 0.8 and 0.6 Ga affected the Embu Complex, including an igneous event at ca. 0.81 Ga represented by orthogneiss.

These results demonstrate that the Embu Complex was not part of the Apiaí Terrane but that the Apiaí and Embu terranes amalgamated during the ~ 0.8 Ga regional metamorphism that affected both units and prior to final development along the Ediacaran transcurrent shear zone system.

We propose that Embu Complex be based on the rock association SW of São Paulo City where it was originally defined and this be used as the template for extending it, and defining its limits in the Ribeira Belt. It is a predominantly a metasedimentary succession along with orthogneiss units. We separate the Embu Complex from the "Pilar Complex", which in its type-area (Pilar do Sul) should be replaced by the "Votuverava Group". The lithological associations and age patterns of the Votuverava Group at Pilar do Sul are different from the Embu Complex across the range of metamorphic grades displayed by both units.

Similarities between the Embu Complex and other units such as the Moine Supergroup in terms of their lithological, metamorphic, igneous and structural associations but also in the age patterns of deposition and superimposed metamorphic and igneous events, do not necessarily reflect a spatial association, but are consistent with their common accumulation on the margin of the Rodinia supercontinent. The most probable main source area for detrital zircons was the Grenville-Sveconorwegian-Sunsás orogen with only minor detritus from neighboring cratons, which likely occupied low ground at the time of accumulation of the Embu Complex.

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References

Almeida, F.F.M. de; Amaral, G.; Cordani, U.G.; Kawashita, K. 1973. The Precambrian evolution of the South American cratonic margin south of Amazon River. In: Nairn, E.M. and Stehli, F.G. (eds.) *The ocean basins and margins*. New York, Plenun., 1, 411-446.

Alves, A.; Janasi, V. A.; Campos Neto, M. C.; Heaman, L.; Simonetti, A. 2013. U-Pb geochronology of the granite magmatism in the Embu Terrane: Implications for the evolution of the Central Ribeira Belt, SE Brazil. In: *Precambrian Research* v. 230, p. 1-12.

Babinski, M., Tassinari, C.C.G., Nutman, A.P., Sato, K., Martins, P.R. and Iyer, S.S., 2001. U/Pb SHRIMP zircon ages of migmatites from basement of the Embu Complex, Ribeira Fold Belt, Brazil: Indications of ~1.3-1.4 Ga Pb-Pb and Rb-Sr “isochron” ages of no geological meaning. In: III South American Symposium on Isotope Geology, Pucon, Chile, *Extended Abstracts*.

Basei, M. A. S.; Siga Junior, O.; Machiavelli, A.; Mancini, F. 1992. Evolução Tectônica dos Terrenos entre os Cinturões Ribeira e Dom Felciano (PR-SC). *Revista Brasileira de Geociências*, v. 22, n.2, p. 216-221.

Basei, M.A.S., McReath, I., Siga Junior, O., 1998. The Santa Catarina Granulite Complex of Southern Brazil. *Gondwana Research* 1, 383–391.

Basei, M.A.S., Frimmel, H.E., Nutman, A.P., Preciozzi, F., 2008. West Gondwana Amalgamation Based on Detrital Zircon Ages from Neoproterozoic Ribeira and Dom Feliciano Belts of South America and Comparison with Coeval Sequences from SW Africa. *Special Publications* 294. Geological Society, London, pp. 239–256.

Black, L. P., Kamo, S. L., Allen, C. M., Davis, D. W., Alenikoff, J. N., Valley, J. W., Mundif, R., Campbell, I. H., Korsch, R. J., Williams, I. S., Foudoulis C., 2004. Improved ^{206}Pb^{238}U microprobe geochronology by the monitoring of trace element related matrix effect; SHRIMP, ID-TIMS, ELA-ICP-MS and oxygen isotope documentation for a series of zircon standards. *Chemical Geology* 205, 115–140.

Brito Neves, B. B.; Van Schmus, W. R. ; Santos, E. J. ; Campos Neto, M. C. ; Kozuch, M. . O Evento Cariris Velhos na Província Borborema: integração de dados, implicações e perspectivas. *Revista Brasileira de Geociências,* v. 25, n. 04, p. 279-296.

Campanha, G. A. C.; Sadowski, G. R. 1999. Tectonics of the Southern Portion of the Ribeira Belt (Apiaí Domain). *Precambrian Research*, v. 98, n. 1, p. 31 - 51.

Campanha, G.A.C., Basei, M.S., Tassinari, C.C., Nutman, A.P. and Faleiros, F.M., 2008. Constraining the age of the Iporanga Formation with SHRIMP U-Pb zircon: implications for possible Ediacaran glaciation in the Ribeira Belt, SE Brazil. *Gondwana Research*, v. 13, n.1, p. 117-125.

Campanha, G.A.C., Faleiros, F.M., Basei, M.A.S., Tassinari, C.C.G., Nutman, A.P., Vasconcelos, P.M., 2015. Geochemistry and age of mafic rocks from the Votuverava Group, southern Ribeira Belt, Brazil: evidence for 1490 Ma oceanic back-arc magmatism. *Precambrian Research* 266, 530-550

Campanha, G.A.C.; Basei, M.A.S. ; Faleiros, F.M. ; Nutman, A.P. 2016. The Mesoproterozoic to Early Neoproterozoic passive margin Lajeado Group and Apiaí Gabbro, Southeastern Brazil. *Geoscience Frontiers*, v. 7, p. 683-694.

Campos Neto, M.C. and Figueiredo, M.C.H. 1995 The Rio Doce Orogeny, Southeastern Brazil. *Journal of South American Earth Sciences*, 8(2): 143-162. Pergamon Press.

Campos Neto, M. C. 2000. Orogenic systems from southwestern Gondwana. An approach to Brasiliano-Pan African Cycle and orogenic collage in southeastern Brazil. In: Cordani, U.

G.et al. (Eds.). International Geological Congress, 31st, 2000, Rio de Janeiro. *Tectonic Evolution of South America.* Rio de Janeiro: SBG, 2000. p. 335-365.

Cawood, P.A., Nemchin, A.A., Strachan, R.A., Kinny, P.D., Loewy, S., 2004. Laurentian provenance and an intracratonic tectonic setting for the Moine Supergroup, Scotland, constrained by detrital zircons from the Loch Eil and Glen Urquhart successions. *J. Geol. Soc. London* 161, 861–874.

Cawood, P.A., Strachan, R., Cutts, K., Kinny, P.D., Hand, M., Pisarevsky, S., 2010, Neoproterozoic orogeny along the margin of Rodinia: Valhalla orogen, North Atlantic. *Geology*, v. 38, p. 99–102, doi: 10 .1130 /G30450 .1 .

Cawood, P.A., Strachan, R.A., Merle, R.E., Millar, I.L., Loewy, S.L., Dalziel, I.W.D., Kinny, P.D., Jourdan, F., Nemchin, A.A., Connelly, J.N. 2015. Neoproterozoic to early Paleozoic extensional and compressional history of East Laurentian margin sequences: The Moine Supergroup, Scottish Caledonides. *Geological Society of America Bulletin*, v. 127, no. 3/4

Cawood, P.A., Strachan, R.A., Pisarevsky, S.A., Gladkochub, D.P., Murphy, J.B. 2016. Linking collisional and accretionary orogens during Rodinia assembly and breakup: implications for models of supercontinent cycles. *Earth Planet. Sci. Lett.*, 449 (2016), pp. 118-126

Cawood, P.A., Pisarevsky, S.A. 2017. Laurentia-Baltica-Amazonia relations during Rodinia assembly. *Precambrian Research* 292 pp. 386–397

Chemale Jr., F., Dussin, I.A., Alkmim, F.F., Martins, M.S., Queiroga, G., Armstrong, R., Santos, M.N., 2012. Unravelling a Proterozoic basin history through detrital zircon geochronology: The case of the Espinhaço Supergroup, Minas Gerais, Brazil. *Gondwana Research* 22, pp. 200–206.

Cordani, U. G.; Coutinho, M. V.; Nutman, A. P. 2002. Geochronological constrains on the evolution of the Embu Complex, São Paulo, Brazil. *Journal of South American Earth Sciences*, Amsterdam, v. 14, p. 903-910.

Cordani, U. G.; Fraga, L. M. ; Reis, N. ; Tassinari, C. C.G. ; Brito Neves, B. B. 2010. On the origin and tectonic significance of the intra-plate events of Grenvillian-type age in South America: a discussion. *Journal of South American Earth Sciences*, v. 29, p. 143-159

Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P., 2003. Atlas of zircon textures. *Reviews in Mineralogy and Geochemistry* 53, 469-500.

Costa, R.V., Trouw, R.A.J., Mendes, J.C., Geraldes, M., Tavora, A., Nepomuceno, F., Araújo Junior, E.B.A. 2017. Proterozoic evolution of part of the Embu Complex, eastern Sao Paulo state, SE Brazil. *Journal of South American Earth Science*s V. 79, p. 170 -188

Cumming, G.L., Richards, J.R., 1975. Ore lead isotope ratios in a continuously changing Earth. *Earth and Planetary Science Letters 28*, 155-171

Duffles, P., Trouw, R.A.J, Mendes, J.C., Gerdes, A., Costa, R.V. 2016. U–Pb age of detrital zircon from the Embu sequence, Ribeira belt, SE Brazil. *Precambrian Research* 278, 69–86

Faleiros, F. M.; Campanha, G. A. C.; Martins, L. Vlach, S. R. F.; Vasconcelos, P. M. 2011. Ediacaran high-pressure collision metamorphism and tectonics of the southern Ribeira Belt (SE, Brazil): Evidence for terrane accretion and dispersion during Gondwana assembly. *Precambrian Research* v. 189, p. 263-291.

Faleiros, F. M.; Pavan, M.; Ferrari, V. C.; Rodrigues Pinto, L. G.; Almeida, V. V.; Caltabeloti, F. P.; Costa, V. S. 2013. *Mapa Geológico da Folha Eldorado Paulista, escala 1:100.000*. São Paulo, Programa Geologia do Brasil – PGB, CPRM.

Faleiros, F. M.; Campanha, G. A. C. ; Pavan, M. ; Almeida, V.V. ; Rodrigues, S. W. O. ; Araujo, B. P. 2016. Short-lived polyphase deformation during crustal thickening and exhumation of a collisional orogen (Ribeira Belt, Brazil). *Journal of Structural Geology*, v. 93, p. 106-130.

Fernandes, A. J. 1991. *Complexo Embu no leste do Estado de São Paulo: contribuição ao conhecimento da litoestratigrafia e da evolução estrutural e metamórfica*. Dissertação de Mestrado, Instituto de Geociências, Universidade de São Paulo, 120 p. Available at: http://www.teses.usp.br

Fernandes, A. J.; Campos Neto, M. C.; Figueiredo, M. C. H. 1990. O Complexo Embu no leste do estado de São Paulo: limites e evolução geológica. In: *Anais do XXXVI Congresso Brasileiro de Geologia*, Natal. Sociedade Brasileira de Geologia / Núcleo Nordeste, vol. 6, p. 2755-2763.

Fiori, A.P. 1992. Tectônica e estratigrafia do Grupo Açungui, PR. *Boletim IG-USP série científica*, 23: 55 - 74.

Frugis G.L., Campos Neto, M.C., Lima, R. B. 2018. Eastern Paranapanema and southern São Francisco orogenic margins: Records of enduring Neoproterozoic oceanic convergence and collision in the southern Brasília Orogen. *Precambrian Research*, vol. 308, p. 35-57, ISSN 0301-9268, https://doi.org/10.1016/j.precamres.2018.02.005.

Gubert, M.L., Philipp, R.P., Basei, M.A.S. 2016. The Bossoroca Complex, São Gabriel Terrane, Dom Feliciano Belt, southernmost Brazil: U-Pb geochronology and tectonic implications for the Neoproterozoic São Gabriel Arc. *Journal of South American Earth Sciences* vol. 70, p. 1-17, ISSN 0895-9811, https://doi.org/10.1016/j.jsames.2016.04.006.

Hanson, R.E., 2003. Proterozoic geochronology and tectonic evolution of southern Africa. In: Yoshida, M., Windley, B., Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. *Geological Society London Special Publication* 206, pp. 428–463.

Hartmann, L.A.; Savian, J.F.; Lopes, W.R. 2015. Airborne geophysical characterization of geotectonic relationships in the southern Ribeira Belt, Luís Alves Craton, and northern Dom Feliciano Belt, Brazilian Shield. I*nternational Geology Review*, DOI: 10.1080/00206814.2015.1089424

Hasui, Y.; Sadowski, G. R. 1976. Evolução Geológica do Pré-cambriano na região sudeste do estado de São Paulo. São Paulo, In: *Revista Brasileira de Geociências*, vol. 6, p. 182-200.

Hasui, Y., Carneiro, C.D.R., Coimbra, A.M., 1975. The Ribeira folded Belt. *Revista Brasileira de Geociências* V.5, N.4, p. 257-262.

Hasui, Y. 1975. Evolução polifásica do Pré-Cambriano a oeste de São Paulo. São Paulo, *Boletim do IG*, Instituto de Geociências, Universidade de São Paulo, vol. 6, p. 95-108.

Heilbron, M.; Valeriano, C.; Tassinari, C. C. G.; Almeida, J.; Tupinambá, M.; Siga Jr.., O.; Trouw, R.A. 2008. Correlation of Neoproterozoic terranes between the Ribeira Belt, SE Brazil and its African counterpart comparative tectonic evolution and open questions. In: Pankhurst, R. J., Trouw, R. A. J., Brito Neves, B.B. & De Wit, M. J. (eds) *West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region. Geological Society, London, Special Publications,* 294 , 211 – 237.

Henrique-Pinto, R., Janasi, V.A., Vasconcellos, A.C.B.C., Sawyer, E.W., Barnes, S.J., Basei, M.A.S., Tassinari, C.C.G., 2015. Zircon provenance in meta-sandstones of the São Roque Domain: Implications for the Proterozoic evolution of the Ribeira Belt, SE Brazil. *Precambrian Research*, 256: 271-288.

Henrique-Pinto, R., Janasi, V.A., Campanha. G.A.C. 2018. U-Pb dating, Lu-Hf isotope systematics and chemistry of zircon from the Morro do Polvilho meta-trachydacite: constraints on sources of magmatism and on the depositional age of the São Roque Group. *Geologia USP*, v. 18, n. 2, p. 4-56. https://doi.org/10.11606/issn.2316-9095.v18-125793.

Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside-out? *Science*, 252 (5011), pp. 1409-1412.

Janasi, V. A.; Lima, R. B. 2003. Gnaisses da Grande São Paulo: geologia, petrografia e geoquímica dos granito gnássicos do extremo leste do Batólito Agudos Grandes. In: Simpósio de Geologia do Sudeste, 8, 2003, São Pedro. *Boletim de Resumos*... São Pedro: SBG – Núcleo SP. p. 36.

Juliani, C. 1992. O embasamento pré-cambriano da Bacia de São Paulo. *In*: *ABAS/ABGE/SBG-SP. Atas do Seminário de Problemas Geológicos e Geotécnicos na Região Metropolitana de São Paulo*, São Paulo, p. 3-20.

Kirkland, C.L., Strachan, R.A., Prave, A.R. 2008. Detrital zircon signature of the Moine Supergroup, Scotland: Contrasts and comparisons with other Neoproterozoic successions within the circum-North Atlantic region. *Precambrian Research*, vol.163, Issues 3–4, p. 332-350, ISSN 0301-9268, https://doi.org/10.1016/j.precamres.2008.01.003.

Krabbendam, M., Bonsor, H., Horstwood, M.S.A., Rivers, T. 2017a. Tracking the evolution of the Grenvillian foreland basin: Constraints from sedimentology and detrital zircon and rutile in the Sleat and Torridon groups, Scotland. *Precambrian Research*, vol. 295, p. 67-*to Agudos Grandes–SP*. Doctoral Thesis, Instituto de Geociências, Universidade de São Paulo,218 pp. Available at: http://www.teses.usp.br

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambrian Research* 160 (1), 179–210.

Litherland, M., Annels, R.N., Appleton, J.D., Berrange, J.P., Boomfield, K., Darbyshire, D.P.F., Fletcher, C.J.N., Hawkins, M.P., Klinck, B.A., Mitchell, W.I., O'Connor, E.A., Pitfield, P.E.J., Power, G., Webb, B.C., 1986. The geology and mineral resources of the Bolivian Precambrian Shield. *Overseas Memoir*. British Geological Survey, vol. 9, p. 153.

Litherland, M., Annels, R.N., Hawkins, M.P., Klinck, B.A., O'Connor, E.A., Pitfield, P.E.J., Power, G., Darbyshire, D.P.F., Fletcher, C.N.J., Mitchell, W.I., Webb, B.C., 1989. The Proterozoic of eastern Bolivia and its relationships to the Andean mobile belt. *Precambrian Research* 43, pp. 157–174.

Ludwig, K.R., 2003. Isoplot 3.00: A Geochronological Toolkit for Microsoft Excel. Berkeley, California, *Berkeley Chronology Center Special Publication* No. 4.

Mantovani, M.S.M., Brito Neves, B.B., 2005. The Paranapanema Lithospheric Block: Its importance for Proterozoic (Rodinia, Gondwana) Supercontinent Theories. *Gondwana Research* 8, 303–315.

Matteini, M., Dantas, E.L., Pimentel, M.M., Alvarenga, C.J.S. de, Dardenne, M.A. 2012. U–Pb and Hf isotope study on detrital zircons from the Paranoá Group, Brasília Belt Brazil: Constraints on depositional age at Mesoproterozoic – Neoproterozoic transition and tectono-magmatic events in the São Francisco Craton. *Precambrian Research*, vol. 206–207,p. 168-181, ISSN 0301-9268, https://doi.org/10.1016/j.precamres.2012.03.007.

Maurer, V.C. 2016. *Caracterização geocronológica (U-Pb), geoquímica e isotópica(Sr, Nd, Hf) do Complexo Rio Capivari no Terreno Embu*. Dissertação de Mestrado, Instituto de Geociências da USP, 290 p. Available at: http://www.teses.usp.br

Mazza, S.E., Mako, C., Law, R.D, Caddick,M.J., Krabbendam, M.,Cottle,J. 2018. Thermobarometry of the Moine and Sgurr Beag thrust sheets, northern Scotland. J*ournal of Structural Geology* Volume 113, pages 10-32.

Meira, V. T.; García-Casco, A. ; Juliani, C. ; Almeida, R. P. ; Schorscher, J. H. D. 2015. The role of intracontinental deformation in supercontinent assembly: insights from the Ribeira

Belt, Southeastern Brazil (Neoproterozoic West Gondwana). *Terra Nova*, v. 27, p. 206-217.

Meira, V.T., 2014. *Evolução Tectono-Metamórfica Neoproterozoica dos complexos Embu e Costeiro no context de formação do Gondwana Ocidental (leste do Estado de São Paulo)*. Unpublished doctoral thesis, IGc-USP, São Paulo, 266p. Available at: http://www.teses.usp.br

Merdith, A.S., Collins, A.S., Williams, S.E., Pisarevsky, S., Foden, J.D., Archibald, D.B., Blades, M.L., Alessio, B.L., Armistead, S., Plavsa, D., Clark, C., Müller, R.D. 2017. A full-plate global reconstruction of the Neoproterozoic. *Gondwana Research* 50, pp. 84–134

Motidome, M. J. 1993. *Geologia do Complexo Embu na região entre Santa Isabel e Biritiba-Mirim, SP*. Dissertação de Mestrado, Instituto de Geociências, Universidade de São Paulo, 172 p. Available at: http://www.teses.usp.br

Paula-Santos, G.M. and Babinski, M. 2018. Sedimentary provenance in the southern sector of the São Francisco Basin, SE Brazil. *Brazilian Journal of Geology*, V.48. n.1, p. 51-74. DOI: 10.1590/2317-4889201820170061.

Peixoto, C.A., Heilbron, M., Ragatky, D., Armstrong R., Dantas, E., Valeriano, C.M., Simonetti, A. 2017. Tectonic evolution of the Juvenile Tonian Serra da Prata magmatic arc in the Ribeira Belt, SE Brazil: Implications for early West Gondwana amalgamation. *Precambrian Research*, vol. 302, p. 221-254, ISSN 0301-9268, https://doi.org/10.1016/j.precamres.2017.09.017.

Pimentel, M.M., Rodrigues J.B., Giustina, M.E.S.D., Junges, S., Matteini, M., Armstrong R. 2011. The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil, based on SHRIMP and LA-ICPMS U–Pb sedimentary provenance data: A review. *Journal of South American Earth Sciences*, vol. 31, Issue 4, p. 345-357, ISSN 0895-9811, https://doi.org/10.1016/j.jsames.2011.02.011.

Pimentel, M.M., . 2016 The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. *Brazilian Journal of Geology,* V.46, n., p.67-82. http://dx.doi. org/10.1590/2317-4889201620150004

Piuzana, D., Pimentel, M.M., Fuck, R.A., Armstrong, R. 2003. SHRIMP U–Pb and Sm–Nd data for the Araxá Group and associated magmatic rocks: constraints for the age of sedimentation and geodynamic context of the southern Brasília Belt, central Brazil. *Precambrian Research* vol. 125, Issues 1–2, p.139-160, ISSN 0301-9268, https://doi.org/10.1016/S0301-9268(03)00107-4.

Porada, H. 1979. The Damara-Ribeira Orogen of the Pan-African - Brazilian cycle in Namibia (South West Africa) and Brazil as interpretation in terms of continental collision. *Tectonophysics* 57, 237–265.

Rainbird, R.; Cawood, P.; Gehrels, G. 2012. The great Grenvillian sedimentation episode: record of supercontinent Rodinia's assembly. In: Cathy Busby and Antonio Azor, *Tectonics of Sedimentary Basins: Recent Advances*, First Edition, Blackwell Publishing Ltd.

Reis Neto, J.M. dos 1994. *Faixa Itaiacoca: registro de uma colisão entre dois blocos continentais no Neoproterozóico. São Paulo*, 253 p., anexos (Ph. D. thesis, Instituto de Geociências da Universidade de São Paulo). Available at: http://www.teses.usp.br

Rodrigues, J.B., Pimentel, M.M., Dardenne, M.A., Armstrong R.A. 2010. Age, provenance and tectonic setting of the Canastra and Ibiá Groups (Brasília Belt, Brazil): Implications for the age of a Neoproterozoic glacial event in central Brazil. *Journal of South American Earth Sciences* vol. 29, Issue 2, p. 512-521, ISSN 0895-9811, https://doi.org/10.1016/j.jsames.2009.08.008.

Rodrigues, J.B., Pimentel, M.M., Buhn, B., Matteini, M., Dardenne, M.A., Alvarenga, C.J.S., Armstrong, R.A. 2012. Provenance of the Vazante Group: New U–Pb, Sm–Nd, Lu–Hf isotopic data and implications for the tectonic evolution of the Neoproterozoic Brasília Belt. *Gondwana Research* vol. 21, Issues 2–3, p.439-450, ISSN 1342-937X, https://doi.org/10.1016/j.gr.2011.07.017.

Sadowski, G.R., Bettencourt, J.S., 1996. Mesoproterozoic tectonic correlations between eastern Laurentia and the western border of the Amazonian Craton. *Precambrian Research* 76, pp. 213–227.

Santos, E. J. ; Van Schmus, W. R. ; Kozuch, M. ; Brito Neves, B. B. 2011. The Cariris Velhos tectonic Event in Northeast Brazil. *Journal of South American Earth Sciences*, v. 29, p. 61-76.

Sato, K., Tassinari, C.C. G., Basei, M.A.S., Siga Júnior, O., Onoe, A. T., Souza, M.D., 2014. Sensitive High Resolution Ion Microprobe (SHRIMP IIe/MC) of the Institute of Geosciences of the University of São Paulo, Brazil: analytical method and first results. *Geologia USP Série Científica* 14, 3–18.

Schmitt R. S., Trouw R. A. J., Van Schmus W. R., Pimentel M. M. 2004. Late amalgamation in the central part of Western Gondwana: new geochronological data and the characterization of a Cambrian collision orogeny in the Ribeira Belt (SE Brazil) *Precambrian Research* 133:29–61.

Siga Jr., O., Basei, M.A.S., ; Machiavelli, A. 1993. Evolução Geotectônica da Porção Nordeste de Santa Catarina e Sudeste do Paraná com base em Interpretações Geocronológicas. *Revista Brasileira de Geociências* v. 23, n.3, p. 215-223.

Siga Jr., O., Basei, M.A.S., Passarelli, C.R., Sato, K., Cury, L.F., Mcreath, I., 2009. Magmatic records of lower neoproterozoic and upper neoproterozoic in Itaiacoca belt (Paraná-Brazil): zircon ages and lithostratigraphy studies. *Gondwana Research* 15, 197-208.

Siga Jr., O., Basei, M.A.S., Sato, K., Passarelli, C.R., Nutman, A., McReath, I., Prazeres Filho, H.J., 2011a. Calymmian (1.50 1.45 Ga) magmatic records in Votuverava and Perau sequences, south-southeastern Brazil: Zircon ages and Nd–Sr isotopic geochemistry. *Journal of South American Earth Sciences* 32, 301–308.

Siga Junior, O., Cury, L.F., McReath, I., Ribeiro, L.M.A.L., Sato, K., Basei, M.A.S., Passarelli, C.R., 2011b. Geology and geochronology of the Betara region in south-southeastern Brazil: evidence for possible Statherian (1.80–1.75 Ga) and Calymmian (1.50–1.45 Ga) extension events. *Gondwana Research* 19, 260–274.

Siga Junior, O. ; Campanha, G. A. C. ; Faleiros, F. M. ; Basei, M. A. S.; Sato, K. ; Dantas, E. ; McReath I. 2012. Detrital Zircon U-Pb and Hafnio Geochronology from the Capiru and Turvo-Cajati Formations (S-SE BRAZIL): Tectonic Implications. In: VIII South American Symposium on Isotope Geology - SSAGI, 2012, Colombia. Summaries. Colombia, 2012.

Slagstad T., Roberts N.M.W., Kulakov, E. 2017. Linking orogenesis across a supercontinent; the Grenvillian and Sveconorwegian margins on Rodinia. G*ondwana Research* v. 44 p. 109–115. http://dx.doi.org/10.1016/j.gr.2016.12.007

Soares, P.C. 1987. Seqüências tectono-sedimentares e tectônica deformadora no centro-oeste do Escudo Paranaense. *III Simpósio Sul Brasileiro de Geologia*, SBG. Curitiba, vol. 1, pp. 245–258.

Stephens, M. A. 1992. Introduction to Kolmogorov (1933) on the empirical determination of a distribution. In: S.Kotz and N.L. Johnson, 1992, *Breakthroughs in statistics*. Springer-Verlag, New York, NY, 1992, p. 93-105.

Steiger, R.H., Jager, E., 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters* 36, 359–362.

Stein, D.P.; Campanha, G.A. Da C.; Fernandes, L.A. 1986. A Formação Perau na região de Pilar do Sul. In: Congresso Brasileiro de Geologia, 34, Goiânia, 1986. *Anais*... Goiânia, SBG. v.2, p.919-930.

Stern, R.A. 1998. High-resolution SIMS determination of radiogenic trace-isotope ratios in minerals. In: Cabri, L.J.; D.J. Vaughan, D.J. (eds.) *Modern approaches to ore and environmental mineralogy*. Ottawa, Mineralogical Association of Canadá. p. 241-267. (Short Course Handbook, 27).

Stratchan, R.A., Smith, M., Harris, A.L., Bluck, B.J.., 2002. The Northern Highland and Grampian terranes. In: Trewin, N.H., 2002, *The Geology of Scotland*. The Geological Society of London, p.81-148.

Teixeira, W., Geraldes, M.C., Matos, R., Ruiz, A.S., Saes, G.,Vargas-Mattos, G.. 2010. A review of the tectonic evolution of the Sunsás belt, SW Amazonian Craton. *Journal of South American Earth Sciences* 29, p. 47–60.

Valladares, V.C.S., Machado, N., Heilbron, M., Gauthier, G. 2004. Ages of Detrital Zircon from Siliciclastic Successions South of the São Francisco Craton, Brazil: Implications for the Evolution of Proterozoic Basins. *Gondwana Research* vol. 7, Issue 4, p.913-921, ISSN 1342-937X, https://doi.org/10.1016/S1342-937X(05)71074-1.

Vauchez, A.; Tommasi, A.; Slva, M.E. 1994 Self-indentation of a heterogeneous continental lithosphere. *Geology*, v. 22, pp. 967-970.

Vieira, S. R. S. S. 1996. *Estudo de processos metamórfico-metassomáticos nos Complexos Embu e Pilar no bloco Juquitiba, SP*. Tese de Doutorado, Instituto de Geociências, Universidade de São Paulo, 210 p. Available at: http://www.teses.usp.br

Vieira, S. R. S. S.; Tassinari, C. C. G. 1988. Estudo petrológico e geocronológico das rochas da região de Embu-Guaçu, estado de São Paulo. *In*: *Anais do XXXV Congresso Brasileiro de Geologia*, Belém. Sociedade Brasileira de Geologia, vol. 3, p. 1391-1399.

Vieira, S. R. S. S. 1990. Geologia e evolução geológica da região de Embu-Guaçu - Parelheiros, SP. *Revista Brasileira de Geociências*, V. 20, N.1-4, p.277-281.

Vieira, S. R. S. S. 1989. *Estudo lito-estrutural da região de Embu-Guaçu-Parelheiros, São Paulo*. Dissertação de Mestrado, Instituto de Geociências, Universidade de São Paulo, 122p. Available at: http://www.teses.usp.br

Vlach, S. R. F. 2001. Microprobe monazite constrainst for an early (ca 790 Ma) Brasiliano Orogeny: The Embu Terrane, Southeastern Brazil. In:*II South American Symposium on Isotope Geology*, Cordoba. p. 518-521.

Vlach, S. R. F. 2008. *Mineralogia, análise e datação de monazita e xenotima com microssonda eletrônica e aplicações*. Tese de Livre-Docência, Instituto de Geociências, Universidade de São Paulo, 186 p. Available at: http://www.teses.usp.br

Williams, I.S., 1998. U-Th-Pb geochronology by ion microprobe. *Reviews in Economic Geology* 7, 1-35.

Legends of the figures

Figure 1 – a) Simplified geotectonic map of South America; cratons: Am – Amazonian, SF – São Francisco, Pp – Paranapanema, RDLP – Rio de La Plata. b) Regional map showing the distribution of the Embu and surrounding tectonic terranes in Southeast Brazil with the location of the studied area (Fig. 2).

Figure 2 – Geologic map of the studied region and studied samples; sample AN49 from Cordani et al. (2002).

Figure 3 - $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$ concordia diagrams for metamafic rock from the Votuverava Group, Pilar do Sul region: (a) low metamorphic grade sample WSP04; (b) medium to high metamorphic grade sample WSP13.

Figure 4 - $^{207}Pb/^{235}U$ versus $^{206}Pb/^{238}U$ concordia diagrams for zircons grains in metasedimentary rocks.

Figure 5 - Frequency diagrams for detrital zircon grains in metasedimentary rocks. For the Embu Complex they are those older than 900 Ma.

Figure 6 - Cathodoluminescence (CL) images from the younger detrital zircon grains and older metamorphic overgrowths in zircon grains from the Embu Complex.

Figure 7 - Probability density distribution diagram for metamorphic rings of zircon grains from Embu Complex analyzed samples.

Figure 08 - Cumulative distribution plots (CDP) for detrital zircon ages of the Embu Complex, Votuverava and São Roque groups samples.

Figure 09 - Probability density distribution diagrams for detrital zircon of the analized samples in this paper compared with those from the Moine Supergroup. Gray fields correspond to the main detrital age ranges of the Embu Complex.

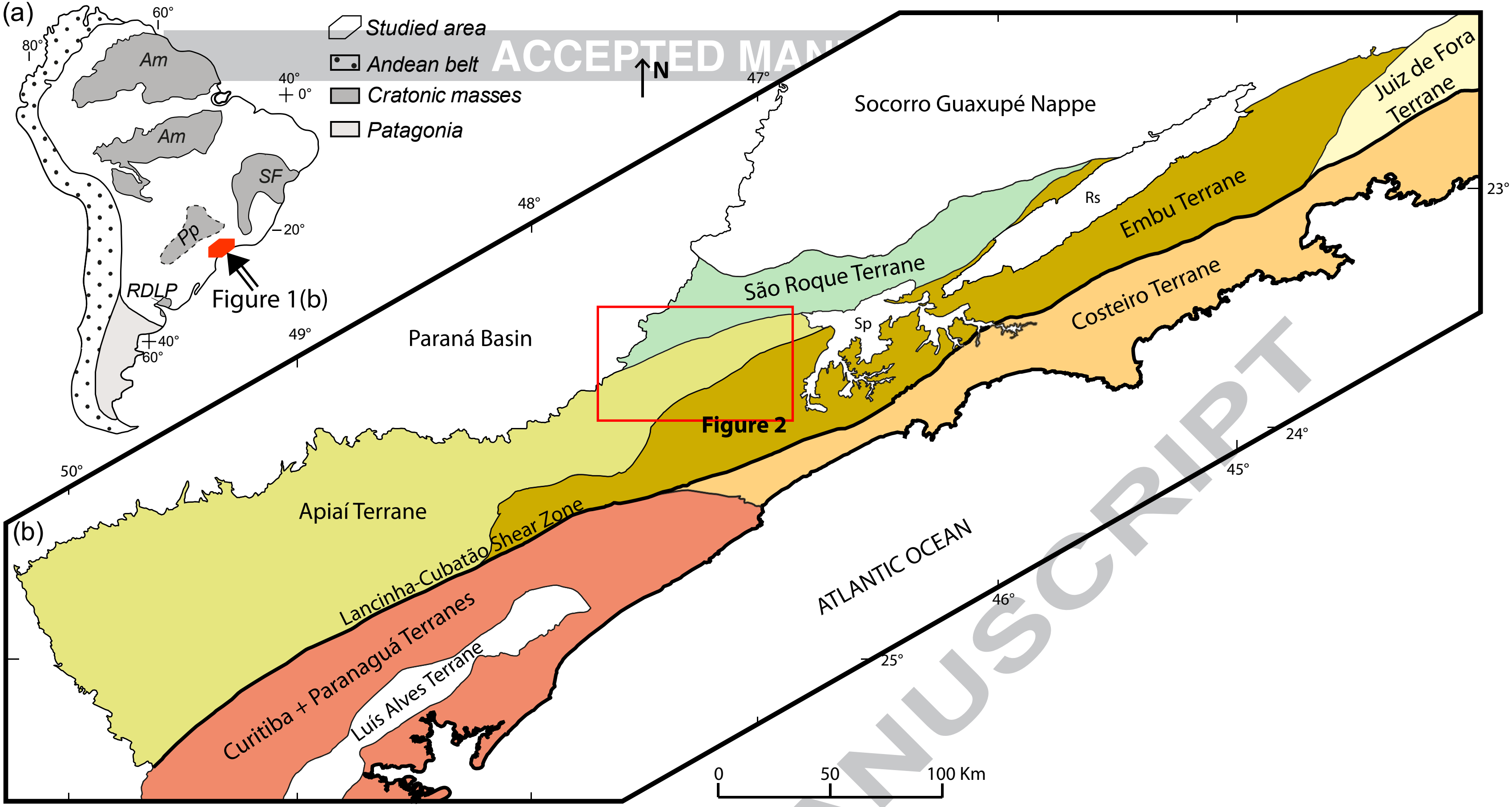
Figure 10 - Tectonostratigraphic relationships of the Embu Complex and neighboring units in the studied area.

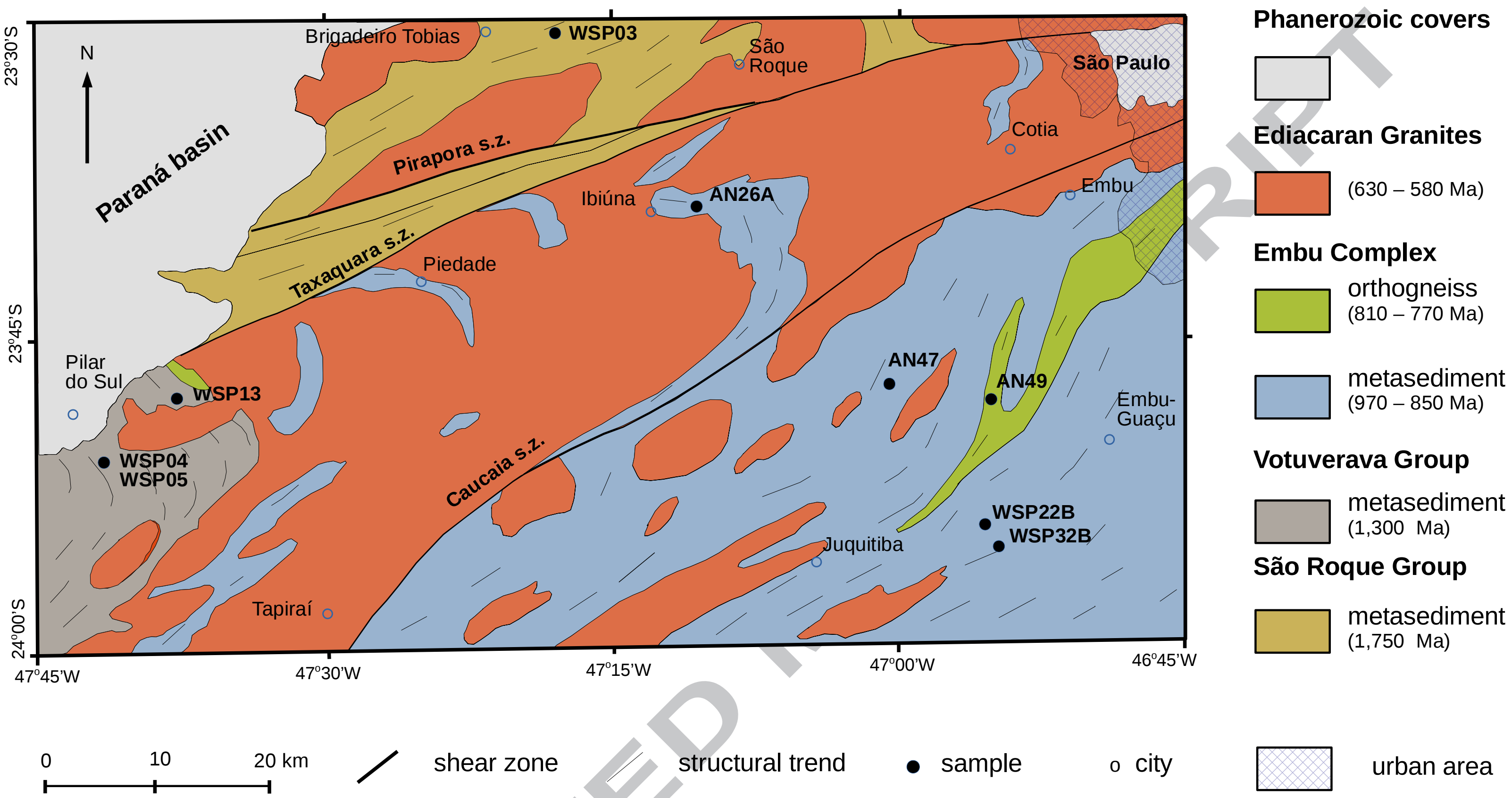
Figure 11 – Integraded probability density distribution diagrams for detrital zircon from some regional units in Southeast and South Brazil and Eastern Africa. Gray fields correspond to the main detrital age ranges of the Embu Complex. Data from: Gariep – Rocha-Damara, Dom Feliciano, Apiaí belts (Basei et al., 2008), Curitiba terrane (Faleiros et al, unpublished data), São Roque Group (Henrique-Pinto et al., 2015), Espinhaço Sg.(Chemale et al., 2012), Bambui (Paula-Santos and Babinski, 2018), Andrelândia Nappe System (Frugis et al., 2018), São João Del Rei (Valladares et al., 2004), Ibiá and Canastra (Rodrigues et al., 2012), Araxá (Piuzana et al., 2003), Paranoá (Matteini et al., 2012).

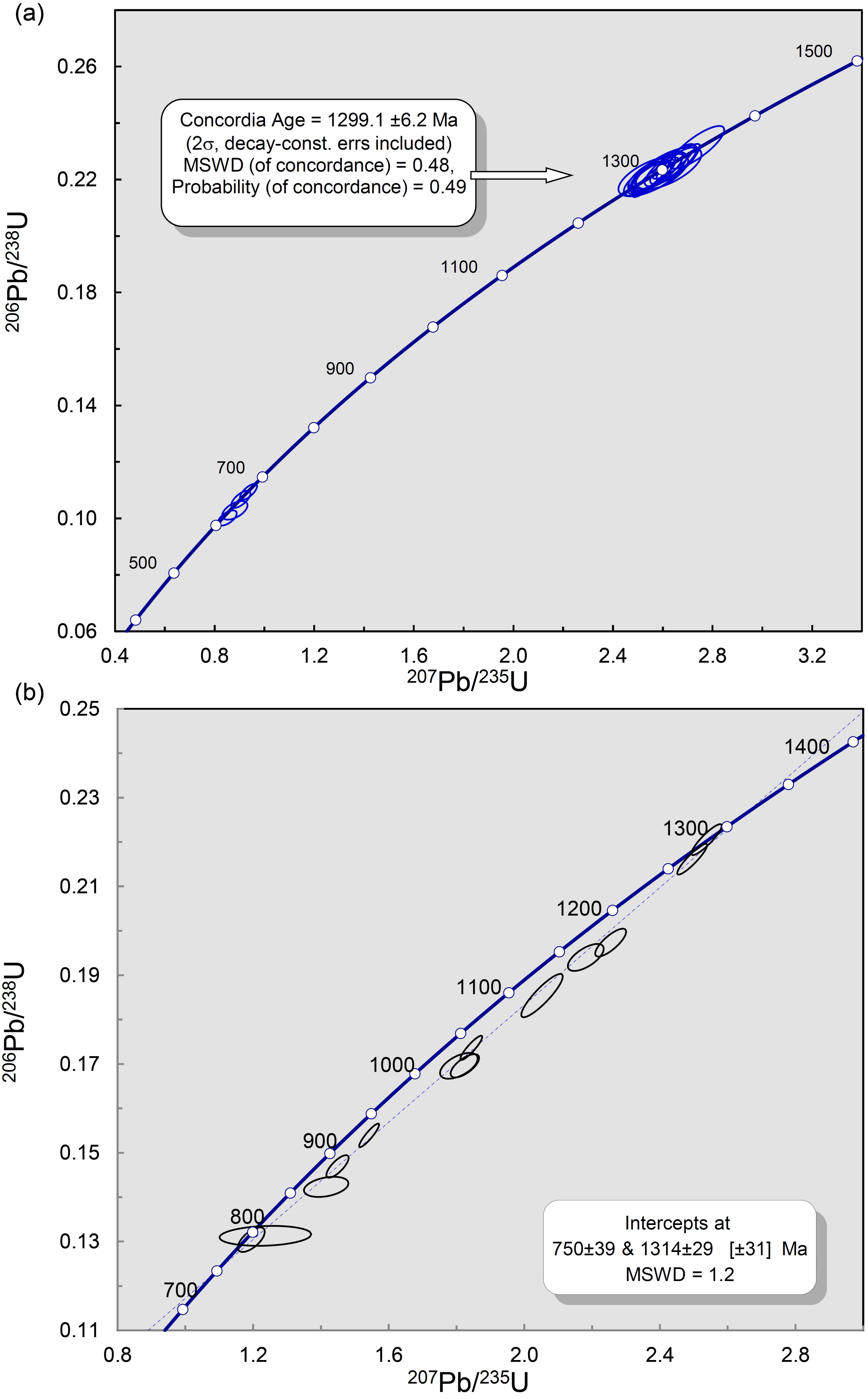
Figure 12 - Main Mesoproterozoic units and cratons in South America and Africa. Cratons: (A) Amazonian, (SF) São Francisco, (Pp) Paranapanema, (RDLP) Rio de la Plata, (C)

Congo, (K) Kalahari, (WAC) West African, (S) Sahara meta-craton. Mesoproterozoic belts: (1) Apiaí, São Roque and Embu terranes, (2) Sunsás, (3) Espinhaço, (4) Cariris Velho, (5) Kibaran, (6) Irumide, (7) Namaqua, (8) Kunene. Other units: (A) Andean belt; (P) Patagonian platform.

Figure 13 - Rodinia reconstruction with the main Grenvillian correlated belts and possible locations of the Embu terrane at deposition time. L - Laurentia, Am - Amazonian, Ba - Baltica, WAC - West Africa, SF-C - São Francisco - Congo, K - Kalahari, EA - East Antarctica, In - India, Au - Australia, Si - Siberia (modified from Hoffman, 1991, Cordani et al., 2010, Cawood and Pisarevsky, 2017).


(a)
60°
80°
Am
Am
SF
Pp
RDLP
40°
0°
20°
40°
60°
Figure 1(b)
Studied area
Andean belt
Cratonic masses
Patagonia
N
47°
48°
49°
50°
45°
46°
23°
24°
25°
Socorro Guaxupé Nappe
Juiz de Fora Terrane
Rs
Embu Terrane
São Roque Terrane
Sp
Costeiro Terrane
Paraná Basin
Figure 2
Apiaí Terrane
Lancinha-Cubatão Shear Zone
(b)
Curitiba + Paranaguá Terranes
Luís Alves Terrane
ATLANTIC OCEAN
0
50
100 Km


23°30'S
23°45'S
24°00'S
47°45'W
47°30'W
47°15'W
47°00'W
46°45'W
N
Paraná basin
Brigadeiro Tobias
WSP03
São Roque
São Paulo
Cotia
Pirapora s.z.
Taxaquara s.z.
Ibiúna
AN26A
Embu
Piedade
Pilar do Sul
WSP13
WSP04
WSP05
AN47
AN49
Embu-Guaçu
Caucaia s.z.
WSP22B
WSP32B
Juquitiba
Tapiraí
Phanerozoic covers
Ediacaran Granites
(630 – 580 Ma)
Embu Complex
orthogneiss
(810 – 770 Ma)
metasediment
(970 – 850 Ma)
Votuverava Group
metasediment
(1,300 Ma)
São Roque Group
metasediment
(1,750 Ma)
0
10
20 km
shear zone
structural trend
sample
city
urban area



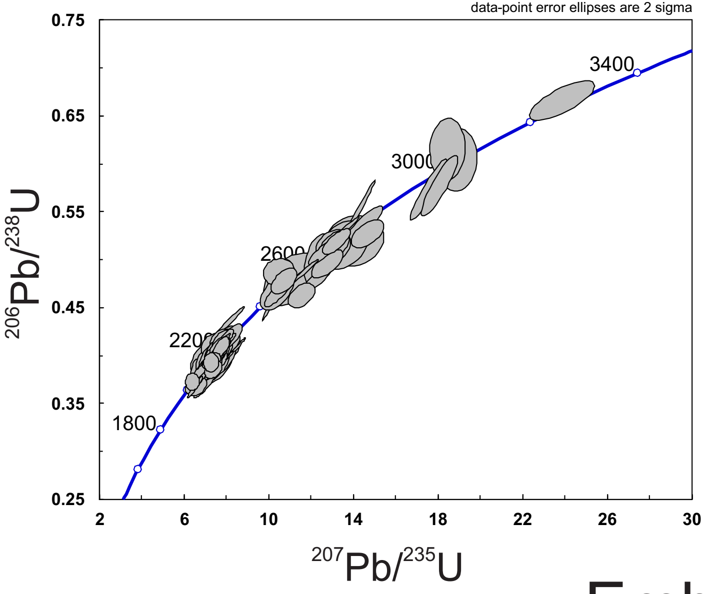
Concordia Age = 1299.1 ±6.2 Ma
(2σ, decay-const. errs included)
MSWD (of concordance) = 0.48,
Probability (of concordance) = 0.49

Intercepts at
750±39 & 1314±29 [±31] Ma
MSWD = 1.2

São Roque Group

WSP - 03 - Metasandstone

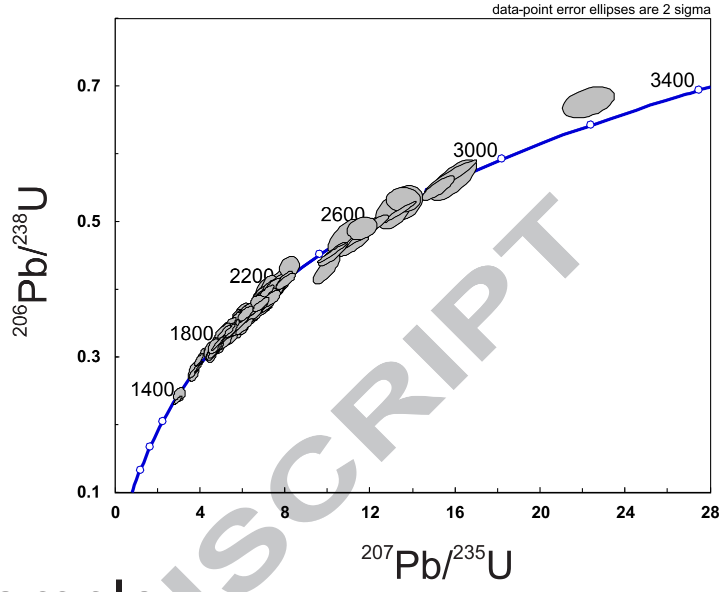
(n = 95)



Votuverava Group

WSP - 05 - Metasandstone

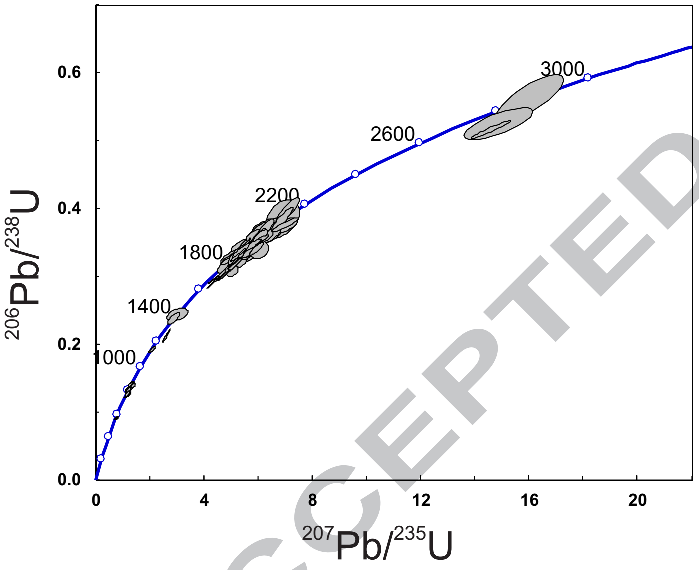
(n = 94)



Embu Complex

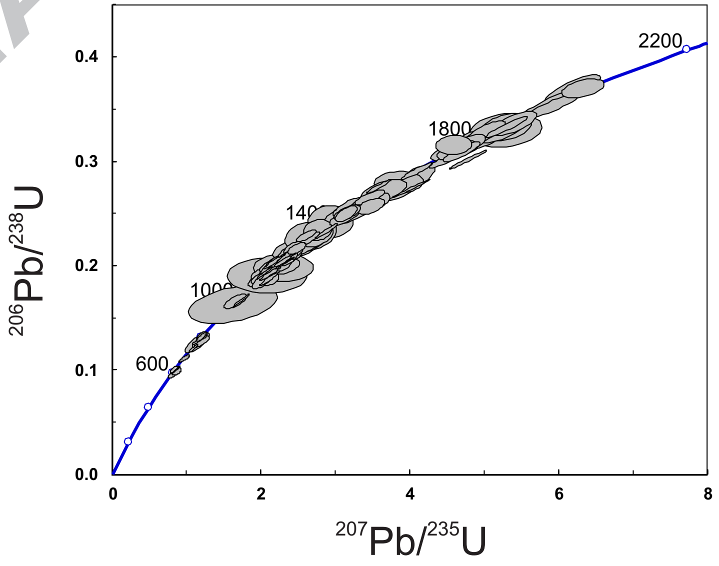
AN - 47 - Metasandstone

(n = 74)



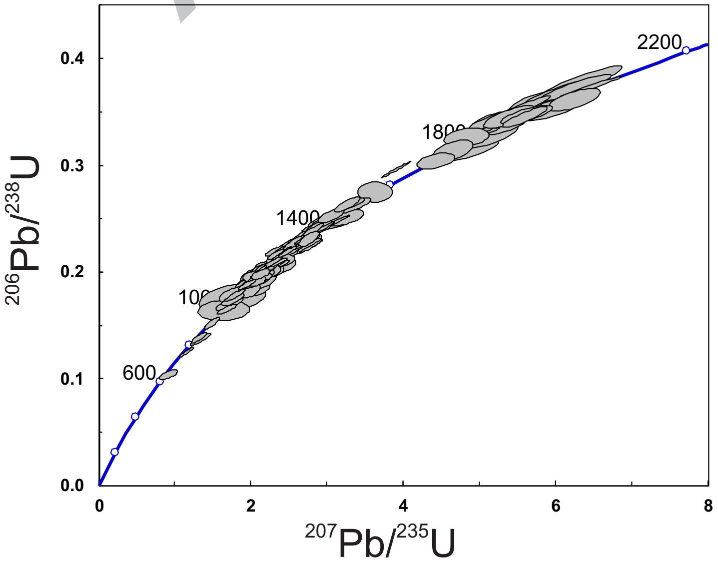
AN - 26A - Metasandstone

(n = 97)



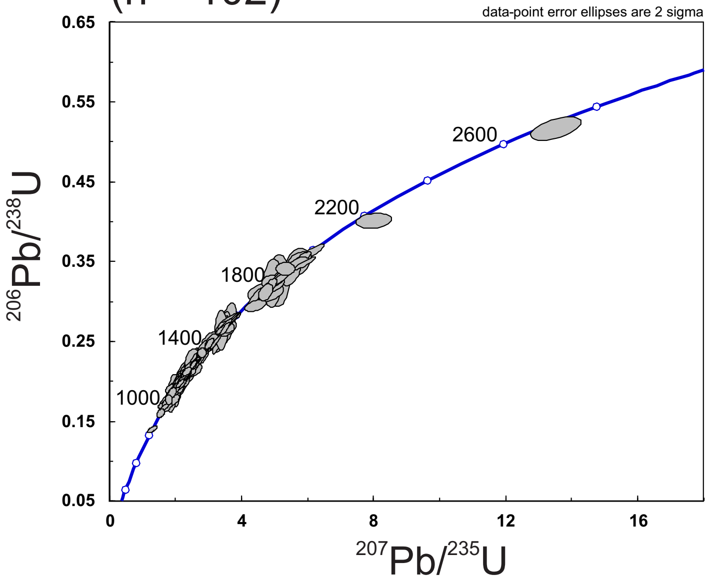
WSP - 22B - Metasandstone

(n = 89)

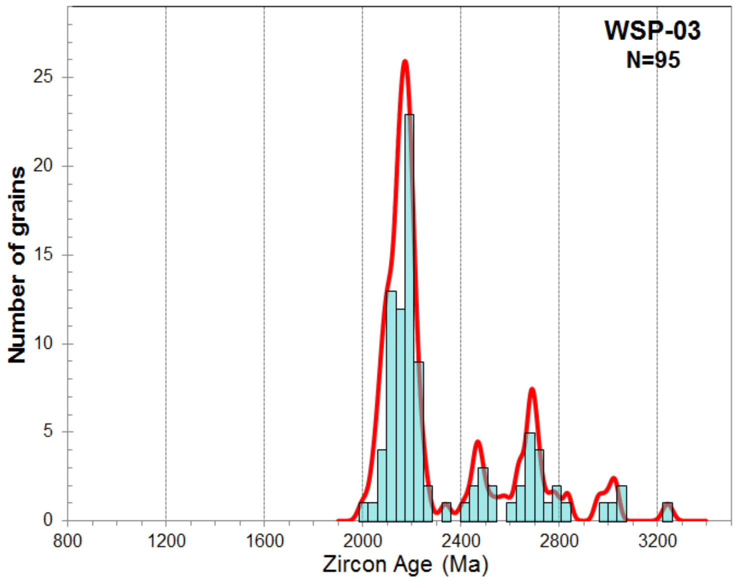


WSP - 32B - Metasandstone

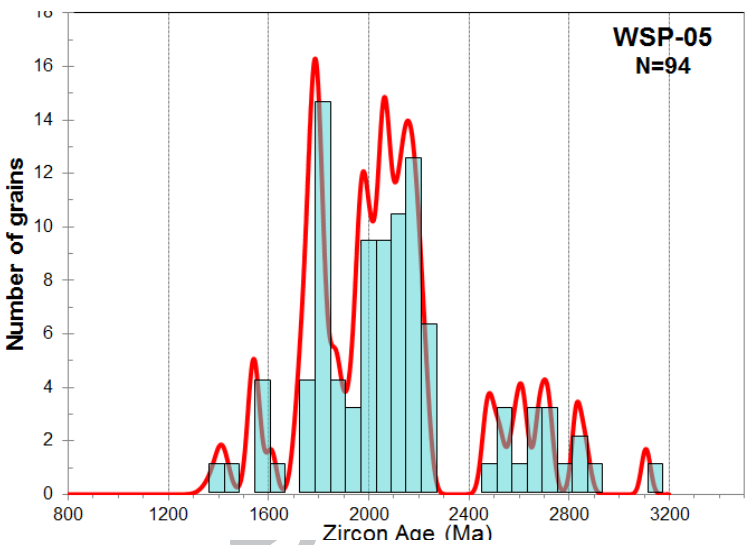
(n = 102)



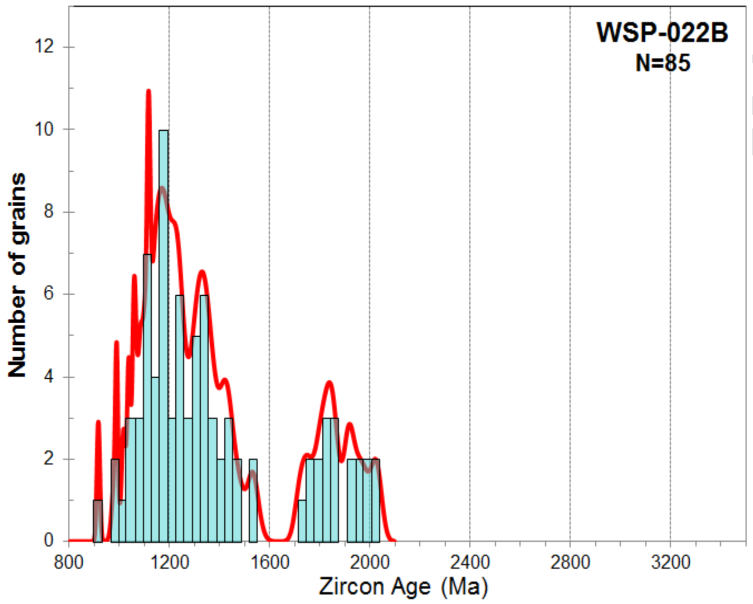
São Roque Group

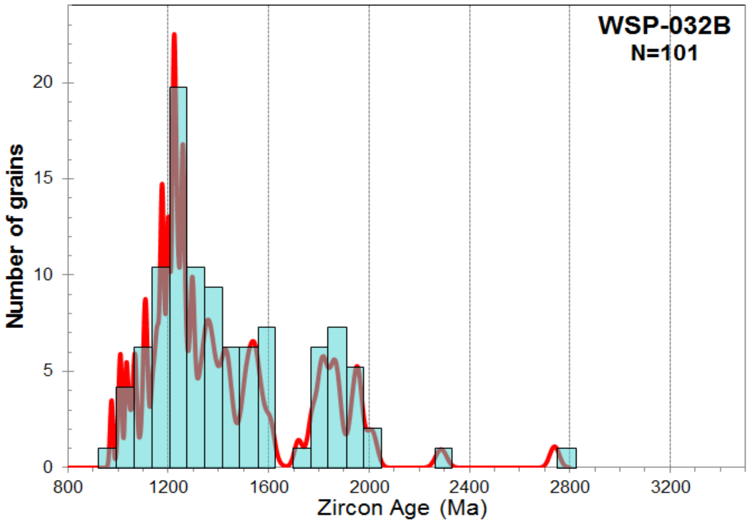


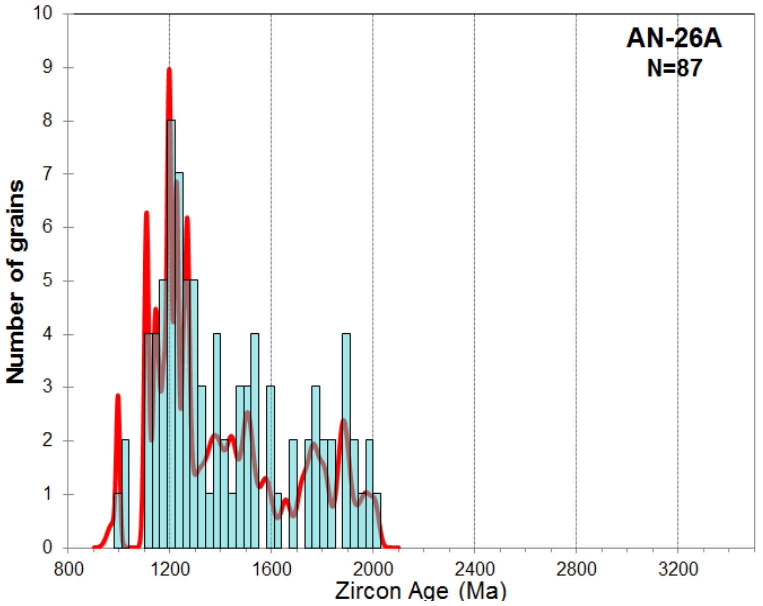
Votuverava Group

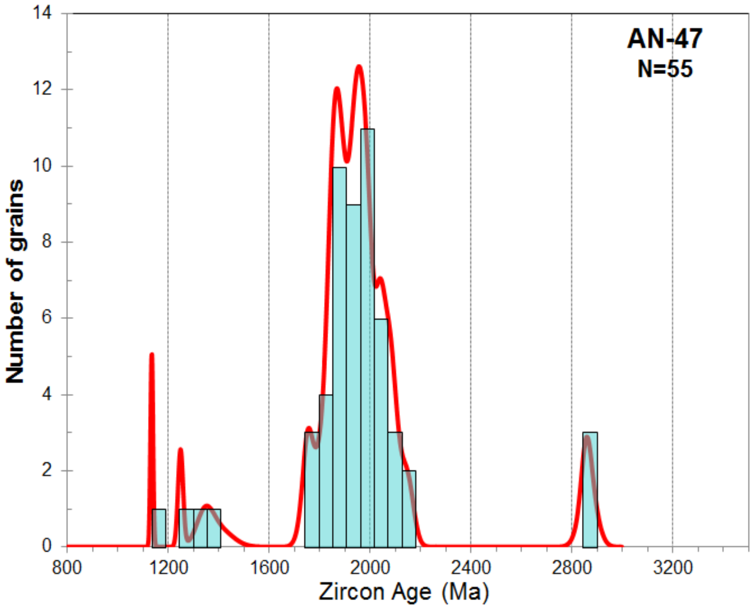


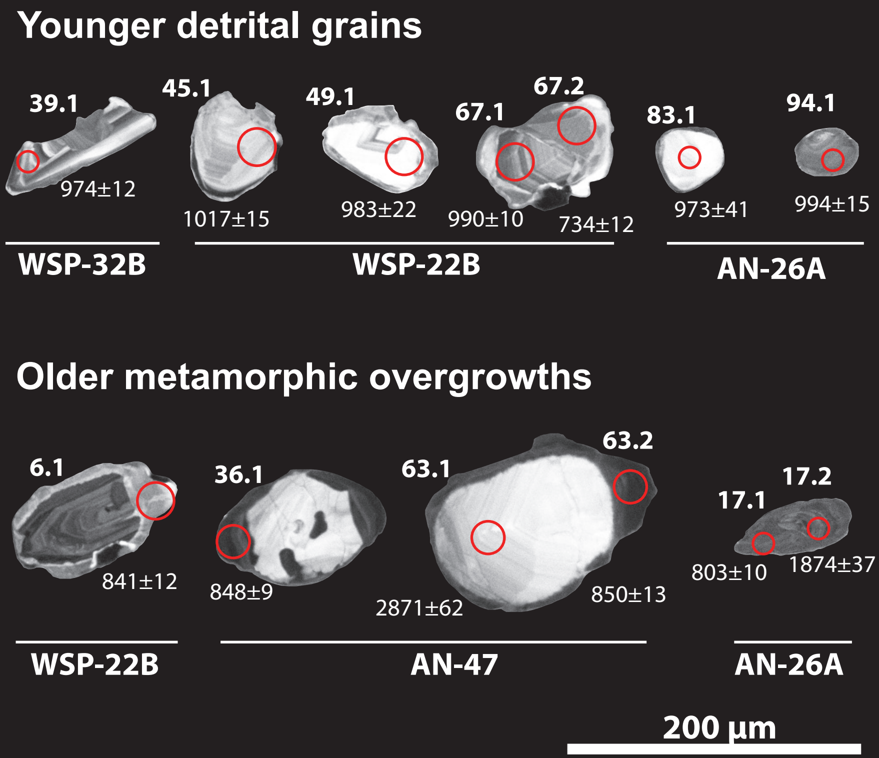
Embu Complex

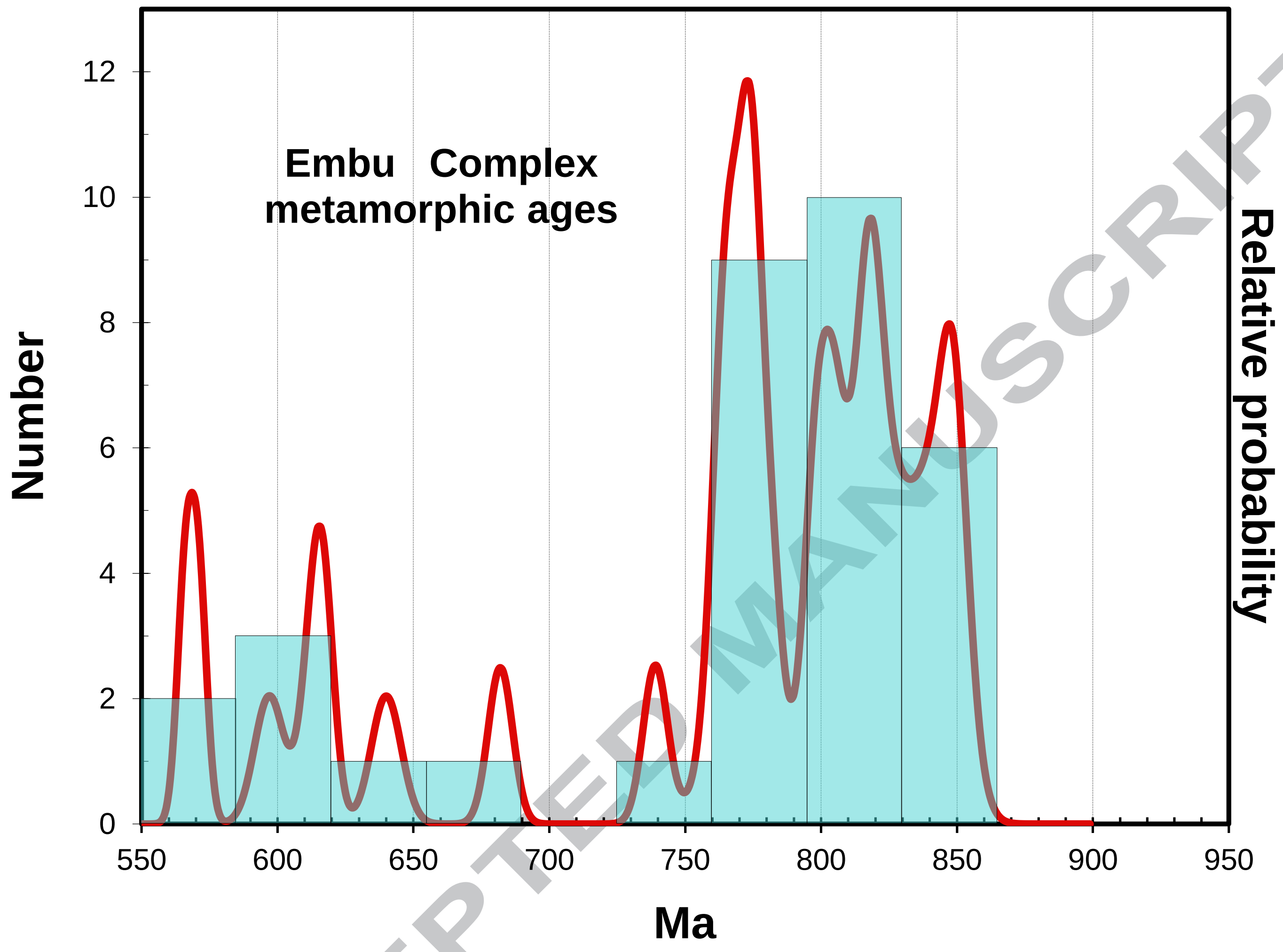


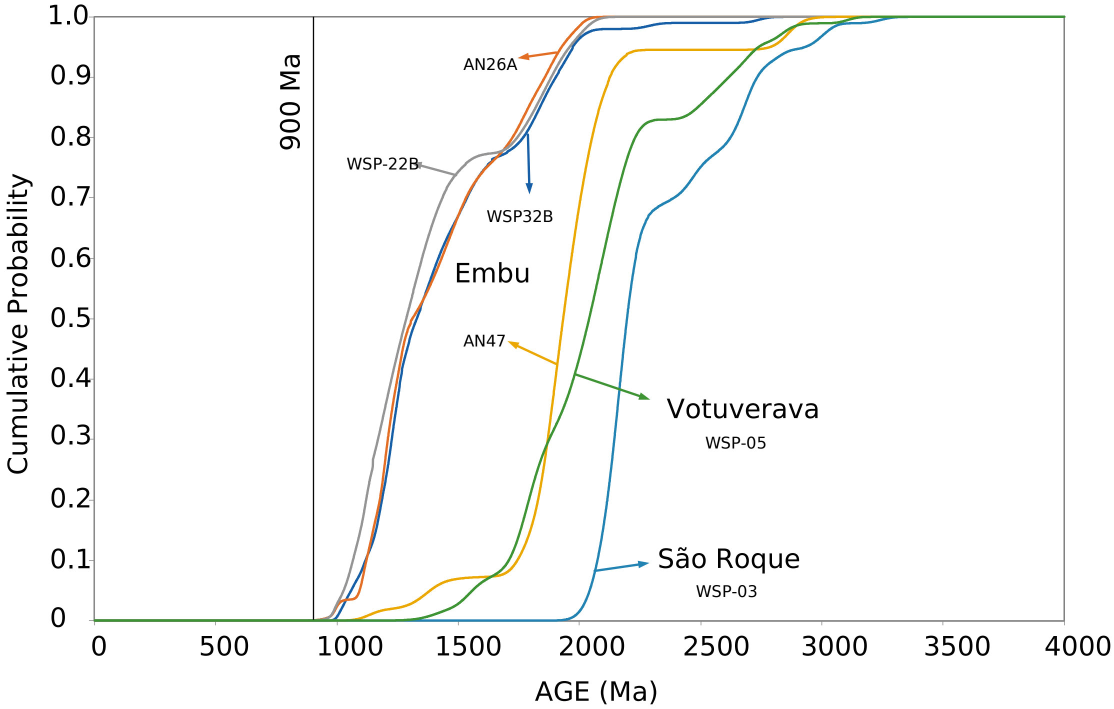


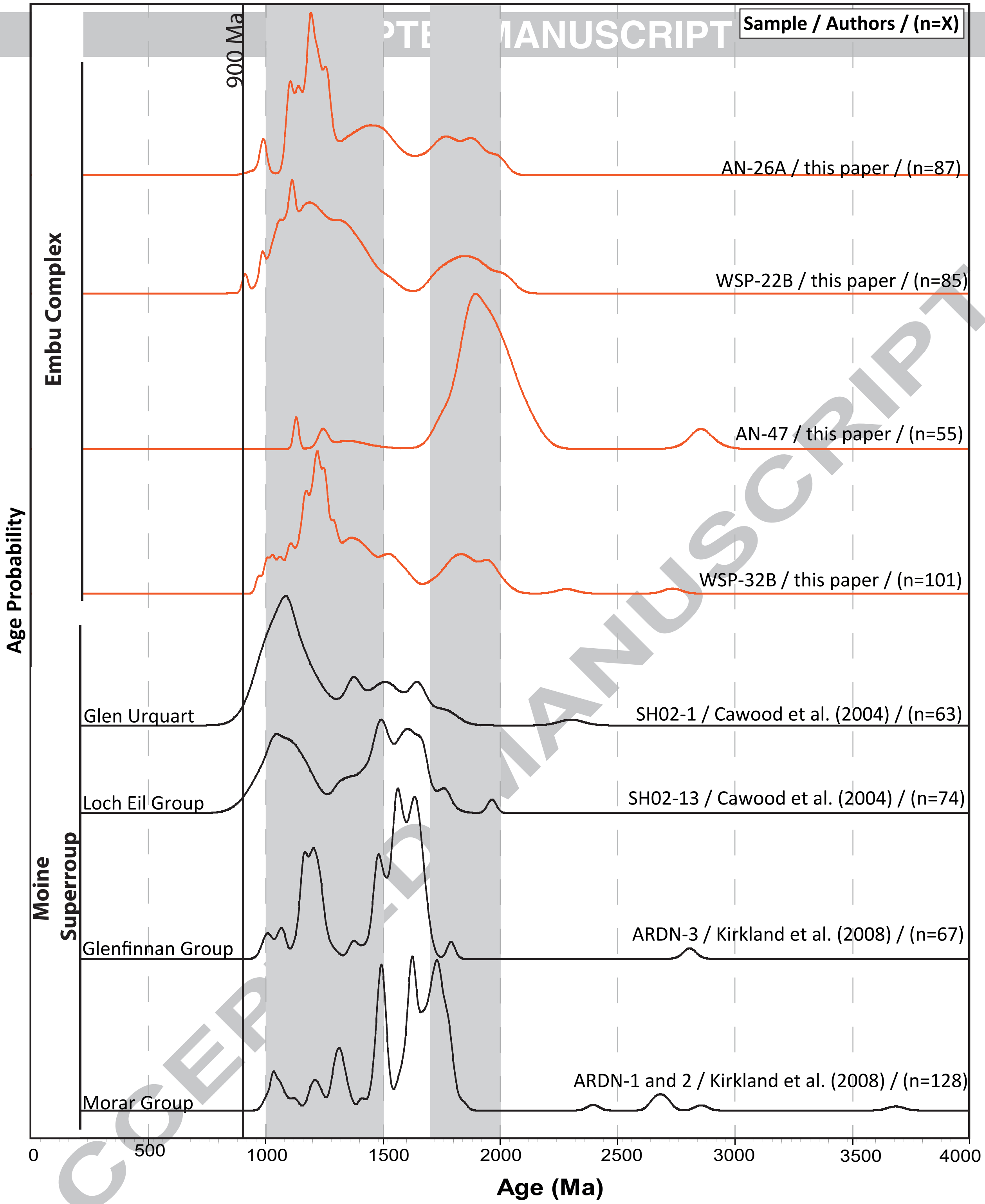


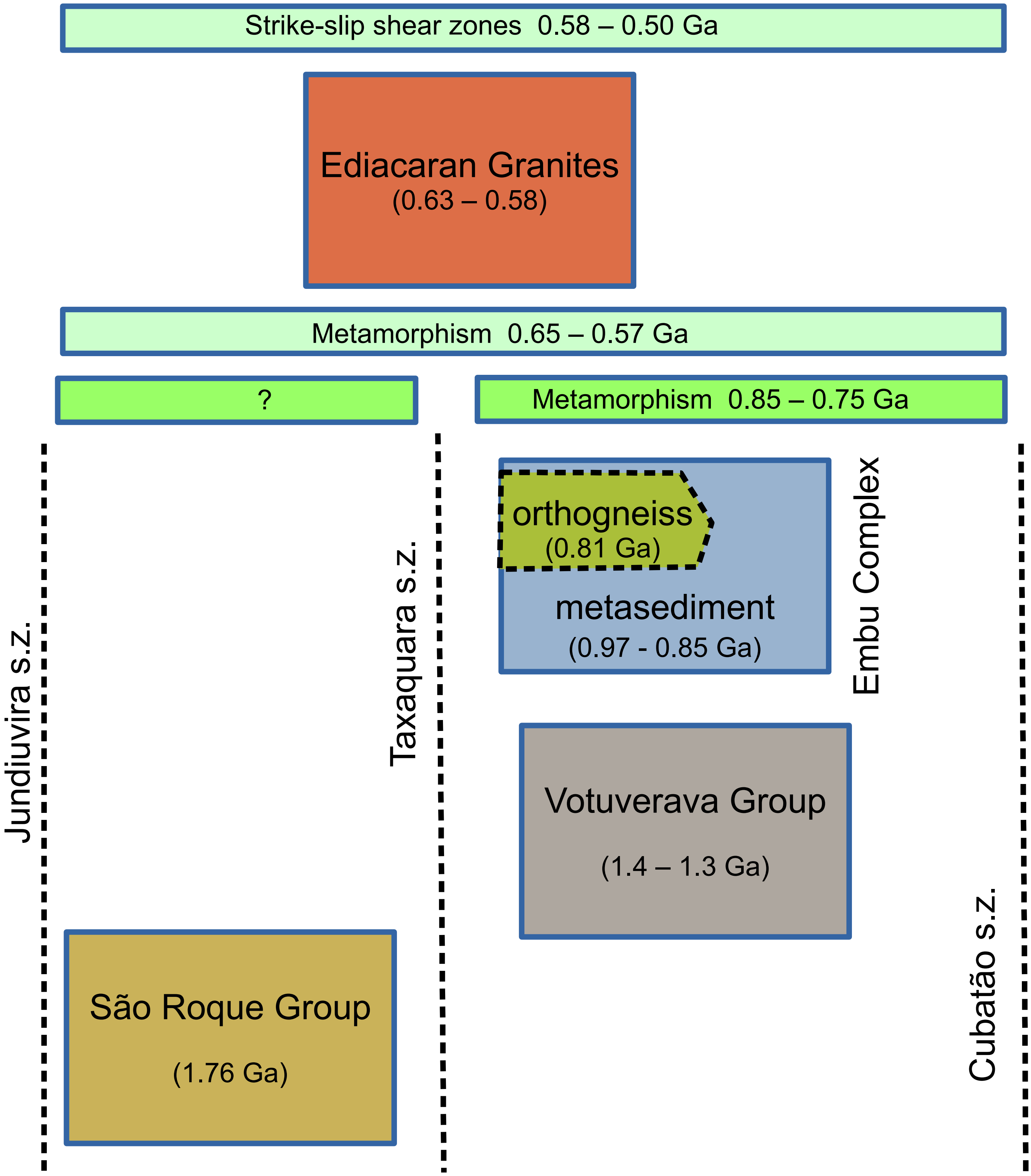


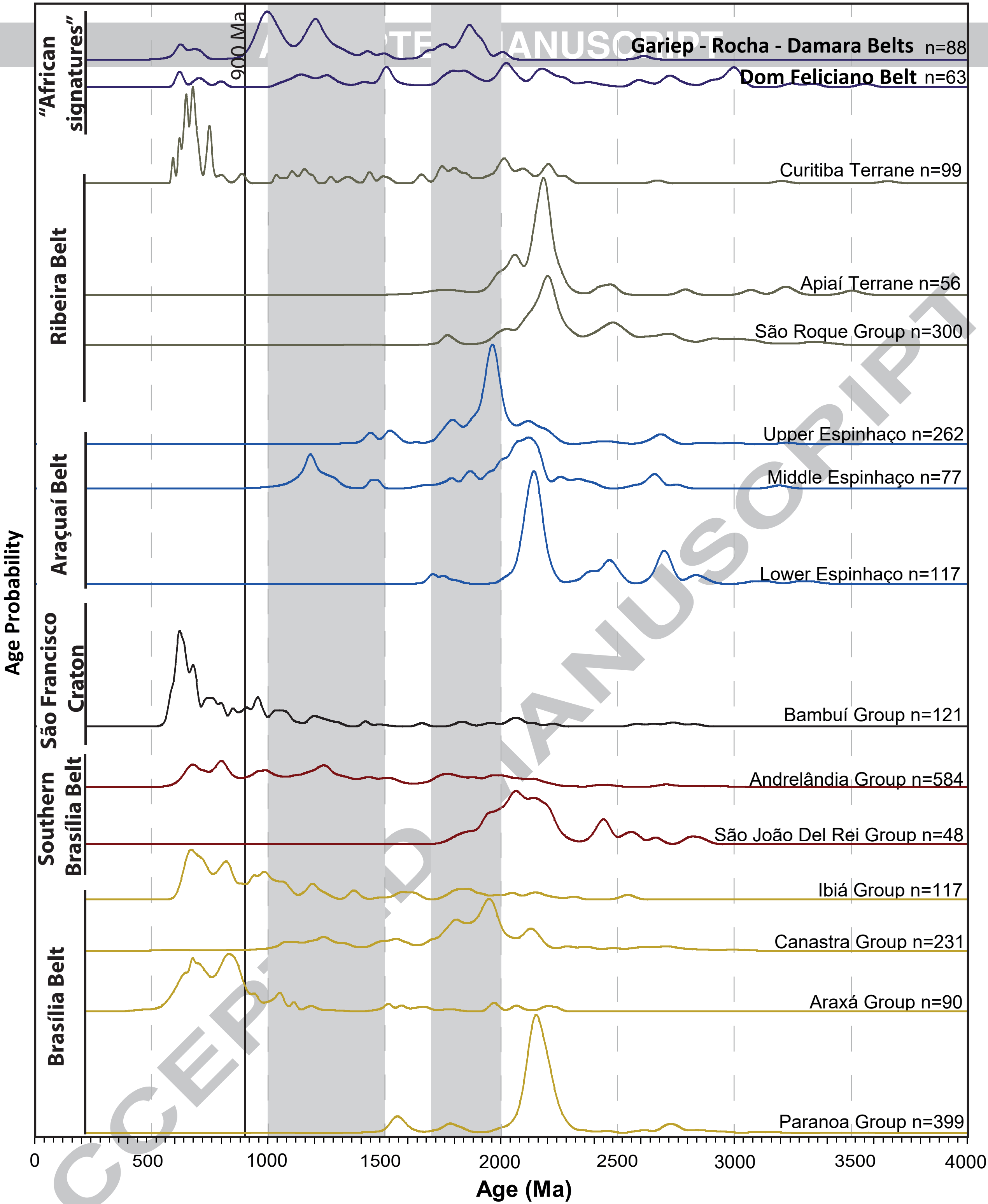

Younger detrital grains
39.1
974±12
WSP-32B
45.1
1017±15
49.1
983±22
67.1
990±10
67.2
734±12
WSP-22B
83.1
973±41
94.1
994±15
AN-26A
Older metamorphic overgrowths
6.1
841±12
WSP-22B
36.1
848±9
63.1
2871±62
63.2
850±13
AN-47
17.1
803±10
17.2
1874±37
AN-26A
200 µm

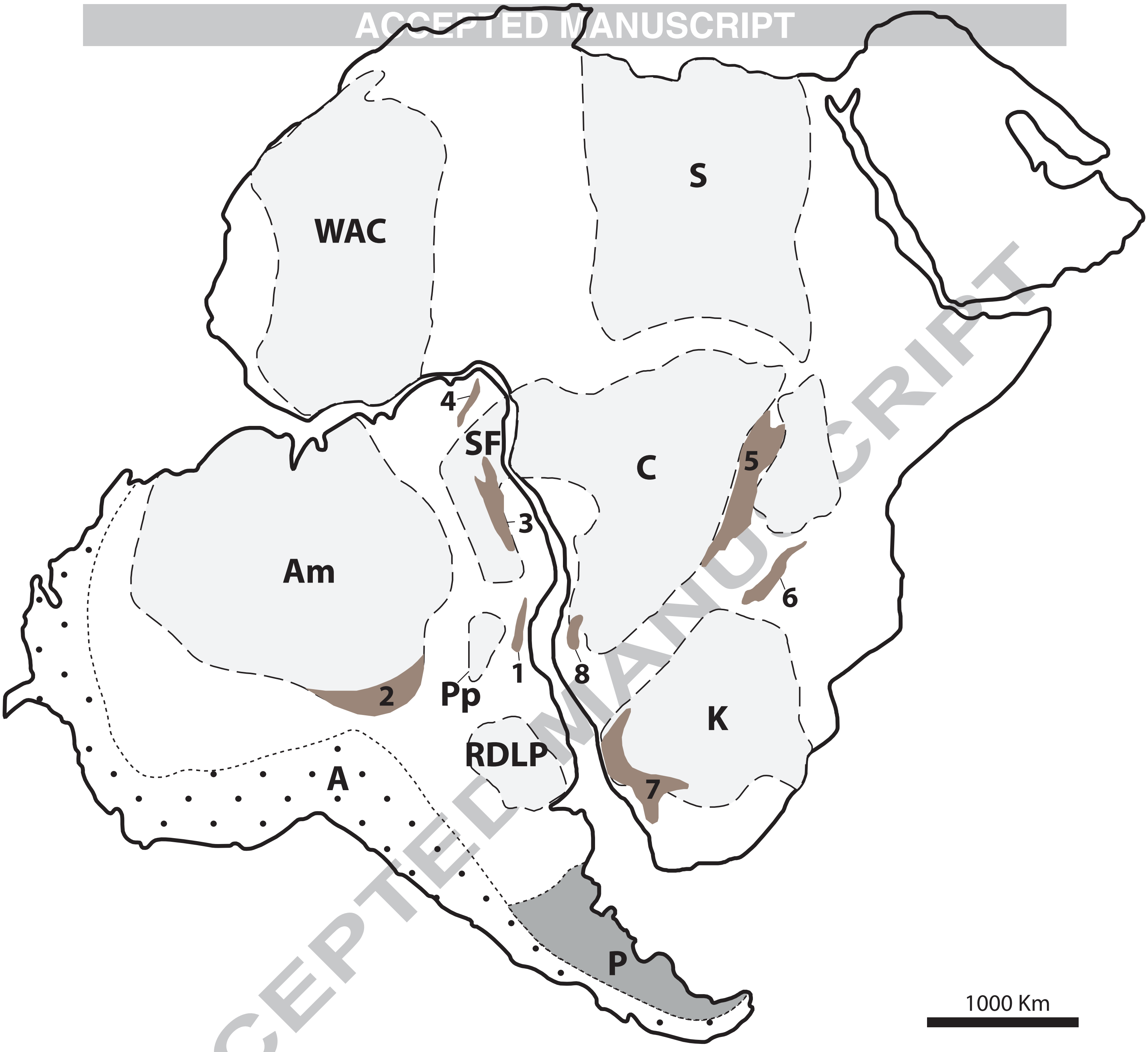

Embu Complex
metamorphic ages
Number
Relative probability
Ma
0
2
4
6
8
10
12
550
600
650
700
750
800
850
900
950


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cumulative Probability
0
500
1000
1500
2000
2500
3000
3500
4000
AGE (Ma)
900 Ma
AN26A
WSP-22B
WSP32B
Embu
AN47
Votuverava
WSP-05
São Roque
WSP-03


Sample / Authors / (n=X)
900 Ma
Embu Complex
Age Probability
AN-26A / this paper / (n=87)
WSP-22B / this paper / (n=85)
AN-47 / this paper / (n=55)
WSP-32B / this paper / (n=101)
Moine Superroup
Glen Urquart
SH02-1 / Cawood et al. (2004) / (n=63)
Loch Eil Group
SH02-13 / Cawood et al. (2004) / (n=74)
Glenfinnan Group
ARDN-3 / Kirkland et al. (2008) / (n=67)
Morar Group
ARDN-1 and 2 / Kirkland et al. (2008) / (n=128)
0
500
1000
1500
2000
2500
3000
3500
4000
Age (Ma)


Strike-slip shear zones 0.58 – 0.50 Ga
Ediacaran Granites
(0.63 – 0.58)
Metamorphism 0.65 – 0.57 Ga
?
Metamorphism 0.85 – 0.75 Ga
Jundiuvira s.z.
Taxaquara s.z.
orthogneiss
(0.81 Ga)
metasediment
(0.97 - 0.85 Ga)
Embu Complex
Votuverava Group
(1.4 – 1.3 Ga)
Cubatão s.z.
São Roque Group
(1.76 Ga)


"African signatures"
900 Ma
Gariep - Rocha - Damara Belts n=88
Dom Feliciano Belt n=63
Curitiba Terrane n=99
Ribeira Belt
Apiaí Terrane n=56
São Roque Group n=300
Upper Espinhaço n=262
Araçuaí Belt
Middle Espinhaço n=77
Lower Espinhaço n=117
Age Probability
São Francisco Craton
Bambuí Group n=121
Southern Brasília Belt
Andrelândia Group n=584
São João Del Rei Group n=48
Ibiá Group n=117
Canastra Group n=231
Brasília Belt
Araxá Group n=90
Paranoa Group n=399
0
500
1000
1500
2000
2500
3000
3500
4000
Age (Ma)


WAC
S
4
SF
C
5
3
Am
6
8
1
2
Pp
K
RDLP
A
7
P
1000 Km

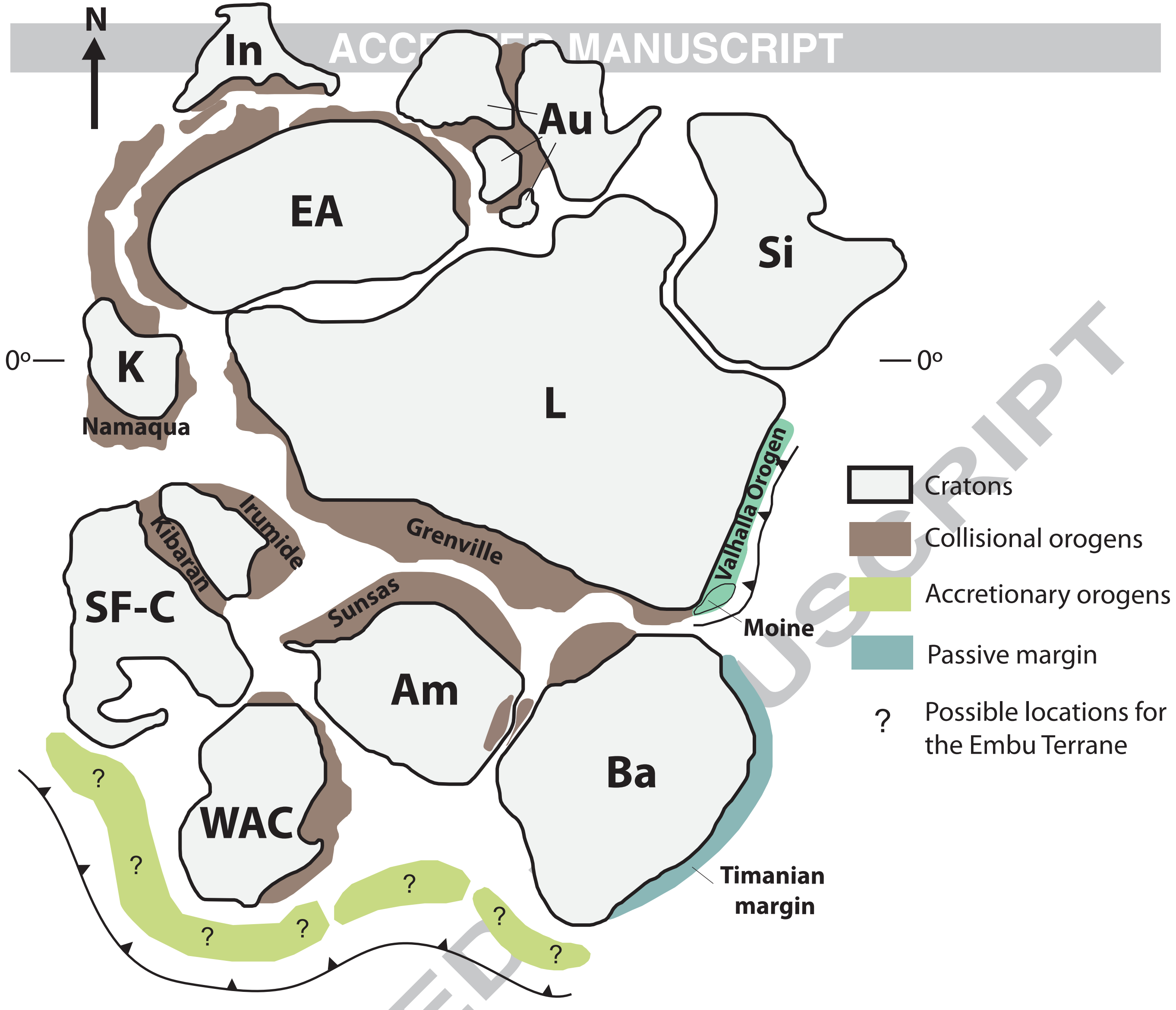

N
In
Au
EA
Si
K
L
0°
0°
Namaqua
Irumide
Kibaran
Grenville
Valhalla Orogen
SF-C
Sunsas
Moine
Am
Ba
WAC
Timanian margin
?
Cratons
Collisional orogens
Accretionary orogens
Passive margin
? Possible locations for the Embu Terrane

Table 01. Studied samples; for metabasic rocks the crystalization age is shown, and for the metasedimentary rocks the youngest detrital age.

Sample	Rock	Unit	Material	Method	Latitude	Longitude	Site	Age (Ma)	Concordant /Total detrital/Total analyses (n)
AN47	Metasandstone	Embu C.	detrital zircons	LA-ICP-MS	7367391	295264	Caucaia do Alto	1135 ± 10	55 / 73 / 102
WSP32B	Metasandstone	Embu C.	detrital zircons	LA-ICP-MS	7353208	305225	Embu-Guaçu	974 ± 12	101* / 103 / 104
WSP22B	Metasandstone	Embu C.	detrital zircons	LA-ICP-MS	7354987	303966	Embu-Guaçu	983 ± 22	85* / 90 / 104
AN26A	Metasandstone	Embu C.	detrital zircons	LA-ICP-MS	7382812	277906	Ibiuna	973 ± 41	87* / 91 / 103
WSP04	Metamafic	Votuverava G.	igneous zircons	SHRIMP	7359866	225967	Pilar do Sul	1299.1 ± 6.2	18 / - / 18
WSP13	Metamafic	Votuverava G.	igneous zircons	SHRIMP	7365532	232072	Pilar do Sul	1314 ± 29 Ma	10 / - / 21
WSP05	Metasandstone	Votuverava G.	detrital zircons	LA-ICP-MS	7359529	226177	Pilar do Sul	1390 ± 78	94* / 104 / 104
WSP03	Metasandstone	São Roque G.	detrital zircons	LA-ICP-MS	7398021	265378	Brigadeiro Tobias	2001 ± 40	95* / 99 / 99

Coordinates in meters UTM zone 23S SAD69 datum

* Concordant detrital analyses

Table 02 - Analytical results (SHRIMP) for zircons of the WSP-04 sample (metamafic rock) of the Votuverava Group.

Labels	Sites	U (ppm)	Th/U	Pb*(ppm)	^{204}Pb(ppb)	^{206}Pb/^{238}U	Error(1σ)	^{207}Pb/^{235}U	Error(1σ)	^{207}Pb/^{206}Pb	Error(1σ)		Age (Ma)			%Conc
												6/38	Error	7/6	Error	
WSP04-1.1	m, fr, hd	193.2	0.8	36.6	0	0.22048	1.15162	2.53995	1.55118	0.08355	1.03777	1284.4	13.4	1282	20	100
WSP04-2.1	m, fr, sz	107.4	0.8	20.6	0	0.22261	1.28815	2.57798	1.62046	0.08399	0.98293	1295.6	15.1	1292	19	100
WSP04-3.1	m, fr, sz	128.7	0.6	25.6	0	0.23143	1.33219	2.73778	1.63108	0.08580	0.94084	1342.0	16.1	1334	18	101
WSP04-4.1	m, fr, sz	80.5	0.6	15.5	0	0.22404	1.35639	2.62414	2.04541	0.08495	1.52779	1303.2	16.0	1314	30	99
WSP04-5.1	m, fr, sz	431.7	1.6	83.9	0	0.22643	1.11253	2.64284	1.30654	0.08465	0.68447	1315.8	13.2	1308	13	101
WSP04-6.1	m, fr, hb	112.2	0.6	21.7	0	0.22494	1.32476	2.63180	1.62271	0.08486	0.93710	1307.9	15.7	1312	18	100
WSP04-7.1	m, fr, hd	225.2	0.8	43.5	0	0.22486	1.17597	2.64340	1.45750	0.08526	0.85883	1307.5	13.9	1321	17	99
WSP04-8.1	e, fr, sz	124.0	0.7	23.6	0	0.22108	1.29512	2.54904	2.03551	0.08362	1.56511	1287.6	15.1	1284	31	100
WSP04-9.1	e, fr, hd	538.9	0.8	102.1	0	0.22041	1.22336	2.56286	1.34560	0.08433	0.55912	1284.1	14.2	1300	11	99
WSP04-10.	e, rd, hd/o	710.4	0.3	66.8	0	0.10941	1.06306	0.93625	1.49619	0.06206	1.05155	669.3	6.8	676	23	99

1	sc															
WSP04-11.1	m, fr/rd, sz	1094.4	0.2	100.7	1	0.10676	1.16185	0.90536	1.73512	0.06151	1.27593	653.9	7.2	657	28	100
WSP04-12.1	m, rd, hd/osc	424.4	0.3	36.6	0	0.10014	1.09643	0.85114	1.81498	0.06164	1.44395	615.3	6.4	662	31	92
WSP04-13.1	e, rd, hd/sz	916.4	0.4	81.6	2	0.10285	1.30493	0.88120	2.36303	0.06214	1.93446	631.1	7.8	679	42	92
WSP04-14.1	m, fr, hd	522.1	0.6	99.2	1	0.22069	1.07156	2.54264	1.32113	0.08356	0.76067	1285.5	12.5	1282	15	100
WSP04-15.1	m, fr, sz	345.3	1.0	66.0	0	0.22218	1.10656	2.56120	1.44274	0.08361	0.91837	1293.4	13.0	1283	18	101
WSP04-16.1	m, fr, hb	128.9	0.8	24.6	0	0.22212	1.28011	2.58142	1.91093	0.08429	1.41806	1293.0	15.0	1299	28	100
WSP04-17.1	e, fr, hd	190.2	0.8	36.5	0	0.22311	1.20719	2.59192	1.63269	0.08425	1.09532	1298.3	14.2	1298	21	100
WSP04-18.1	m, fr/rd, hd	241.8	0.8	46.9	0	0.22614	1.17040	2.66258	1.34615	0.08539	0.66400	1314.2	13.9	1325	13	99

x.y: grain number followed by analysis number

Grain habit: p = prim, eq = equant, fr = fragment, r = rounded, rp = rounded prism

Site: e = end or edge, m = middle, r = rim/overgrowth

CL image microstructures: osc = oscillatory zoning, sz = sector zoning, h = homogeneous (b = bright or d = dark)

U-Pb data corrected for non-radiogenic Pb based on measured ^{204}Pb and 2000 Ma model Pb of Comming and Richards (1975)

All uncertainties are 1σ

Highlights

U-Pb zircon data presented for the Embu Complex, Ribeira Belt, Brazil.

Main zircon ages span 1500-1000 and 2000-1700 Ma (detrital) and 850-570 Ma (metamorphic).

The youngest detrital grain is dated at 974 ± 12 Ma

Detrital and metamorphic zircon ages indicate Tonian deposition (970-850 Ma).

Main source area is the Grenville-Sveconorwegian-Sunsás orogen.

Embu Complex accumulated on margin of Rodinia.